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Characterization of Spatial and Temporal Trends in Water Quality in Puget Sound

Final Report

Puget Sound Estuary Program

FINAL REPORT

CHARACTERIZATION OF SPATIAL AND TEMPORAL TRENDS IN WATER QUALITY IN PUGET SOUND

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EXECUTIVE SUMMARY

The primary purpose of this characterization study is to assess whether water quality in Puget Sound has changed over time. The major focus of this study is nutrient enrichment and the enhancement of algal blooms. The physical variables investigated are salinity and water temperature. The chemical variables investigated are concentrations of dissolved oxygen, inorganic nitrate, and orthophosphate. The intensity of algal blooms is measured by the concentration of chlorophyll a, percent dissolved oxygen saturation in surface water, and Secchi disk depth. The concentration of sulfite waste liquor is evaluated as an index of pulp mill pollution. The concentration of fecal coliform bacteria is evaluated as an index of sewage contamination. Although toxic contaminants are an important environmental concern in Puget Sound, they were not investigated during this study. The project was sponsored by the U.S. Environmental Protection Agency (EPA), Office of Marine and Estuarine Protection (OMEP); and the U.S. EPA Region X, Office of Puget Sound as part of the estuarine characterization initiative.

Data for this study were compiled from existing data sources and now exist in a unique database. Oceanographic data were obtained from the University of Washington Department of Oceanography, the Washington Department of Ecology, the Washington Department of Fisheries, and the Municipality of Metropolitan Seattle. Climatic data were obtained from the National Oceanic and Atmospheric Administration. Sources of oceanographic data were screened to determine where data were collected (i.e., location) and the timeframe in which data were collected. Quality assurance reviews were also performed to assess the validity of the field and laboratory techniques used to generate the data. Before the above data sets were used, they were examined for completeness and corrected for errors and inconsistencies in data coding and units of measurement.

Numerous changes in the water quality of Puget Sound were observed despite limited availability of high quality, long-term monitoring data. Changes in station locations and data sources also limited data interpretation in some areas (e.g., Port Gardner, Budd Inlet, Oakland Bay). Hence, results should not be overinterpreted. The absence of detectable changes in a study area may indicate that changes have not occurred <u>or</u> that the available data did not provide sufficient resolution to detect changes that have occurred. Also, substantial distances separating most of the sampling stations from onshore pollutant sources may have limited the ability of the analyses to reveal changes that may have occurred near such sources when inputs from those sources charged. Moreover, because data were available at most sites only for the upper 10-30 m of the water column, changes in conditions below these depths could only be detected if they affected the water column relatively close to the surface. Finally, changes detected at a given sampling station do not demonstrate that the same types of changes have occurred throughout the body of water that contains the station.

SPATIAL AND TEMPORAL TRENDS IN WATER QUALITY IN PUGET SOUND

Temporal trends in water quality were analyzed at 13 study areas around Puget Sound. Study areas were located in northern Puget Sound (one), central Puget Sound (four), southern Puget Sound (five), and Hood Canal (three). Trend analyses were conducted for each study area during that area's algal bloom season. Although oceanographic data are available dating back to 1932, data sets for most of the study areas began in the 1950s. Results are summarized below.

Physical Conditions

Salinity values decreased and water temperature values increased in most study areas. Salinity values declined in 8 of the 13 study areas. No explanation is available for the decreasing salinity values, but the available rainfall data are inconsistent with the salinity declines. The observed decline in rainfall in the Seattle area would have been expected to increase, rather than to decrease, salinity in the sound. One possible explanation for the salinity declines is that decreased volumes of oceanic water entering the sound from the Strait of Juan de Fuca may have contributed to the salinity decreases.

Water temperature values increased in 7 of the 13 study areas and decreased in only 2 of the 13 study areas. Water temperatures appear to be influenced by climate. At the study sites where increases in water temperatures were detected, data collection began during the cool periods of the early 1930s and the early 1950s.

Dissolved Oxygen

Dissolved oxygen concentrations increased in 7 of the 13 study areas, all of which are located in the southern sound or Hood Canal. The sites in the southern sound were influenced by unusually high dissolved oxygen concentrations in 1986, the last year included in the study. Although the cause of these high dissolved oxygen concentrations could not be determined, they may have occurred during intense algal blooms. Neither temporal increases in dissolved oxygen concentrations, nor unusually high concentrations of dissolved oxygen in 1986 were observed in the northern or central sound study areas.

Very low dissolved oxygen concentrations were rarely observed during the study. At all study areas except Point Jefferson, the deepest samples were only collected from 10 or 30-m depth. Because of active circulation, low dissolved oxygen concentrations are unlikely to occur in the Point Jefferson study area. Also, minimum dissolved oxygen concentrations typically do not occur during the algal bloom season. The lowest mean dissolved oxygen concentration (4.3 mg/L) was observed at 30-m depth in the South Hood Canal study area.

A single exception to the apparent absence of low dissolved oxygen concentrations occurred at the Oakland Bay study area during the mid-1950s. Discharges of sulfite waste liquor from the ITT-Rayonier pulp mill in the City of Shelton lowered dissolved oxygen concentrations, occasionally down to zero. Very low dissolved oxygen concentrations were not found in the Oakland Bay study area after this mill closed in 1957.

Nutrients

Nitrate data are available since the mid-1970s. Well-developed trends appear to have occurred only in the study areas in Port Gardner, City Waterway, Carr Inlet, and Hood Canal. Except for the City Waterway study area, substantial decreases in nitrate concentrations were detected in all these sites. In Hood Canal, progressively less-developed decreases were detected in the Mid-Hood Canal and Dabob Bay study areas. It appears that the factor affecting nitrate concentrations in Hood Canal [apparently algal blooms (see below)] probably was most influential in southern Hood Canal. The decrease in nitrate concentrations in the Carr Inlet study area also may be attributed to increased algal blooms. No explanations were apparent for the nitrate decrease in the Port Gardner study area or the nitrate increase in the City Waterway study area.

Temporal changes in phosphate concentrations were detected at 11 study areas. Long-term decreases (since the 1950s) were detected in seven of the nine study areas from which long-term phosphate data are available. Recent increases (since the mid-1970s) were detected in six study areas. Five of these six increases were statistically significant at $P<0.05$; the significance level of the sixth increase was $P=0.08$. No statistically significant ($P<0.05$) decreases have been detected since the mid-1970s.

The cause(s) of the widespread decreases in phosphate concentrations observed since the 1950s are unknown. One explanation involves decreased inputs of phosphate from the Strait of Juan de Fuca. However, this hypothesis has not been tested. Because the declines were detected in both rural and urban study areas, anthropogenic influences do not explain these results. Although it was not possible to calibrate the analytical techniques used in the 1950s with those used recently, the older techniques generally were reasonably accurate.

All recent increases in phosphate concentrations occurred in urban study areas: Bellingham Bay (Bellingham), Port Gardner (Everett), Sinclair Inlet (Bremerton), City Waterway (Tacoma), Budd Inlet (Olympia), and Oakland Bay (Shelton). The cause(s) of these phosphate increases are not known. However, the absence of such increases in rural study areas suggests that these increases may be attributed to anthropogenic factors. Changes in the quantities and characteristics of pulp mill discharges since the mid-1970s may have influenced phosphate concentrations in Bellingham Bay, Port Gardner, and City Waterway. Substantial decreases in the discharges of sulfite waste liquor occurred near the Bellingham Bay and Port Gardner study areas. Because sulfite waste liquor removes phosphate from seawater solution, increased phosphate concentrations in these two areas could have been in response to decreased sulfite waste liquor concentrations. Phosphoric acid has been added to the effluent of the kraft pulp mill located on Commencement Bay since 1977. This additional phosphate may have contributed to the recent increase in phosphate concentrations observed at the nearby City Waterway study area. No specific anthropogenic factors were identified to explain the phosphate increases that have occurred since the mid-1970s in the other three urban areas (Sinclair Inlet, Budd Inlet, Oakland Bay).

Indicators of Phytoplankton Growth

Few credible trends in the values of the standard phytoplankton indicators were detected in most of the study areas. Phytoplankton concentrations appear to have increased in the Carr Inlet study area. A statistical decrease in phytoplankton concentrations was detected at the Point Jefferson study area, while a statistical increase in phytoplankton concentrations was detected at the Nisqually Reach study area. However, both of these changes appear to have been caused by erratic fluctuations, rather than by systematic trends.

Increases in percent dissolved oxygen saturation and decreases in nutrient concentrations were detected at depths of 10- and 30-m depths in the Hood Canal study areas. These changes suggest that rates of photosynthesis may have increased at depth in the Hood Canal study areas.

The lack of statistically significant changes in the values of the standard phytoplankton indicator variables in most of the study areas may be attributed in part to inadequacies in the database. Sampling frequencies were insufficient to assess algal bloom dynamics. Data on cell density, photosynthesis rates, or chlorophyll _a_ concentrations would have provided direct measures of phytoplankton abundance, but few such data are available. The surrogate variables used as phytoplankton indicators in this study (i.e., percent dissolved oxygen saturation at the surface and Secchi disk depth) only provide information about conditions near the surface. Phytoplankton maxima can occur well below the surface, particularly in areas with clear water, such as Hood Canal. Also, both surrogate variables are affected by variations in environmental variables other than phytoplankton abundance. Percent dissolved oxygen saturation at the surface is affected by the oxygen content of the source water, while Secchi disk depth is affected by the turbidity associated with suspended sediments.

Pollutants

Concentrations of sulfite waste liquor declined in all four study areas near pulp mills: Bellingham Bay, Port Gardner, City Waterway, and Oakland Bay. The decline of sulfite waste liquor concentrations in the Oakland Bay study area coincided with the closure of the ITT-Rayonier pulp mill in the City of Shelton. Declines at the other sites generally coincided with improvements in the effluent treatment procedures used by the local mills.

Temporal changes in concentrations of fecal coliform bacteria may be attributed to changes in point sources near the Bellingham Bay and Port Gardner study areas. Declines at the Bellingham Bay site coincided with improvements in the sewage treatment facilities and closures of combined sewer overflows. An apparent increase in fecal coliform bacteria concentrations in the Port Gardner study area followed the initiation of secondary effluent treatment by the nearby Scott sulfite pulp mill. This increase probably was due to discharges of the bacterium, _Klebsiella_, an organism that is detected in standard fecal coliform tests and that grows rapidly in the secondary treatment facilities of sulfite pulp mills.

A decline in fecal coliform bacteria concentrations was detected at the Nisqually Reach study area. One relatively high value was recorded in 1978, near the beginning of data collection for fecal coliform bacteria at this site. This high value, which was detected in a sample collected near the end of a heavy rainstorm, has been followed by very low values since 1978. These results suggest that the high value in 1978 reflected an unusual influence of contaminated runoff.

SENSITIVITY TO NUTRIENT ENRICHMENT

The sensitivity of an estuary to the deleterious effects of algal blooms caused by nutrient enrichment depends on several factors, including the amounts of inputs, flushing rates, and density stratification. Because of their physical conditions and/or their proximities to large population centers, the following areas were judged to be most vulnerable to nutrient enrichment:

- Sinclair Inlet
- Budd Inlet
- Oakland Bay
- South Hood Canal.

RECOMMENDATIONS FOR ENVIRONMENTAL MONITORING IN PUGET SOUND

The water quality characterization study provides a unique opportunity to assess existing monitoring programs by using the data in a water quality trends analysis. Key recommendations derived from the results of this study and comments of work group members are outlined below.

- One organization should oversee all water quality monitoring programs to facilitate compatibility of field and laboratory techniques and database formats, and to coordinate geographic coverage. Use of the protocols recommended by the Puget Sound Estuary Program (U.S. EPA 1986a) would standardize the field and laboratory techniques of monitoring programs in Puget Sound.

- Changes in field and laboratory techniques should be documented; new techniques should be calibrated with old techniques.

- The goals of the monitoring program should be developed quantitatively before the study design is finalized (e.g., how much change in dissolved oxygen concentrations should be detectable over a given time period?). Alternative study designs should be evaluated with statistical power analysis, using existing data.

- The influence of physical factors (e.g., climate, bulk flows of oceanic and fresh water) on water quality should be monitored to improve understanding of ecosystem function and to enable comparison of the impacts of physical and anthropogenic factors on water quality.

- Environmental sampling should reflect the seasonal, temporal, and spatial scales of variation of the individual variables of most interest. The following suggestions are provided to improve upon the historical monitoring programs in Puget Sound:

    - Samples collected to assess the impacts of major contaminant sources should be collected close to those sources

- Sampling plans designed to detect low dissolved oxygen concentrations should emphasize frequent sampling of the bottom waters at the heads of poorly flushed inlets (e.g., Budd Inlet) during late summer

- Sampling of algal blooms should occur frequently during the peak bloom season of each individual study area

- Sampling of episodic events (e.g., discharges from combined sewer overflows or pulp mills) should occur when the discharges occur.

• Water quality in Budd Inlet should be monitored to determine whether nitrogen removal by the Lacey, Olympia, Tumwater, and Thurston County (LOTT) sewage treatment plant reduces bloom intensity.

• Specific and quantitative measures of phytoplankton density (e.g., concentration of chlorophyll _a_, species-level identification) and suspended sediments (e.g., concentration of suspended solids) should be used in place of Secchi disk depth. Species-level identification of phytoplankton combined with chlorophyll _a_ data provides the most sensitive measure of changes in the phytoplankton community.

• A microbiological test is needed to distinguish between bacterial contamination from sewage and secondary effluents from sulfite pulp mills. Because current fecal coliform tests cannot make this distinction, shellfish beds may be closed because of exposure to pulp mill effluent rather than exposure to sewage. Although not well studied in Puget Sound, the health risk associated with _Klebsiella_ contamination from secondary pulp mill effluent appears to be less than the health risk associated with sewage contamination.

CHAPTER 1. WATER QUALITY CHARACTERIZATION STUDY FOR THE PUGET SOUND ESTUARY PROGRAM

INTRODUCTION

This report presents the results of the analysis of spatial and temporal trends in the water quality of Puget Sound. The sound is an estuary located in western Washington State, USA (see Chapter 2 for a detailed discussion). This study was sponsored by the U.S. Environmental Protection Agency (U.S. EPA), Office of Marine and Estuarine Protection (OMEP); and U.S. EPA Region X, Office of Puget Sound.

The objective of this project is to characterize the water column of Puget Sound by analyzing historical and current water quality data. Physical and chemical variables were analyzed to assess nutrient enrichment and algal blooms in the water column. In addition, contaminants from pulp mill and sewage discharges were analyzed.

This report comprises six chapters: Chapter 1 introduces the water quality characterization study and the Puget Sound Estuary Program (PSEP); Chapter 2 provides an overview of the physical environment, oceanography, and history of Puget Sound; Chapter 3 describes the study design; Chapter 4 details the procedures used for data analysis; Chapter 5 presents the results of the analysis of 13 selected study areas; and Chapter 6 includes the summary of results and recommendations for monitoring in the sound.

The Estuarine Environment

An estuary is a semi-enclosed coastal body of water with an open connection to the sea. The seawater in an estuary is diluted by fresh water from upland sources. This fresh water typically provides substantial inputs of nutrients to an estuary. Compared with the open ocean, most estuaries are shallow and protected. Thus, the estuarine environment usually is conducive to high rates of biological productivity. Because estuaries are often natural connecting points between oceanic transportation systems and onshore populations, most coastal cities and sea ports are situated on or near estuaries. Consequently, estuaries are vulnerable to the environmental degradation that is often associated with an urbanized, industrial society.

The impact of pollution on an estuary depends on the amount and type of inputs, and the capacity of the system to assimilate or export excesses. In the case of nutrient enrichment, the initial effect is to stimulate primary production, principally by phytoplankton in the water column. Moderate increases in primary production may be beneficial because increased energy inputs into the food chain may enhance fish and shellfish production. However, excessive nutrient enrichment in estuaries can overstimulate primary production. The subsequent sinking and decay of dead plant material may cause declines in dissolved oxygen concentrations, which become increasingly severe with depth (Neilson and Cronin 1981). Large inputs of organic material (e.g., untreated raw sewage or pulp mill wastes) may also lower dissolved oxygen concentrations at depth as the material decays. Low dissolved oxygen concentrations in the water column can have severe deleterious effects on an estuary, causing declines or mortality of fish and bottom-dwelling invertebrates, and the occurrence of fouled and malodorous waters.

PUGET SOUND ESTUARY PROGRAM

PSEP was initiated in 1985 under OMEP's National Estuary Program. The purpose of the National Estuary Program is to protect and restore water quality and living resources in the nation's estuaries. The major participants in PSEP are the U.S. EPA Region X, Office of Puget Sound, the Puget Sound Water Quality Authority (PSWQA); and the Washington Department of Ecology (Ecology). Agencies involved with PSEP seek to maintain water quality standards for Puget Sound that protect public health and welfare; assure protection and propagation of fish, shellfish, and wildlife populations; and allow recreational activities.

One of the highest priorities of PSEP is the comprehensive characterization (i.e., description) of Puget Sound. The goals of characterization are to 1) identify environmental changes and determine relationships between environmental conditions and resource use, 2) identify adverse changes in the biological system, 3) identify the causes and importance of such adverse changes, and 4) identify key measures needed to track changes and improvements in the environment.

THE PUGET SOUND WATER QUALITY CHARACTERIZATION PROJECT

In keeping with the National Estuary Program's characterization initiative, one focus of PSEP's characterization work is the synthesis of historical data that have not been analyzed completely. Trends in water quality emerged as a priority for historical characterization studies in 1987. This topic was chosen by the U.S. EPA's Office of Puget Sound after extensive consultation with their Technical Advisory Committee, PSWQA, and interested scientists from universities and other governmental agencies in the region.

Content and Scope of Work

This water quality characterization report examines temporal trends in several nutrient-related variables (i.e., conventional pollutants), including turbidity and concentrations of nitrate, phosphate, dissolved oxygen, and chlorophyll *a* in the water column of Puget Sound. Fecal coliform bacteria and sulfite waste liquor are included as indices of domestic and pulp mill discharges. Salinity and water temperature data are also analyzed to facilitate interpretation of the variables of interest. The study is geographically comprehensive, with detailed analyses of the available data from numerous locations throughout the sound.

The investigation of conventional pollutants in this project complements PSEP's studies of toxic contamination in Puget Sound (e.g., U.S. EPA 1986b). Toxic contaminants (i.e., metals and organic chemicals) cause serious problems in some urbanized areas of the sound [e.g., metals in the sediments of Commencement Bay (Tetra Tech 1985)]. However, investigating trends in contamination by toxic substances was beyond the scope of the present study.

Because of constraints on time and level-of-effort, most of the work consisted of analyzing existing data sets that were reasonably complete and readily accessible. However, substantial efforts were devoted to completing the entry of water column data from the University of Washington and the Washington Department of Fisheries into STORET, U.S. EPA's computerized database of water quality information.

Rationale

The purpose of this report is to fill a large gap in the existing body of information on water quality in Puget Sound with a synthesis of historical data. The sound is a critical resource that supports an abundance of commercially and recreationally important fish and shellfish. The sound also serves as a major shipping corridor (U.S. EPA 1984). However, growth of population and industry in the Puget Sound region have caused the introduction of large quantities of nutrients and other wastes into the sound. This analysis of water quality trends throughout the sound will attempt to provide an early warning of potential problems and a long-term historical basis for interpreting future monitoring data. This information may also be used to facilitate the design of the sampling program for the Puget Sound monitoring plan presently being developed by PSWQA (Tetra Tech 1986).

Previous analyses of temporal trends in conventional water quality variables in Puget Sound have not detected long-term degradation of water quality caused by nutrient enrichment. However, most of these studies have been limited to the central basin of the sound [e.g., Duxbury 1975; National Oceanic and Atmospheric Administration (NOAA) 1985]. Jones and Stokes (1984) reported that "nutrient loading can become, or is, a problem in relatively shallow, poorly flushed embayments of Puget Sound," and indicated that future population growth could cause deteriorating conditions in other regions of the sound. Localized effects of high nutrient concentrations, which may be anthropogenic in origin, have been observed in certain areas [e.g., in Budd Inlet (URS 1986a)]. Thus, a comprehensive study encompassing all the regions of the sound was conducted.

Characterization Work Group and Peer Review

A work group consisting of local scientists with experience in water quality research in Puget Sound was assembled to provide advice and peer review (Table 1.1). Dr. John Armstrong of the U.S. EPA monitored the project. External review was provided by Dr. Gordon Bilyard of Tetra Tech, Inc., and Dr. Michael Connor, Dr. Eric Crecelius, and Mr. Richard McGrath of Battelle. Dr. Alyn Duxbury of Washington Sea Grant was retained by PSEP as a consultant for this project. He provided detailed recommendations on the design of the study.

TABLE 1.1. MEMBERS OF THE WORK GROUP FOR THE PUGET SOUND WATER CHARACTERIZATION PROJECT

Name	Affiliation
John Armstrong	U.S. EPA
Chuck Boatman	URS, Inc.
Ned Cokelet	NOAA
Eugene Collias	University of Washington (retired)
Jeffery Cox	Evans-Hamilton, Inc.
Ralph Domenowske	Metro
Alyn Duxbury	Washington Sea Grant
Alan Mearns	NOAA
Marvin Tarr	Washington Department of Fisheries
Don Weston	U.S. EPA
John Yearsley	U.S. EPA

CHAPTER 2. OVERVIEW OF PUGET SOUND

This chapter contains background information about Puget Sound. The information provides a context in which the water quality analyses can be interpreted. The chapter consists of three sections:

- Physical environment and oceanography of Puget Sound
- History of the development of the Puget Sound area
- Factors affecting the sensitivity of Puget Sound to nutrient enrichment.

PHYSICAL ENVIRONMENT AND OCEANOGRAPHY OF PUGET SOUND

Location

Puget Sound is a fjord-like estuary (i.e., narrow and deep) with a maximum depth of approximately 280 m (see Figure 2.1). It is connected to the Pacific Ocean by the Strait of Juan de Fuca to the west and the Strait of Georgia to the north. A shallow sill at Admiralty Inlet separates the sound from the two straits.

Basin Configuration

South of Admiralty Inlet, Puget Sound is subdivided into the Main Basin, Whidbey Basin, South Basin, and the Hood Canal Basin. The Main Basin lies between sills at Admiralty Inlet and Tacoma Narrows. It contains about 60 percent of the total volume of the sound south of Admiralty Inlet. Whidbey Basin lies between Whidbey Island to the west and the mainland to the east; it is not bordered by a sill. The Hood Canal Basin is long and narrow. It is oriented primarily north and south, with a major embayment (Dabob Bay) to the west and an eastern arm at its head. The Hood Canal

Basin is separated from Admiralty Inlet by a sill 50 m deep. The South Basin lies south of the sill at Tacoma Narrows. This basin has a complex arrangement of deep (down to nearly 200 m) channels, shallow embayments, islands, and sills.

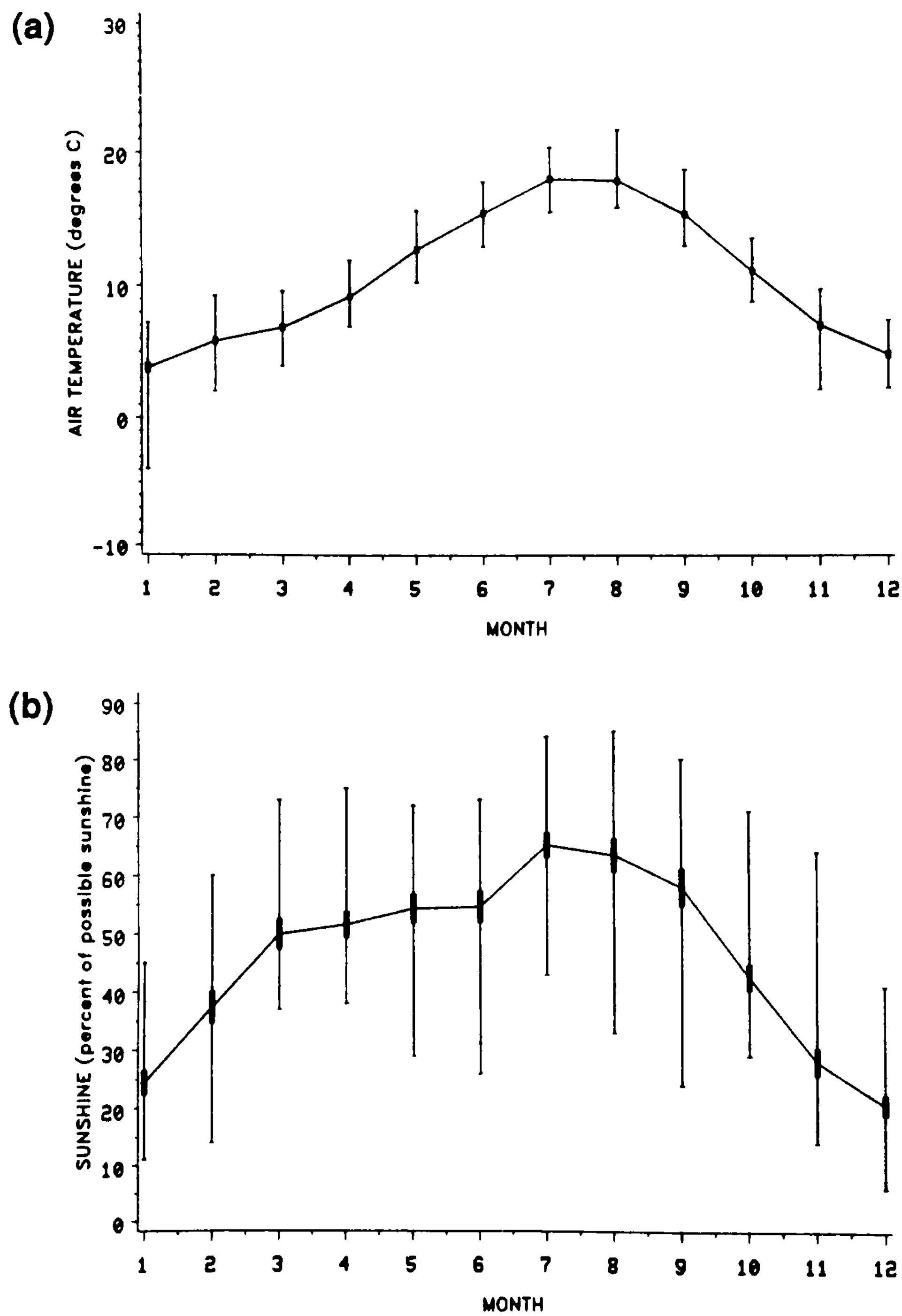
Climatic Patterns

The climate in Puget Sound has a strong seasonal component. Meteorological data collected at the Seattle-Tacoma International Airport from 1945 to 1985 (NOAA 1945-1985) show that July and August generally are warm, sunny, and dry. Late autumn, winter, and early spring generally are cool, cloudy, and damp (see Figure 2.2a-c). About three-quarters of the annual precipitation occurs from October to March. These patterns are long-term averages; individual years may deviate substantially from the norms. For example, from 1945 to 1985, air temperature averaged 12.1^{o} C during the warmest year (1958) and 8.9^{o} C during the coolest year (1955). Prevailing winds have the highest average velocity during the wet season (Figure 2.2d) and tend to come from the south and southeast during this period (Figure 2.2e). The calmest winds occur during the summer, when the prevailing direction is from the west.

Water Sources

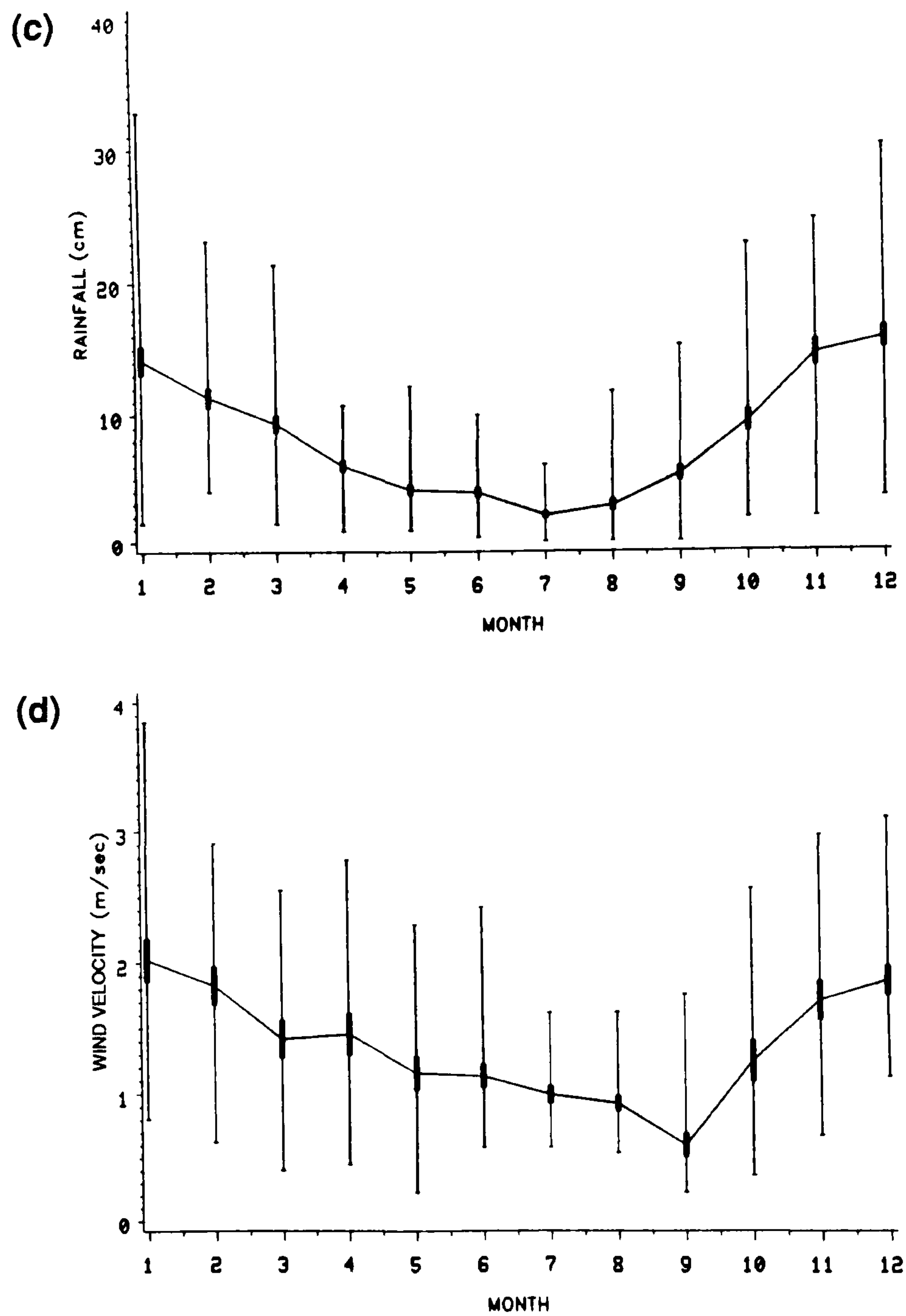
Coastal seawater flows into the Strait of Juan de Fuca at depth (Collias et al. 1974). Compared with water already in the sound, the coastal seawater is relatively dense (σ_t >26), salty (salinity >33 ppt), and cold (temperature <8^{o} C). Although most of the coastal seawater exiting the Strait of Juan de Fuca flows north into the Strait of Georgia, a substantial amount flows south through Admiralty Inlet and into the Main Basin.

Rivers that discharge into Puget Sound are its primary source of fresh water (Collias et al. 1974). The average flow of fresh water into the sound is approximately 1,600 m^3/sec (Table 2.1). The largest rivers discharging into Puget Sound are in the northern and central regions. Because fresh water is less dense than salt water, it tends to remain near the surface until turbulence mixes it into deeper layers.



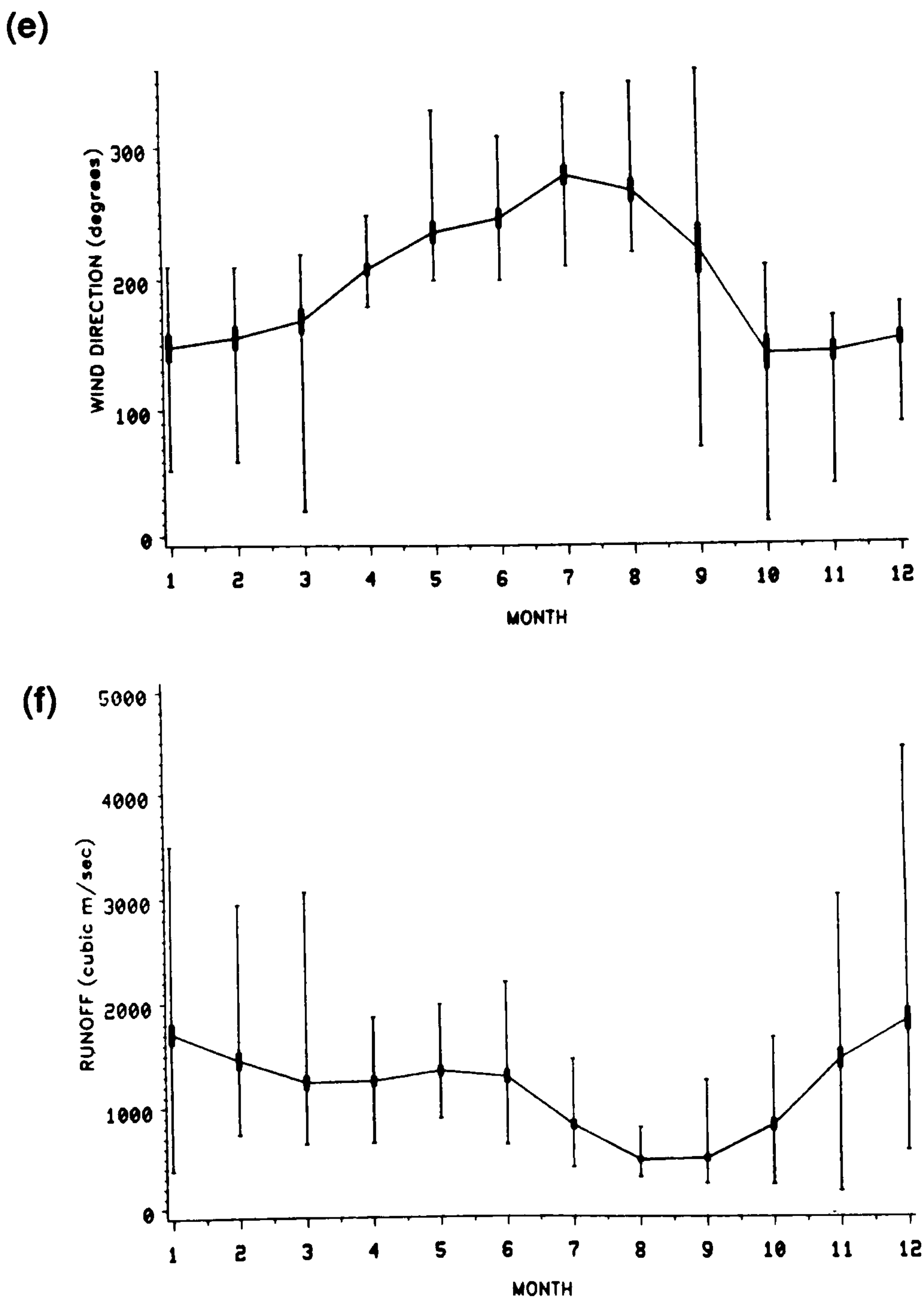
NOTE: Data collected at the Seattle-Tacoma International Airport.

Figure 2.2. Monthly mean climatic conditions in the Puget Sound area.
a. Air temperature (data from 1945 to 1985).
b. Percent of possible sunshine (data from 1965 to 1985).



NOTE: Data collected at the Seattle-Tacoma International Airport.

Figure 2.2. (Continued). Monthly mean climatic conditions in the Puget Sound area.
c. Rainfall (data from 1945 to 1985).
d. Wind velocity (data from 1965 to 1985).



NOTE: Wind data collected at the Seattle-Tacoma International Airport; runoff data collected from 7-22 USGS gauging stations.

Figure 2.2. (Continued). Monthly mean climatic conditions in the Puget Sound area.
e. Wind direction (data from 1965 to 1985).
f. Total freshwater runoff to Puget Sound (data from 1930 to 1978).

TABLE 2.1. LOCATION AND FLOW OF RIVERS DISCHARGING INTO PUGET SOUND

River	Location of Discharge	Average Flow (m^3/sec)	Percent Total Flow
Skagit	Skagit Bay	470	30
Snohomish	Everett Harbor	290	18
Stillaguamish	Port Susan	130	8
Nooksack	Bellingham Bay	110	7
Puyallup	Commencement Bay	95	6
Nisqually	Nisqually Reach	70	5
Sammamish-Cedar	Shilshole Bay	50	3
Green-Duwamish	Elliott Bay	50	3
Elwha	Dungeness Bay	40	2
Skokomish 1	Southern Hood Canal	35	2
Skokomish 2[a]	Southern Hood Canal	30	2
Deschutes	Budd Inlet	25	1
Dosewallips	Central Hood Canal	20	1
Duckabush	Central Hood Canal	15	1
Hamma Hamma	Central Hood Canal	15	1
Dungeness	Dungeness Bay	13	1
Samish	Samish Bay	5	<1
Big Quilcene	Quilcene Bay	5	<1
Tahuya	Southern Hood Canal	4	<1
Whatcom	Bellingham Bay	3	<1
Little Quilcene	Quilcene Bay	2	<1
Other		60	3
Total		1,590	100

[a] Skokomish 2 is the outlet from Cushman powerhouse No. 2.

Reference: Evans-Hamilton, Inc. and D.R. Systems, Inc. (1987).

The volume of fresh water runoff entering the sound varies with volume of rainfall, except during spring and early summer when mountain snowmelt augments riverine inputs (see Figure 2.2f) (NOAA 1984a). Runoff from snowmelt occurs primarily in the Whidbey, Main, and Hood Canal Basins. Because the area around the southern sound contains few mountains, the early summer rise in runoff from snowmelt has little effect in the southern sound.

Patterns of Water Circulation

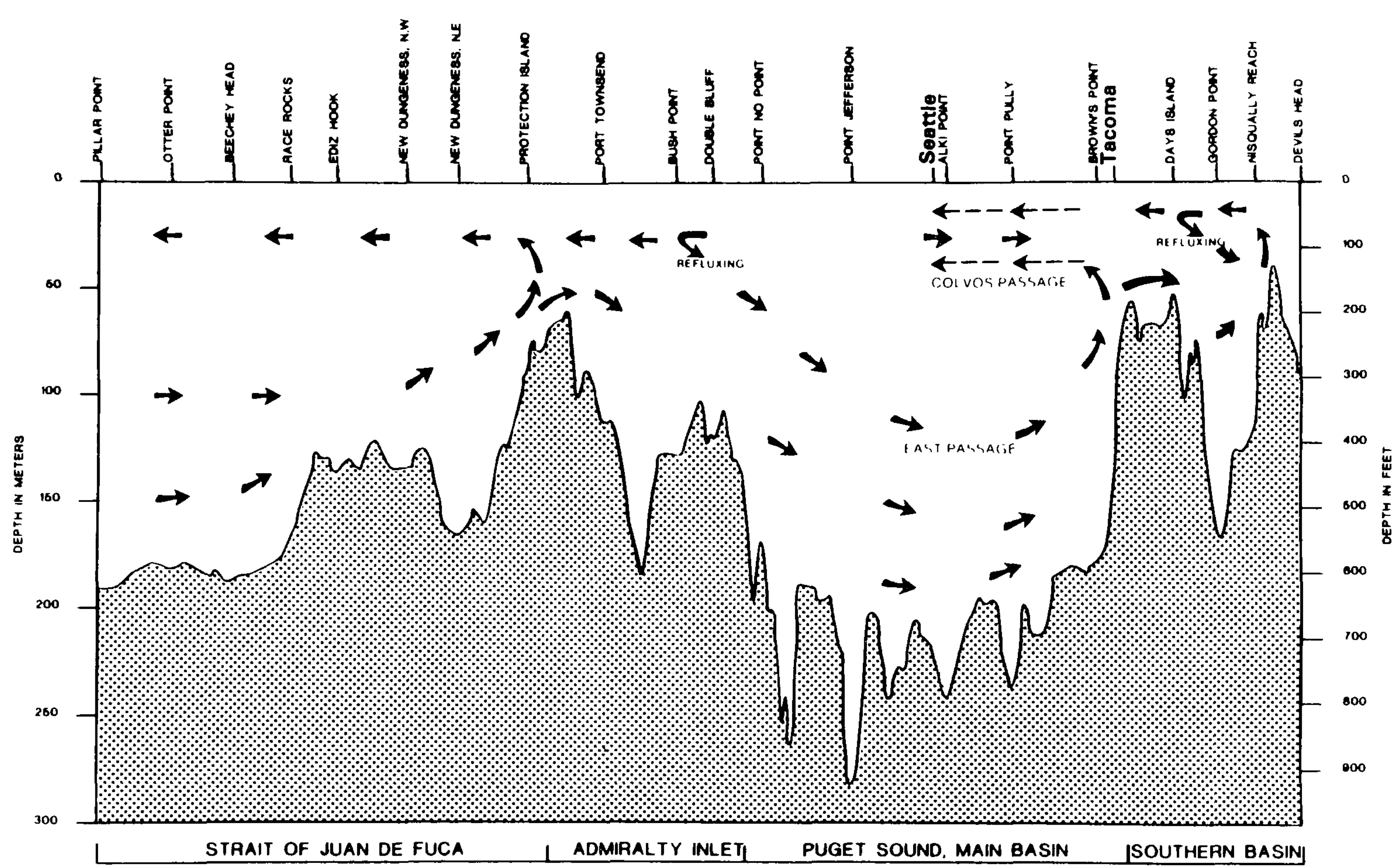
A two-layered pattern of net water circulation occurs in Puget Sound (Collias et al. 1974; Ebbesmeyer and Barnes 1980). Lighter, less saline water flows seaward near the surface, while denser, more saline oceanic water flows landward near the bottom (Figure 2.3). The seaward surface flow is driven by riverine inputs. Vertical mixing, particularly at the heads of embayments, entrains deeper oceanic water up toward the surface, driving the landward flow of the deeper layers and providing salt to the surface layers. This two-layered circulation pattern is complicated by the presence of islands and shallow sills.

Large, oscillating tidal currents are superimposed on the net circulation pattern of surface outflow and deep inflow. Tidal exchange drives much of the vertical and horizontal mixing in Puget Sound, particularly at the sills at Admiralty Inlet and Tacoma Narrows. This mixing causes a substantial amount of low-salinity surface water to reflux into deeper layers (Figure 2.3). Approximately one-third to one-half of the surface water passing over the sill at Admiralty Inlet recirculates into the Main Basin via the deep layer before exiting the sound (PSWQA 1986a).

Patterns of Physical and Chemical Variation in Puget Sound

Salinity--

The outflow of surface waters removes water and salt from the sound. Salt is replenished by the inflow of oceanic water along the bottom. Surface salinity values are near zero at river mouths and reach approximately



Reference: PSWQA (1986b).

Figure 2.3. Generalized vertical cross section of Puget Sound, showing depth profile and net circulation pattern.

32 ppt in the Strait of Juan de Fuca. Bottom salinity values range from 28 to 33 ppt in the Main Basin and in the deep (>50 m) inlets. Bottom water with the highest salinity values is found in the western (Pacific) end of the Strait of Juan de Fuca and in the northern sound. Bottom water with the lowest salinity values is found at the heads of shallow (<20 m) inlets, particularly in the southern sound. Typically, there is a replacement of bottom water in the landward basins by dense, high-salinity seawater during the late summer or early autumn (Collias et al. 1974).

Depth gradients of salinity are affected by storms and wind direction. Winter storms and the prevailing winter southerly winds promote vertical mixing and break down vertical salinity gradients in the water column. The calmer summer weather and the prevailing summer westerly winds reduce rates of vertical mixing. These factors allow the development of density stratification in the water column. In areas where inputs of fresh water are substantial, density stratification results in vertical salinity gradients (particularly during calm periods), with the least dense and lowest salinity water at the surface.

Water Temperature--

The annual pattern of variation in surface water temperature usually lags behind the annual pattern of variation in air temperature (see Figures 2.2a and 2.4). Highest surface water temperatures typically occur in July or August. Differences among annual mean surface water temperatures can reach approximately 1.0^{o} C. Temperature at depth is less variable than at the surface, responding more to advective processes than to heat exchange. Thermal depth stratification is well developed during the summer, except in areas such as Admiralty Inlet, where turbulence caused by currents passing over sills mixes the water column. Thermal depth stratification breaks down during the winter because of storms and the prevailing wind direction.

Ranges in surface water temperatures vary geographically. Generally, the more enclosed, shallow, sluggishly circulating areas undergo more summer warming and winter cooling than the more open, deeper, turbulently mixed areas (Figure 2.4). The maximum summer monthly mean surface water tempera-

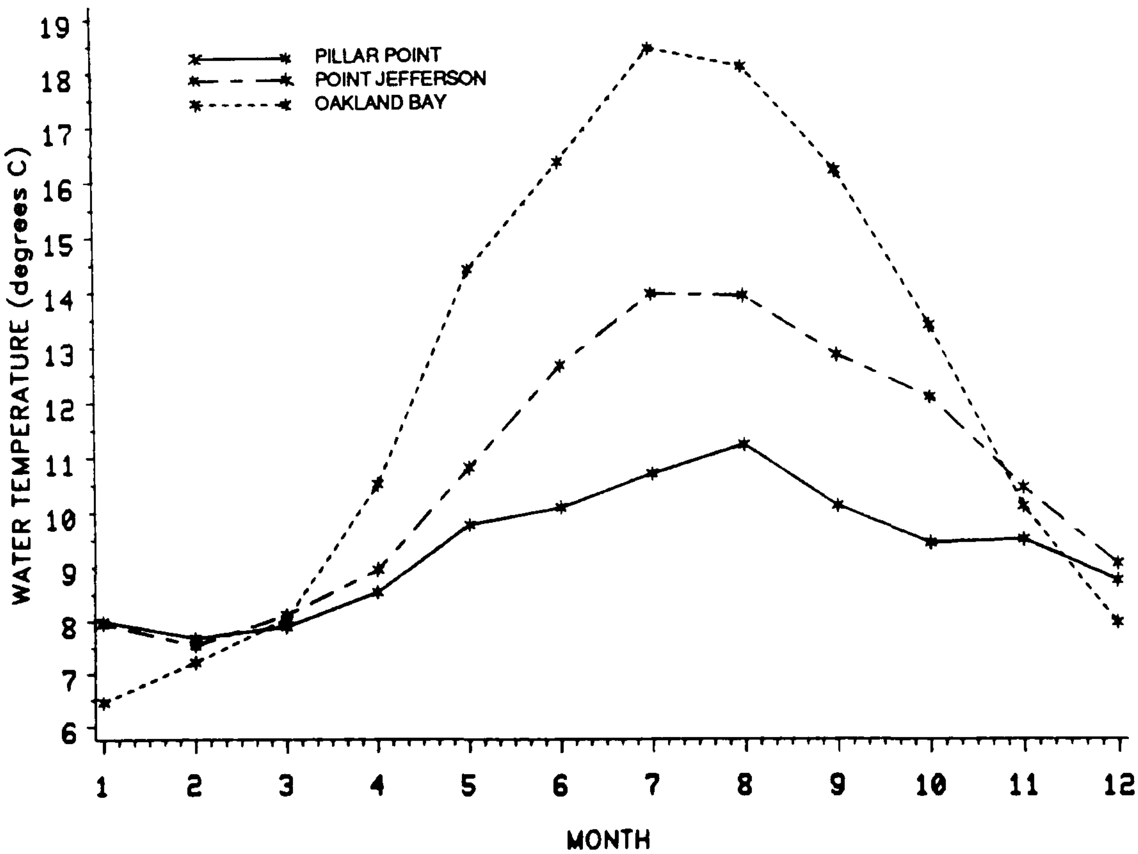


Figure 2.4. Monthly mean surface water temperatures at Pillar Point, Point Jefferson, and Oakland Bay.

ture is approximately 18.3° C at Oakland Bay, a shallow southern embayment. However, the maximum summer monthly mean surface water temperature is only about 11.2° C at Pillar Point, a deep area in the Strait of Juan de Fuca. Winter surface water temperatures vary over a smaller range. Minimum winter monthly mean surface water temperature is approximately 6.5° C at Oakland Bay and 7.7° C at Pillar Point.

Dissolved Oxygen--

Surface gas exchange and photosynthesis are the principal sources of dissolved oxygen in Puget Sound. Decay of organic material consumes oxygen, particularly in deeper waters. These factors produce vertical gradients of dissolved oxygen concentrations with lower values at depth. This gradient is enhanced by vertical density stratification during the warmer months, which prevents mixing of the surface and bottom layers. These effects, along with the entrainment of oxygen-poor bottom waters into the heads of embayments by net circulation, can cause periods of low dissolved oxygen in the heads of Dabob Bay, Lynch Cove, Port Susan, and northern Saratoga Passage.

Results from recent studies of Budd Inlet (URS 1986a) suggest that diurnal vertical migration of dinoflagellates may also contribute to vertical gradients of dissolved oxygen concentrations during dinoflagellate blooms in southern embayments. During such blooms, oxygen produced by photosynthesis during the day may cause surface waters to become supersaturated. At night the dinoflagellates consume oxygen in deeper waters. This concentration gradient is then maintained by density stratification.

Phytoplankton and Nutrients--

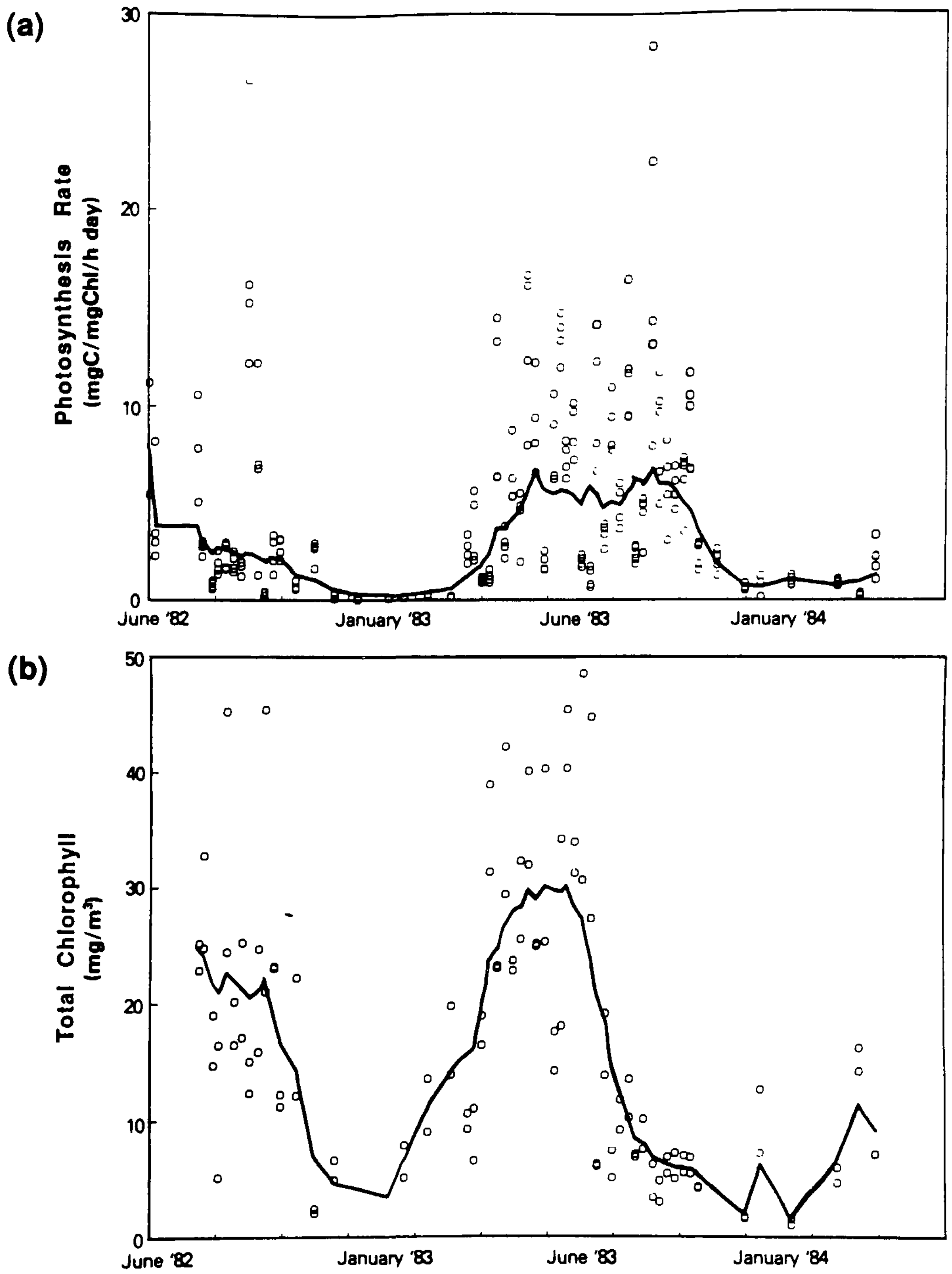
In central Puget Sound, phytoplankton growth usually is controlled by the amount of light available for photosynthesis and by vertical mixing rates. Vertical mixing removes algal cells from the photic zone. Winter et al. (1975) reported that over 50 percent of the chlorophyll a in the water column of central Puget Sound was below the photic zone, and that at the end of phytoplankton blooms, nitrate concentrations in the photic zone fell below levels needed for phytoplankton growth for periods of 2-3 days. They also reported that phosphate and silicate concentrations dropped during blooms, but remained above levels needed for phytoplankton growth. Lower rates of vertical mixing in the sluggishly circulating embayments may reduce the rates of removal of algal cells from the photic zone and the rates of renewal of nutrients to the surface layers from deeper waters (Collias et al. 1974; Duxbury 1975; Anderson et al. 1984; NOAA 1985). Therefore, limitation of algal growth by low nutrient concentrations may be more important in the southern embayments and in Hood Canal than in central Puget Sound.

The annual phytoplankton cycle begins with a spring diatom bloom. Diatom abundance tends to drop off in midsummer, although a secondary diatom bloom may occur in late summer. Dinoflagellate abundances gradually increase through the spring and reach a peak bloom in midsummer. Photosynthetic rates and algal standing stocks tend to be highest near the summer solstice and lowest near the winter solstice (Figures 2.5a,b) (Anderson et al. 1984).

Nutrient concentrations generally reflect the annual cycle of algal growth and dieoff. Lowest concentrations of nitrate and phosphate usually occur near midsummer, and highest concentrations usually occur near the winter solstice (Figure 2.6a,b) (Collias et al. 1974; Anderson et al. 1984). Phosphate in Puget Sound is replenished via the late summer replacement of resident water by upwelled oceanic water that is high in phosphate. Another factor that augments phosphate concentrations is the decay of sinking organic particles. Subsequently, phosphate-rich deep water is entrained to the surface by net circulation. Nitrate regeneration results primarily from riverine inputs during periods of high runoff in the winter (Robinson and Brown 1983).

A HISTORY OF THE DEVELOPMENT OF THE PUGET SOUND AREA

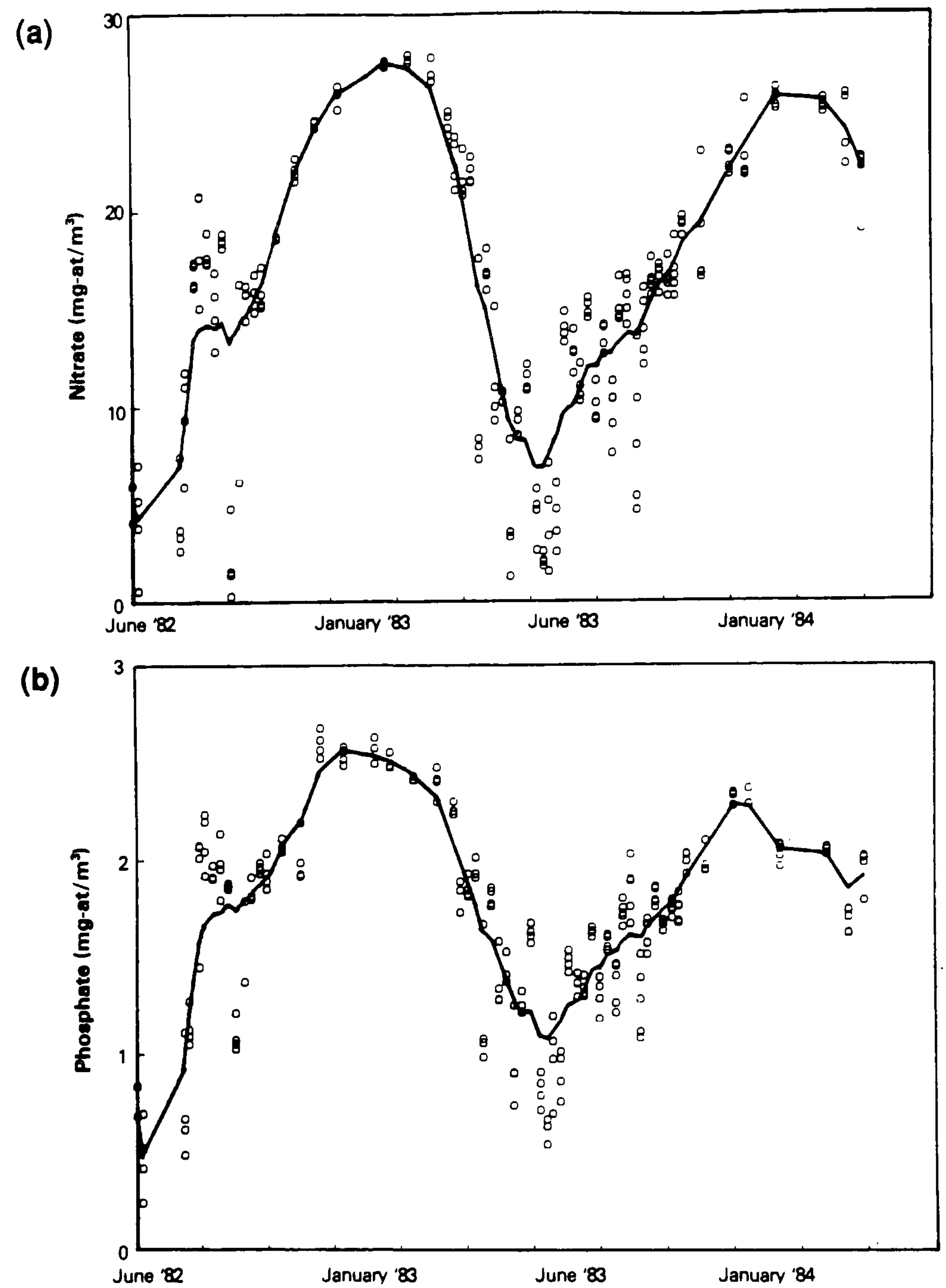
The potential for water quality deterioration resulting from anthropogenic inputs is influenced by a variety of sociological factors, including population size, land use patterns, and economic activities. Environmental



NOTE: Data collected at Seahurst Bight.

Reference: Anderson et al. (1984).

Figure 2.5. Dynamics of phytoplankton in central Puget Sound.
a. Chorophyll-specific photosynthesis rate (smoothed distribution).
b. Total chlorophyll concentration in the photic zone (smoothed distribution).



NOTE: Data collected at Seahurst Bight.

Reference: Anderson et al. (1984).

Figure 2.6. Dynamics of nutrient concentrations in central Puget Sound.
a. Dissolved inorganic nitrate.
b. Dissolved orthophosphate.

impacts can be affected not only by changes in these factors (e.g., population growth may increase the amount of sewage discharged into a receiving environment), but also by changes in governmental regulations and programs. For example, construction of a regional sewage treatment system by the Municipality of Metropolitan Seattle (Metro) reduced the number of raw sewage discharges into Puget Sound from 46 to zero between the late 1950s and 1970 (Metro 1969).

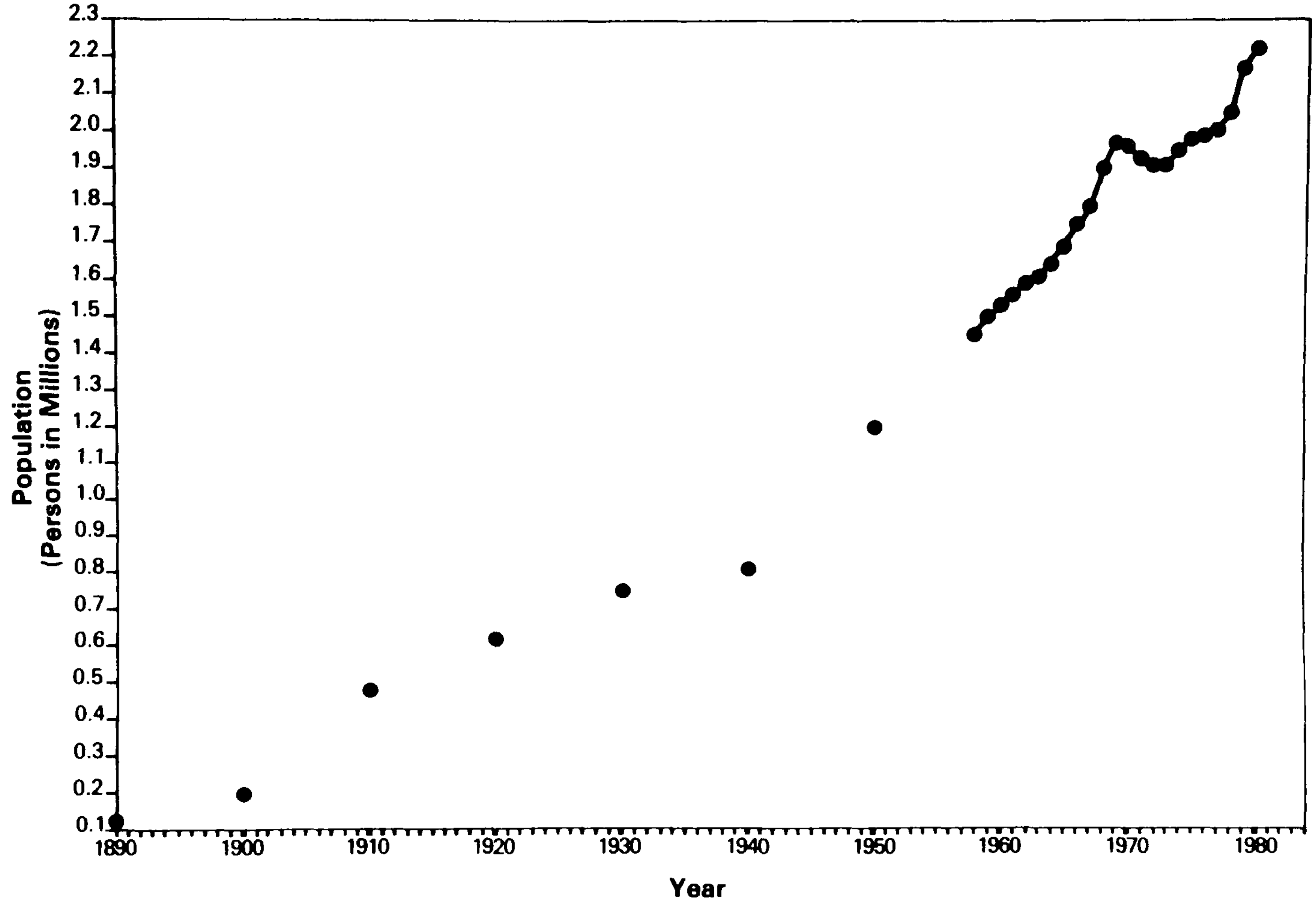
Human population activities may affect water quality directly by the production of domestic wastes and by other activities (e.g., industrial production) that generate wastes. Land use patterns affect the distribution and types of impacts caused by the population. Dredging or filling of wetlands to increase navigable waterways and usable land area can reduce the capacity of an estuary to trap sediments and absorb nutrients. Urban development concentrates the human population and local environmental impacts, increases runoff by increasing the amount of impervious land surface (e.g., roads, buildings), and increases nonpoint contamination from sources such as automobiles, farms, and households. While concentration of the urban population may facilitate the development of municipal sewage treatment systems, decentralization of the urban population may cause environmental problems to become more diffuse and less easily solved by local institutions and centralized treatment facilities.

Historical and current economic activities may have produced or may be producing characteristic types of environmental impacts in Puget Sound. For example, manufacturing processes that have been used in the region can introduce oxygen-demanding wastes and toxic wastes from point sources (e.g., pulp and lumber mills). Agricultural activities in the region may cause releases of organic wastes, nutrients, and pesticides from nonpoint sources. A forestry-based economy may lead to problems with upland erosion, sedimentation, and contamination by wood debris and chemicals that are used in the manufacture of products derived from wood (e.g., pulp).

The following historical information on the settlement and economic development of the Puget Sound region has been summarized from three sources: Chasan (1981), NOAA (1985), and PSWQA (1986b). Detailed information is available from these sources.

European settlement of the Puget Sound region began in 1845. Timber products and shipping were the major industries during the nineteenth century. Fisheries and agriculture were also important industries. By 1900, the population of the region had reached 200,000 (Figure 2.7). After 1910, resource-based industries (e.g., fishing, logging) peaked and began to decline, while manufacturing, transportation, and service industries began to grow. By 1920, substantial portions of the wetlands in Puget Sound had been diked and filled for agriculture (Shapiro and Associates 1983). During the 1920s, adverse impacts of pulp mills were becoming apparent. Communities around Lake Washington began treating sewage in the 1930s. The first routine monitoring of Puget Sound by the University of Washington began in 1932. Population growth continued in both urban and agricultural areas. Total population of the region reached 1 million by the mid-1940s.

After World War II, the economy became more diversified, with emphasis on the shipping, aerospace, and manufacturing sectors. The Washington State Pollution Control Commission was established in 1945. Resource-based and agricultural sectors continued to decline, although forestry-based employment and manufacturing remained important. In 1958, Metro was formed to develop and operate a regional sewage treatment system in the Seattle area. Industrial activity and residential land development became increasingly decentralized during the post-war period. For example, the average population density in pre-1960 residential areas was 20.5 persons/ha. In residential developments after 1960, the population density was approximately 11 persons/ha. The West Point Sewage Treatment Plant, which treats the bulk of Seattle's municipal sewage, became operational in 1966. During the 1950s and 1960s, 80,000 ha of commercially managed forest land was converted to urban or industrial use, roads, and farms. After 1970, the service sector became the largest component of the economy. Aerospace and military employment also remained high, while resource-based sectors, including forestry products, continued to decline. Population growth continued to expand into outlying counties.



Reference: NOAA (1985).

Figure 2.7. Total population in the counties of the Puget Sound basin from 1890 through 1980.

By 1985, the population of the Puget Sound region reached approximately 2.9 million. Population growth rates have fallen slightly in the past 15 yr, to below 50,000/yr. "Suburbanization" has continued, along with the associated increases in the coverage of land by impervious surfaces. Between 1965 and 1985, the amount of intensively used urban land in the region nearly doubled, from 135,000 to 260,000 ha. Of the 91 km^2 of coastal wetlands that were present in Puget Sound before European settlement, approximately 60 percent has been converted to other uses. In 1985, the U.S. EPA made the decision to deny all applications for waivers of secondary sewage treatment requirements in the Puget Sound region. The intent of this decision was to forestall future degradation of water quality in the sound that might be caused by future population expansion in the region.

Forecasts suggest that the recent trends in population and economic growth that may affect water quality in Puget Sound will continue (PSWQA 1986b). The population of the region is expected to reach 3.7-3.9 million by the year 2000. The continued growth of low-density residential areas suggests that increases in nonpoint sources of pollution will continue. With the continued shift to a service-based, rather than a manufacturing-based economy, the rate of increase of industrial pollutants may begin to decline. Other future impacts on the water quality of the sound may be related to increased recreational and commercial marine traffic, and an increase in Naval port facilities.

FACTORS AFFECTING THE SENSITIVITY OF PUGET SOUND TO NUTRIENT ENRICHMENT

The impact of pollution on an estuary depends on pollutant input rates and on the physical conditions controlling the capacity of the system to assimilate or export excesses. Because nutrient inputs are affected by the size of the population that discharges wastes, urbanized areas of Puget Sound may be more sensitive to the effects of nutrient enrichment than are rural areas. Major urbanized areas of the sound include Elliott Bay (near Seattle), Commencement Bay (near Tacoma), Bellingham Bay (near Bellingham), Possession Sound/Port Gardner (near Everett), Sinclair Inlet (near Bremerton), Budd Inlet (near Olympia), and Oakland Bay (near Shelton).

The capacity of an estuary to assimilate a given input of nutrients without excess algal blooms and subsequent low dissolved oxygen concentrations depends, in part, on the rate of vertical mixing in the water column. As discussed previously, rapid vertical mixing removes phytoplankton from the photic zone, thereby limiting the rate of algal growth, and facilitating the dispersal of excess nutrients. Slow vertical mixing, which is often associated with a stable density stratification of the water column, allows algal cells to remain in the photic zone where their growth rate is high. Slow vertical mixing also reduces the dispersal of excess nutrients. Stability of the water column is maximal in sheltered areas during warm, calm weather. Because a lack of vertical mixing may allow an algal bloom to exhaust the nutrient supply near the surface (Winter et al. 1975), anthropogenic nutrient enrichment during a bloom in an area with a stratified water column could enhance an algal bloom by artificially replenishing the diminished nutrient supply (URS 1986a).

The capacity of an estuary to export excess inputs of nutrients before algal blooms and dissolved oxygen problems occur is influenced by the flushing rate, or the residence time of water. Rapid flushing removes nutrient inputs before high concentrations can accumulate, and also disperses the nutrients before they can be consumed by the algae. Slow flushing allows nutrient inputs to accumulate, and allows the algae to remain in an area with an enhanced nutrient concentration, which could stimulate the growth of a bloom.

Within Puget Sound, the capacity of an area to assimilate excess nutrients and the capacity of an area to export excess nutrients are closely linked (Strickland 1983). Sheltered embayments frequently have stable water columns and low flushing rates, while areas that are offshore or in the major basins of the sound tend to be both well flushed and well mixed. Thus, areas likely to be vulnerable to nutrient enrichment because of the physical environment include the southern embayments (Carr Inlet, Case Inlet, Henderson Inlet, Budd Inlet, Eld Inlet, Totten Inlet, and Oakland Bay), Hood Canal, Port Susan, Liberty Bay, Dyes Inlet, and several other small embayments, coves, and harbors with limited circulation. Areas not likely to be vulnerable to nutrient enrichment because of the physical environment include the Strait of Juan de Fuca, Admiralty Inlet, Nisqually Reach, and central areas of the Main Basin.

CHAPTER 3. STUDY DESIGN

This chapter describes the components of the study design: 1) the variables investigated to characterize the study areas, 2) the criteria used to select study areas and evaluate data sets, and 3) the quality assurance review and final selection of data sets. The data available for use in this study are from sites scattered throughout the sound. Thus, it was only feasible to characterize environmental conditions and water quality trends at particular sites. It was not possible to characterize the sound, or even portions of the sound, on a large geographic scale (i.e., entire embayments). For example, the results obtained from the Bellingham Bay study area are representative only of the immediate study area, and may not be representative of Bellingham Bay as a whole.

VARIABLES

The purpose of the water quality characterization study was to investigate temporal and spatial variation in water quality variables that are related to conventional pollutants in Puget Sound. These pollutants typically are derived from point discharges of nutrients and oxygen-demanding materials (i.e., municipal and industrial wastes) and from nonpoint sources such as agricultural runoff. Toxic pollutants such as heavy metals, polychlorinated biphenyls (PCBs), and pesticides are also an important concern for Puget Sound, but were not part of this particular study. The major variables chosen for analysis are directly related to nutrient enrichment and algal blooms, and were considered by the work group to be key measures of, or indicators of conventional pollution in Puget Sound. Physical variables were included for descriptive purposes and because physical conditions in an area affect the dynamics of pollutant impacts.

The water quality variables investigated during this study are listed in Table 3.1. The importance of each is summarized below. In addition, climatic data were obtained to facilitate interpretation of the water quality

TABLE 3.1. WATER QUALITY VARIABLES ANALYZED FOR THE CHARACTERIZATION STUDY OF PUGET SOUND

Variable Category	Variable Analyzed
Physical conditions	Salinity Water temperature
Dissolved oxygen	Dissolved oxygen concentration
Nutrients	Dissolved inorganic nitrate Dissolved orthophosphate
Indicators of phytoplankton growth	Chlorophyll *a* concentration Percent dissolved oxygen saturation at the surface Secchi disk depth
Pollutants	Sulfite waste liquor Fecal coliform bacteria

trends detected in the study areas. Climatic variables are summarized following the discussion of the water quality variables.

Salinity

Salinity is the concentration of dissolved salts in a water sample. It is used in this study to determine the extent of density stratification and vertical mixing of the water column. Information on density stratification is important because vertical mixing can remove phytoplankton from the photic zone, reducing the likelihood that a phytoplankton bloom will occur. Alternatively, a stratified water column occurs when vertical mixing rates are low. Stratification reduces the rate of phytoplankton removal from the photic zone and increases the likelihood that a phytoplankton bloom will occur. In an estuary, salinity data also provide an index of seawater dilution and are needed to calculate percent dissolved oxygen saturation.

Water Temperature

Water temperature is used to evaluate climatic influences on the water column, including vertical mixing, density stratification, and the origins of water masses. Warm water and sunshine enhance photosynthetic rates, increasing the likelihood of algal blooms. A well-mixed water column does not exhibit a substantial depth gradient in water temperature. However, a density-stratified water column generally exhibits a depth gradient in water temperature, with warmer water, heated by the sun, near the surface. Water temperature also affects dissolved oxygen concentration because the solubility of oxygen is lower in warm water.

Dissolved Oxygen Concentration

Dissolved oxygen concentrations directly affect the ability of organisms (e.g., fish and invertebrates) to live in the water. Changes in dissolved oxygen concentration are caused by the decay of organic material; by the respiration of pelagic and benthic organisms, both of which consume oxygen; and by photosynthesis in the water column, which produces oxygen. The photosynthetic production of oxygen occurs primarily in near-surface waters.

Dissolved oxygen concentrations may be impacted by anthropogenic inputs of nutrients and oxygen-demanding wastes. Nutrient enrichment can cause an increase in dissolved oxygen concentration in the surface waters if photosynthetic rates are increased by the additional nutrients. Nutrient enrichment can also cause a decrease in dissolved oxygen at depth when an algal bloom caused by enhanced nutrient concentrations dies and decays. Oxygen-demanding wastes (e.g., raw sewage and untreated pulp mill discharges) also reduce dissolved oxygen concentrations as they decay.

Dissolved Inorganic Nitrate

Dissolved inorganic nitrate is a major algal nutrient present in sewage (including primary and secondary effluent) and in agricultural runoff. Nitrogen is often the phytoplankton nutrient in lowest supply (i.e., the limiting nutrient) in Puget Sound (Anderson et al 1984). Therefore, anthropogenic inputs of nitrate into the sound may increase the intensity of algal blooms.

Dissolved Orthophosphate

Like nitrate, dissolved orthophosphate is a major algal nutrient present in sewage (including primary and secondary effluent) and in agricultural runoff. Phosphate often limits phytoplankton growth in fresh water, but it rarely limits phytoplankton growth in estuaries. However, because phosphate generally is not consumed as rapidly as nitrate during phytoplankton blooms in estuaries, concentrations during blooms generally remain above analytical detection limits. Thus, although phosphate may be less important ecologically than nitrate in Puget Sound, phosphate may be a useful index of changes in nutrient concentrations.

Chlorophyll a

Chlorophyll a is a measure of the concentration of photosynthetic pigments in water. It is a rough, but easily obtained, measure of the standing stock of phytoplankton. Chlorophyll a concentration is not a particularly good measure of photosynthetic rate because the photosynthetic rate of a cell containing a given amount of chlorophyll _a_ can vary. Chlorophyll _a_ concentration also is not a good measure of the concentration of living algal cells because dead cells may retain their pigments for a substantial period of time (Winter et al. 1975). However, chlorophyll _a_ has been widely measured in other studies of Puget Sound [e.g., Winter et al. (1975) and Anderson et al. (1984)], and is the only direct measurement of algal concentration for which data are available for a sufficient length of time to warrant trend analysis.

Percent Dissolved Oxygen Saturation

The percent saturation of dissolved oxygen and the dissolved oxygen concentration are closely related. Dissolved oxygen concentration is affected by salinity and temperature, while the calculation of percent saturation compensates for differences in salinity and temperature. Because most water quality studies analyze oxygen concentration rather than oxygen saturation, concentration was the major dissolved oxygen variable analyzed in this study. However, data on percent dissolved oxygen saturation were also analyzed because oxygen saturation above 100 percent in surface water often indicates photosynthetic enhancement of dissolved oxygen.

Values of percent dissolved oxygen saturation were calculated using the method of Weiss (1970). Values were obtained from the ratio of the actual dissolved oxygen concentration in a water sample vs. the concentration that would be found in a water sample of the same salinity and temperature at 100-percent saturation. Percent saturation is calculated by multiplying the above ratio by 100.

Secchi Disk Depth

Secchi disk depth is an easily obtained measurement of the transparency or turbidity of the water column near the surface. The depth of the photic zone (i.e., the portion of the water column where light levels are sufficiently high for photosynthesis to occur) is roughly twice the Secchi depth (Preisendorfer 1986). The Secchi disk depth is the depth at which a white disk (usually 30 cm in diameter) disappears from view. Secchi disk depth decreases as the amount of suspended particulates in the water increases. Changes in phytoplankton standing stock, which can be affected by nutrient enrichment, can be detected by changes in Secchi disk depth.

Several limitations affect the interpretation of Secchi disk depth data. The Secchi disk depth is influenced by concentrations of both phytoplankton and suspended sediment. In addition, the amount of available light and the visual capabilities of the observer affect the data. Moreover, the Secchi disk does not provide information about conditions deeper than the Secchi disk depth. Thus, although Secchi disk depth is a widely used index of water clarity, changes in Secchi disk depth may be difficult to interpret.

Sulfite Waste Liquor

The concentration of sulfite waste liquor is a measurement of the amount of waste discharged from pulp mills that use sulfites. The sulfites are used to separate cellulose fibers from wood for the production of paper. Sulfite waste liquor is toxic in high concentrations and contains large amounts of organic material that consume oxygen as it decays. Sulfites also react directly with oxygen (Strickland and Parsons 1972) and dissolved orthophosphate (Westley and Tarr 1978) in seawater. Because pulp mills have been an important industry in the Puget Sound area since about 1920, the measurement of sulfite waste liquor is an indicator of a major industrial contaminant that affects concentrations of dissolved oxygen and nutrients and that has been discharged for many years into the sound.

Fecal Coliform Bacteria

Fecal coliform bacteria are present in inadequately chlorinated sewage and in runoff from pastures and other agricultural facilities that contain large amounts of animal wastes. These organisms are not directly harmful, but their concentration is used as an index of contamination by pathogens from sewage and runoff from agricultural facilities.

Climatic Variables

The following variables are included in the climatic database: air temperature, wind direction, wind velocity, rainfall, the percentage of possible sunshine (i.e., the percentage of time that the sun shines, unobscured by clouds, between sunrise and sunset), and total estimated runoff to Puget Sound. All these variables can affect algal growth rates and physical conditions in the water column. They may affect algal growth rates directly by influencing the rate of photosynthesis, or indirectly by influencing vertical mixing rates of the water column.

STUDY AREAS

Sites were selected for the characterization study to optimize geographical and temporal coverage. Because data availability varied greatly among candidate study sites, it was not possible to use rigid criteria for site selection. Based on the consensus of the work group, candidate study areas were ranked as high, medium, or low priority within each region of the sound (Strait of Juan de Fuca; northern, central, and southern Puget Sound; and Hood Canal). Only high priority areas were included in the study. The criteria used to evaluate sites are listed below in the approximate order of importance:

- Inclusion of sites from all regions of the sound

- Availability of long-term monitoring data, with sampling extending through 1986

- Inclusion of a wide range of environments (e.g., rural or urban, well or poorly mixed)

- Potential for detecting long-term changes in water quality without interference from excessive, short-term variation (e.g., a station near the mouth of a tidal river could have salinity fluctuations over a tidal cycle that greatly exceeded the magnitude of any possible long-term change)

- Potential for anthropogenic nutrient enrichment to affect water quality

- Computer accessibility of the data.

Thirteen study areas were chosen for inclusion in the characterization study (Figure 3.1). Brief descriptions of each area are given in Table 3.2. Detailed discussions of these 13 areas are provided in Chapter 5. No study area was selected from the Strait of Juan de Fuca because no site had both long-term historical data and present day monitoring.

DATA SOURCES

Two factors were evaluated to determine which of the many Puget Sound water quality data sets would be included in the water quality characterization study:

- Study design and the amount of usable data available for each potential study site

- Analytical techniques used in each study.

Study Design and Amount of Usable Data

Study designs were evaluated to determine the frequency and water depth of sampling. Studies were used that provided at least several data points per year at a site. However, sampling frequency tended to be lower in the earlier studies. For example, the University of Washington monitoring program often sampled once per season from the 1930s through the 1950s. Although this sampling frequency is inadequate by current standards, the University of Washington data set is the only substantial data source for this early period. Therefore, the University of Washington data were used. The depths sampled varied greatly among studies, but studies that included routine sampling to at least a 30-m depth were preferred.

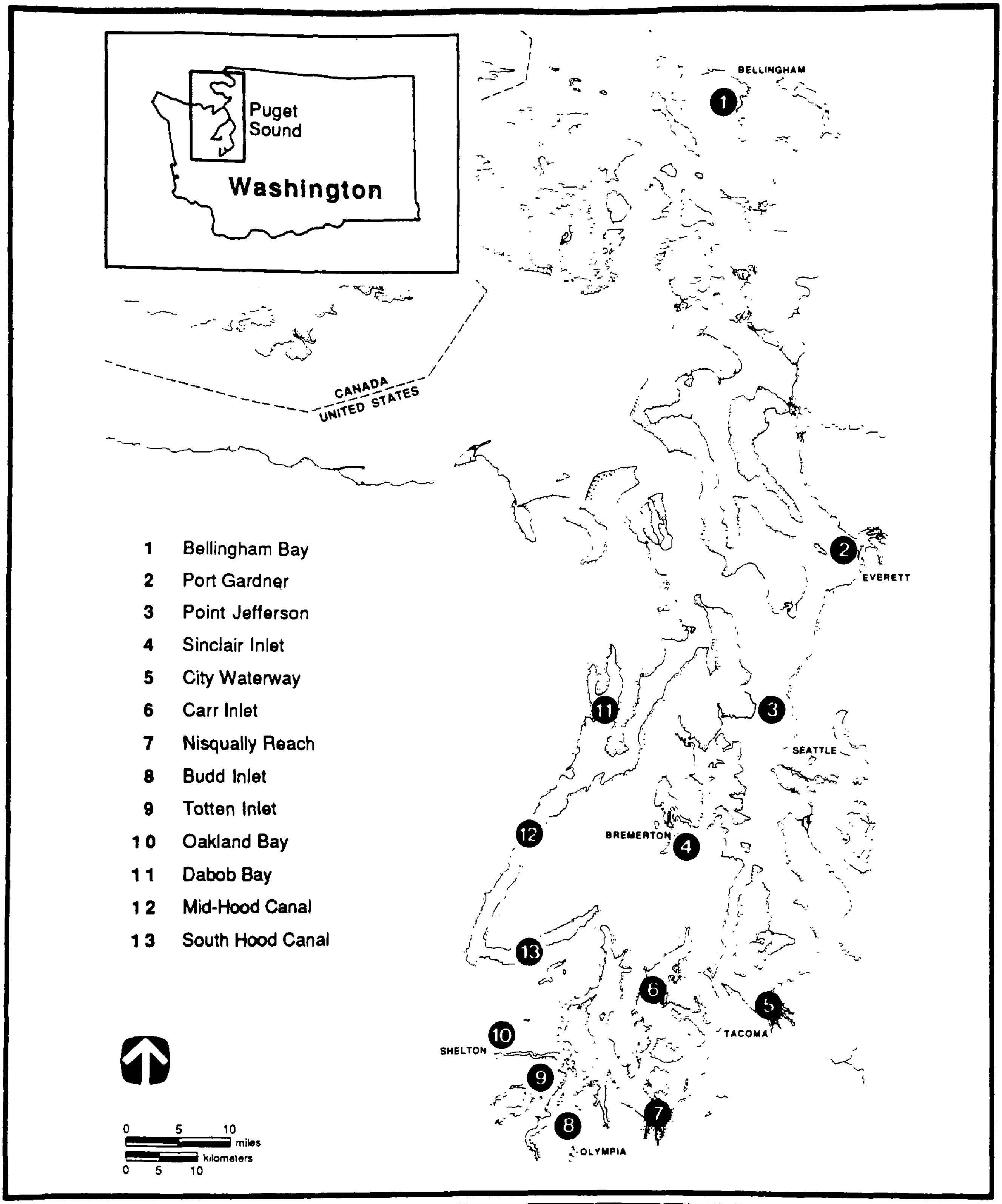


Figure 3.1. Map of Puget Sound showing locations of the study areas in the water quality characterization project.

TABLE 3.2. STUDY AREAS IN THE WATER QUALITY CHARACTERIZATION PROJECT

Study Area	Environmental Characteristics
	NORTHERN SOUND
Bellingham Bay	Urban, moderately deep embayment
	CENTRAL SOUND
Port Gardner	Urban, deep embayment
Point Jefferson	In greater Seattle area, but not highly urbanized; deep, open basin
Sinclair Inlet	Urban, moderately shallow embayment
City Waterway	Urban, at mouth of commercial waterway on deep, open embayment (Commencement Bay)
	SOUTHERN SOUND
Carr Inlet	Rural, deep embayment, lacks major freshwater source
Nisqually Reach	Rural, in mid-southern basin near a sill
Budd Inlet	Urban, shallow sluggishly circulating embayment
Totten Inlet	Rural, shallow sluggishly circulating embayment
Oakland Bay	Urban, very shallow, sluggishly circulating embayment
	HOOD CANAL
Dabob Bay	Rural, deep, sluggishly circulating embayment
Mid-Hood Canal	Rural, deep, sluggishly circulating, in narrow basin
South Hood Canal	Rural, deep, very sluggishly circulating, near head of narrow basin

Data sets were chosen to provide the longest possible period of coverage at study sites throughout the sound. Reports and data summaries from governmental agencies, academic institutions, and the private sector were examined to determine the locations and time periods surveyed and the variables measured. Because the University of Washington Department of Oceanography has the oldest large source of data, other data sources usually were selected to increase the amount of data available for locations initially surveyed by the University of Washington.

Analytical Techniques

Analytical techniques were identified to the extent possible from reports and interviews with the scientists who worked on the original projects. Generally, the techniques applied in the major studies of water quality were widely accepted at the time they were used. However, early measurements for some of the variables suffered from relatively poor accuracy and precision. The techniques used in the studies included in the water quality characterization project are summarized and evaluated in Appendix A. More detailed discussions of these methods can be found in Barnes (1959), Strickland and Parsons (1972), Riley (1975), and Preisendorfer (1986).

Generally, the historical data for salinity, water temperature, and Secchi depth determinations are highly reliable. The difference between Secchi depths determined with a standard 30-cm diameter Secchi disk and the 20-cm diameter Secchi disk used by Ecology (Singleton, L., 22 September 1987, personal communication) is probably only about 1 percent (Preisendorfer 1986). That difference is probably not large enough to be detected in this characterization study. Dissolved oxygen measurements using the Winkler titration method are reliable. Dissolved oxygen measurements made by electronic measuring devices (e.g., oxygen probe) also are reliable when proper calibration and equilibration procedures have been followed. Early measurements of concentrations of nutrients, chlorophyll *a*, and fecal coliform bacteria may have been less reliable because earlier techniques were less accurate and precise. A modest amount of phosphate data from the 1930s and 1950s was retained because the quality of those data was judged to be acceptable. The oldest data judged to be acceptable for concentrations of nitrate, chlorophyll a, and fecal coliform bacteria were collected in the mid-1960s.

Studies of water quality in Puget Sound have been independently conducted by many groups during a 55-yr period. During the assessment of the analytical techniques used in the historical studies, it was assumed (unless other information was available) that sampling and analysis were performed correctly by trained, professional personnel. Where serious errors in the performance of accepted techniques were detected, data were excluded from analysis. Unfortunately, changes in techniques used in the historical water quality studies were often not well documented. In some cases, changes in analytical techniques were not adopted in the interest of obtaining higher quality data, but to increase sampling efficiency (e.g., use of electronic oxygen probes). Generally, minor changes in techniques resulting from turnover in laboratory and field personnel and changes in equipment could not be detected reliably in the historical data sets. Therefore, the effects of these factors could not be assessed or corrected.

DATA SETS USED

Database Quality Assurance-Review

All data files used in this study were subjected to a quality assurance review. Sources of information about the data included existing documentation (as provided by the relevant agencies) and interviews with investigators and database managers.

Initially, the contents of the computer files from the data sources were simply examined. The contents of the computer files were then checked to verify that the time period in the computer files agreed with the time period described in the documentation. If major discrepancies were discovered, corrective actions were taken (e.g., rereading data cards into computer files, adding new data into existing computer files).

Units of measurement for the variables of each data set were checked. Data values were plotted against date for each variable of interest. The ranges of the data values in the plots were compared to the ranges that would have been expected, based on the units cited in the available documentation. Discrepancies were noted and corrected in the computer files. For example, Ecology sampled at depths of 0, 10, and 30 m, but their computer file (STORET) reported depths of 0, 32, and 98 (no units given). Evidently, the depth data had been converted from meters to feet. The depths were reconverted to meters.

Some raw data were entered into computer files for this project. These data were double-punched (i.e., entered twice and compared). Printouts of the newly created files were manually compared to tables of raw data for selected high-priority stations.

The final step of the quality assurance review was to check for outliers. Because this project includes a diverse collection of study areas sampled in all four seasons at various depths, simple range checks were not appropriate. (For example, a water temperature of 20^{o} C at the surface of Budd Inlet recorded in July would not be unusual, but a 20^{o} C temperature at 200-m depth at Point Jefferson in February would be highly unusual.) The data from each source were separated by season and depth, and each variable of interest was plotted by date. Points that appeared to have extreme values (based on visual scans of these stratified plots) were reviewed by contacting the investigators who were involved with the particular monitoring program. Using this approach, a few points were deemed unreasonable or were found to be based on erroneous laboratory procedures. These points were dropped from the characterization database.

Data sets collected by the University of Washington Department of Oceanography, Ecology, Washington Department of Fisheries, and Metro were used for the characterization study. These data sets are described below. Results of the quality assurance reviews for these data sets are summarized in Appendix B. All other data sets were either too restricted in temporal coverage, or did not include suitable study sites. Other potentially useful ancillary water quality data sets are described in Appendix C. These data sets were evaluated, but not used in this study. The sources of climatic data are described in this chapter following the descriptions of the water quality data sets.

University of Washington

The University of Washington Department of Oceanography monitored water quality throughout Puget Sound from 1932 to 1971. Sampling was interrupted by World War II. Data coverage is summarized in Collias (1970). [Some of the data referred to in Collias (1970) actually were collected by the Washington Department of Fisheries or by various Canadian agencies. These data are not in the original STORET database.] A portion of the physical and chemical data collected by the University of Washington is presented graphically in Collias et al. (1974). Overall, approximately 300 stations were occupied at least once. Several stations were sampled throughout most of the monitoring program (e.g., Pillar Point, Point Jefferson, Devil's Head), but most stations were sampled sporadically or for only a few years. Water temperature, salinity, and dissolved oxygen were measured in most surveys; phosphate, nitrate, and Secchi disk depth were measured occasionally. In most cases, a wide range of depths (i.e., surface to bottom) was sampled.

Washington Department of Ecology

Ecology has routinely monitored water quality in Puget Sound since 1967. Winter months were not monitoring during most years, and there was a gap in monitoring during 1971 and 1972. Results of these studies have not been published. Historically, 167 stations were sampled; long-term data are available through 1986 for 52 stations located throughout the sound. Water temperature, salinity, and dissolved oxygen were measured throughout the study and sulfite waste liquor was measured from 1967 to 1984. Monitoring of several nutrients and measurements of bacterial contamination was added in 1973. Measurements of Secchi disk depth and chlorophyll a were added in 1977 and 1979, respectively. From 1967 to 1970, samples were taken at the surface and at a depth of 6 m. After 1973, samples were taken at depths of 0, 10, and 30 m. All data collected through 1986 are available from STORET.

Washington Department of Fisheries

Two water quality data sets were obtained for this project from the Washington Department of Fisheries. Both surveys were conducted under the direction of the University of Washington Department of Oceanography (Collias 1970). One data set spans the late 1950s and contains data from 20 stations in southern Puget Sound and 27 stations in northern Puget Sound. Information from this data set for Bellingham Bay, Totten Inlet, and Oakland Bay were incorporated into the characterization database. Water temperature, salinity, dissolved oxygen, and sulfite waste liquor typically were measured at the surface and at a depth of 6 m. Some deeper samples and some phosphate data also were collected in the northern sites. Prior to the characterization project, these data existed only in unpublished reports by the Washington Department of Fisheries (Westley 1957a,b, 1958; Westley and Tarr 1959, 1960). (Copies of these reports were provided by M.A. Tarr.) The data were entered into computer database for this project.

The second set of water quality data from the Washington Department of Fisheries includes several southern embayments that were sampled from 1964 to 1971 (Case, Eld, and Totten Inlets; Oakland and Quilcene Bays; and Burley Lagoon). In most cases, sampling was performed at three or four stations near the heads of the embayments. Variables included water temperature, salinity, dissolved oxygen, phosphate, nitrate, chlorophyll _a_, Secchi disk depth, and several other nutrients and physical variables. Samples were collected at depths of 1 and 3 m. The data were not summarized prior to the characterization project. M.A. Tarr organized the data into tables [adjusting chlorophyll _a_ calculations to conform to Strickland and Parsons (1972)]. The data were entered into the computer database for this project.

Metro

The Water Quality Division of Metro has been monitoring water quality in the central basin of Puget Sound since 1965. Long-term, routine monitoring data are available for approximately 70 stations. Periodically, Metro has published summaries of their data (e.g., Metro 1986). Variables surveyed include water temperature, salinity, dissolved oxygen, Secchi depth, and fecal coliform bacteria. Depth profiles covered in Metro's monitoring program include the entire water column at many stations. Some data on nitrogen, phosphorus, and phytoplankton standing stock were also recorded. Methods for measuring nitrogen and phosphorus differed from the methods used in the other major water quality studies of Puget Sound. Phosphorus was measured as hydrolyzable phosphorus, and nitrogen was measured as nitrate plus nitrite. These two variables were only measured from 1967 to 1972 (Dalseg, R., 17 September 1987, personal communication). Because this limited temporal coverage was deemed to be insufficient to warrant analysis in the characterization study, these data were dropped. Metro provided their data to this project on a magnetic tape. Much of their data are also in STORET.

Climatic Data

A climatic database containing data on both weather conditions and runoff was developed for the characterization project. The data were obtained from U.S. government reports. Weather data were from Local Climatological Data Reports produced and distributed by NOAA's National Climatic Data Center in Asheville, NC. Runoff data were obtained from NOAA (1984a).

Weather data are recorded at Seattle-Tacoma International Airport. A continuous record was available from 1945 to 1985. Because climatic data in the Local Climatological Data Reports indicated substantial variability in the weather among locations around the sound, the data from the airport serve only as a general index of the climate in the central Puget Sound area. The following weather variables were included in the climatic database as monthly means: air temperature, wind direction, wind velocity, and the percentage of possible sunshine. Monthly totals for rainfall and runoff were also included in the climatic database.

The runoff data were estimates of monthly total runoff to Puget Sound from 1930 to 1978. These estimates were based on data from seven United States Geological Survey (USGS) gaging stations located in large rivers draining into the sound. Station locations (all in Washington State) were Newhalen and Concrete (Skagit River with 60 percent of the volume assumed to exit through Deception Pass), Arlington (Stillaquamish River), Gold Bar (Skykomish River), Carnation (Snoqualmie River), Puyallup (Puyallup River), and Union (Skokomish River). These data serve only as a general index of variation in runoff. The patterns at particular locations may have differed from the patterns analyzed in this report.

CHAPTER 4. DATA ANALYSIS PROCEDURES

A series of procedures was used to prepare the database for analysis. Standard analytical protocols were then implemented to characterize the environment and analyze temporal trends in the water quality of the 13 study areas.

DATABASE PREPARATION

Five major procedures were used to prepare the database for analysis:

- Identification and correction of data values below analytical detection limits
- Evaluation of the comparability of the data from the different data sources
- Selection of representative sampling stations at each study area for pooling data
- Identification of the annual period during which algal blooms occurred in each study area
- Standardization of sampling depths.

Some data records in the water quality data sets contained undetected values for certain variables. This situation occurred when the concentration of the substance being measured was too low to be detected by laboratory procedures. When an undetected value was reported, the data field in the particular record usually contained the actual detection limit, accompanied by a STORET code in another data field that indicated that the value was below the given detection limit. However, because detection limits were not handled in the same manner by the different agencies from which data were obtained, it was necessary to standardize the way in which undetected values were listed in the characterization database (see below). Moreover, some errors in data entry occurred for undetected values because these values were sometimes entered as zeroes or "missing value." These situations were identified by examining plots of the data by date, and by examining printouts of the data in the forms of frequency tables and hard copies of the computer files. Investigators that worked on the monitoring programs used as data sources were also contacted to help resolve the problems with the detection limits.

Three variables (i.e., nitrate, phosphate, and fecal coliform bacteria) had data values below detection limits. For the two nutrients, the problem was most prevalent for nitrate in surface samples, where concentrations were often very low during algal blooms. For each of the above three variables, data values below the detection limits were standardized by converting to the highest detection limit used in any of the data sources (Table 4.1). Using the highest detection limit avoided the possibility of introducing artificial spatial or temporal trends into the data that were actually caused by changes in the detection limits.

Data Comparability Among the Different Data Sources

A comparability analysis was conducted to determine whether the data produced by the different monitoring programs could be used together in the same analysis without correction or calibration. Unfortunately, the monitoring programs used as data sources did not conduct side-by-side sampling and laboratory analyses. Sources of variation other than differences in laboratory and field techniques (among the studies) may have affected the data being compared (e.g., date, time of day, and stage of tide for sampling).

To the extent possible, the four data sources used in the characterization study were compared in a pair-wise fashion. Each of the data sets was scanned to identify stations where sampling overlapped (i.e., where sampling was done in the same season and at or near the same location). It was not possible to control for differences in sampling date or time of day.

TABLE 4.1. LABORATORY DETECTION LIMITS USED IN THE CHARACTERIZATION DATABASE

Variable	Detection Limit
Nitrate	0.714 ug-at/L
Phosphate	0.323 ug-at/L
Fecal coliform bacteria	1 organism/100 mL

Moreover, only data from surface samples were included, because of the lack of data from deeper water.

For the pairs of studies where sampling overlapped at a location, values of the variables included in both studies were compared. Because variances were highly variable (i.e., variances differed by more than a factor of 10), nonparametric statistics were used for these comparisons. The data in the two data sets being compared were stratified by season. The data for each variable were then ranked within the seasons, and the ranks were compared using a one-way analysis of variance (ANOVA). This procedure is equivalent to a Kruskal-Wallis test (SAS 1985, p. 608). Statistical significance of differences between pairs of data sources was determined using Tukey's multiple comparison test.

With the exception of the University of Washington and Washington Department of Fisheries, one pair of stations with overlapping sampling was found for all the pairs of agencies from which data were obtained. However, because much of the monitoring performed by Washington Department of Fisheries was actually conducted for the University of Washington, the absence of a comparison between the University of Washington data and Washington Department of Fisheries data may not be critical. The only location where sampling by University of Washington and Ecology overlapped was near Alki Point (Stations PSB318 and PSB002, respectively), which is not a location included in this trend analysis. Those stations were sampled from 1967 to 1970. University of Washington and Metro both sampled at Point Jefferson from 1966 to 1972 (Stations PSB305 and KSPB01, respectively), and Washington Departments of Fisheries and Ecology both sampled in Oakland Bay from 1967 to 1970 (Stations 23 and OAK004, respectively).

The only variables for which data were collected at pairs of stations with overlapping sampling were dissolved oxygen, salinity, and water temperature. Variables for which data were not collected at both stations, and for which comparisons were not possible, included Secchi disk depths and concentrations of nutrients, chlorophyll a, fecal coliform bacteria, and sulfite waste liquor.

Results of the data source comparisons are summarized in Appendix D. No significant differences ($P<0.05$) were found between measurements of dissolved oxygen, salinity, and water temperature made by Washington Department of Fisheries and Ecology during the overlapping sampling period in Oakland Bay. However, Ecology sample sizes were small, with only 10 observations for the period of overlap.

For the overlapping University of Washington and Metro data from Point Jefferson, salinity observations made by the University of Washington were significantly ($P<0.05$) higher (approximately 1 ppt) than those made by Metro during spring, summer, and autumn. However, they were not significantly different from those made by Metro during the winter. Water temperature observations made by the University of Washington were significantly higher ($P<0.05$) during the spring, but did not differ significantly ($P>0.05$) from those made by Metro during other seasons. No significant differences ($P>0.05$) were detected among dissolved oxygen concentrations.

Although sample sizes for the University of Washington and Ecology were small for the overlapping sampling period at Alki Point, some differences were detected. Dissolved oxygen measurements made by Ecology during the spring were significantly higher ($P<0.05$) than those made by the University of Washington. However, dissolved oxygen measurements made by the University of Washington during the autumn were significantly higher ($P<0.05$) than those made by Ecology. Salinity measurements made by the University of Washington were significantly higher ($P<0.05$) than those made by Ecology during the spring and summer, with an average difference of approximately 2 ppt. Salinity measurements made by the two agencies during the autumn and winter did not differ significantly ($P>0.05$). No significant differences ($P>0.05$) were detected for water temperature.

In summary, most of the paired comparisons did not detect consistent differences among the data sources, although limitations of the data prevented a thorough analysis of data comparability. Dissolved oxygen, salinity, and water temperature data from the different data sources were, therefore, used together in the characterization study with a minimum of caveats. The most consistent difference detected between agencies was the salinity determinations made by Metro and the University of Washington. Values from Metro usually were slightly lower. No conclusions can be drawn about the concentrations of nutrients, chlorophyll a, sulfite waste liquor, or fecal coliform bacteria, or about Secchi disk depths due to the lack of paired data for statistical comparisons.

Selection of Representative Stations in Each Study Area for Pooling Data

Data were pooled (when possible) from several adjacent stations to characterize conditions in a study area. Pooling data increases the number of observations available for analysis and provides better coverage of short-term variations in the measured variables (e.g., salinity changes caused by the tides) because sampling is spread over a longer period of time. In addition, the data are more representative of the general area because they come from more than one location. Combining stations also extends the period of time over which sampling occurred because different stations often were sampled during different years.

Combining water quality data from adjacent stations within a study area requires that conditions at the stations be as similar as possible. For each study area, data were compared statistically for periods of overlap in sampling. All data available for salinity; water temperature; concentrations of dissolved oxygen, nitrate, phosphate, chlorophyll a, sulfite waste liquor, and fecal coliform bacteria; and Secchi disk depth were analyzed. Data from the candidate stations within a given study area were ranked during overlapping years for each variable. Ranking was conducted for the calendar summer data only because most of the rest of the year would not be expected to have algal blooms. Station ranks were then compared using a nonparametric one-way ANOVA. Statistical differences among stations were evaluated using Tukey's multiple comparison test (SAS 1985). Stations that differed significantly ($P<0.05$) from the other stations within a study area for any of the water quality variables were dropped. These analyses were repeated with the reduced station list until no significant differences ($P<0.05$) remained among stations within each study area.

Identification of the Annual Period for Algal Blooms in Each Study Area

Because water quality problems caused by nutrient enrichment are often associated with algal blooms, data collected during the annual period of maximal growth of phytoplankton were analyzed to identify temporal changes. An obvious method to identify the period of maximal growth would be to examine the annual profile of chlorophyll a concentrations. Unfortunately, there were insufficient chlorophyll a data from most of the stations in the characterization study to use this approach. Therefore, the annual period of high percent dissolved oxygen saturation at the surface was chosen as a surrogate for algal standing stock because photosynthesis increases the percent dissolved oxygen saturation at the surface during algal blooms (Winter et al. 1975; Collias and Lincoln 1977).

Because the algal bloom season may occur at different times and for varying lengths of time in different areas, the annual period of occurrence of algal blooms was identified separately for each study area. Monthly means for percent dissolved oxygen saturation at the surface were calculated for each study area. The three consecutive months with the highest means were chosen as the algal bloom season for many of the study areas. For other areas, the bloom (as indicated by elevated surface dissolved oxygen saturation values) appeared to continue over 4 mo. When a fourth month just before or just after the highest three consecutive months had a higher mean surface percent dissolved oxygen saturation than the one of the highest three consecutive months, it was considered part of the algal bloom season.

Standardization of Sampling Depths

Because nearly all data collected since the mid-1960s and used in the characterization study came from Ecology's routine monitoring database, sampling depths from the other data sources were adapted to conform to the design of Ecology's program. The Ecology sampling protocol consisted of collecting samples from the surface and from depths of 10 and/or 30 m. (From 1967 to 1970, Ecology collected samples from the surface and from 6.1-m depth.) Therefore, the standard depths analyzed in this study were limited to the surface and depths of 10 and 30 m. In this study, surface samples were defined as samples taken at depths between 0 and 2 m. Similarly, samples taken from between 9- and 11-m depths were defined as 10-m samples, and samples taken from between 29- and 31-m depths were defined as 30-m samples. Sampling programs other than Ecology's often used different sampling depths. In these situations, data were adjusted to the standard depths by linear interpolation when the available sampling depths bracketed the standard depths. When the sampling depths did not bracket the standard depths, the data were not used.

Because more comprehensive data are available for the Point Jefferson study area, several additional depths were investigated at this site. The standard depths were analyzed as described above, and additional analyses were conducted for selected depths down to 200 m.

STANDARD ANALYTICAL PROTOCOL

A series of analytical procedures was conducted for each study area to characterize the environment and to detect temporal trends in water quality. The time period investigated was the algal bloom period for each individual study area. The analyses were conducted for depths of 0, 10, and 30 m. In addition, possible exceedances of water quality standards were assessed for surface waters. Details are given below.

Characterization of the Environment in the Study Areas

Graphical Analysis--

The environment in each study area was characterized by examining histograms depicting the mean values for each water quality variable at 0-, 10-, and 30-m depths. Back-up tables containing standard errors and coefficients of variation for these variables were also examined. To facilitate comparisons among study areas, four sets of histograms were produced, each of which contained the data from all the study areas within one region of the sound as defined in the characterization study (i.e., the northern, central, and southern sound, and Hood Canal).

Raw data values were used in the histograms depicting the means of all variables except fecal coliform bacteria and sulfite waste liquor. Because the frequency distributions of the data for these two variables were positively skewed, the data for these two variables were transformed. Values for fecal coliform bacteria were log transformed (Greenberg et al. 1985). Values for sulfite waste liquor were transformed to log (X+1) because the database contained values of zero (Steel and Torrie 1960). Thus, the data shown for fecal coliform bacteria and sulfite waste liquor are logs of geometric means.

Statistical Analysis--

Possible cause-and-effect relationships were investigated using correlation analysis to support interpretations of the histograms depicting the environmental data at each site (described above). Product-moment correlation coefficients (Zar 1974) were calculated for each study depth for all possible pairs of the following water quality variables: salinity, water temperature, dissolved oxygen concentration, percent dissolved oxygen saturation (at the surface), Secchi disk depth, nitrate concentration, and phosphate concentration. The minimum data requirement for conducting the correlation analysis on a pair of variables was 10 data points.

Because the data for each variable in each study area were used in several correlation analyses, a conservative approach was adopted for the assessment of statistical significance. The chosen significance level for each correlation coefficient was scaled using the Bonferroni inequality, a simple but highly conservative method that preserves the experiment-wise error rate when the same data are used to calculate several correlation coefficients (Snedecor and Cochran 1980). Using the Bonferroni inequality, each correlation coefficient was interpreted at a significance level of 0.05 and 0.01 divided by the number of correlations investigated using the same data. For example, if dissolved oxygen data were correlated with five other variables in the correlation matrix for a particular station and depth, statistical significance for each of the five individual correlation coefficients involving the oxygen data would be determined at $P<0.05/5=0.01$ and $P<0.01/5=0.002$.

Analysis of Temporal Trends in Water Quality in Each Study Area

Graphical Analysis--

Temporal trends were investigated within each study area by plotting water quality data for the algal bloom period by year. These plots were examined visually to identify possible periods of changes in water quality and to assess exceedance of water quality standards. When two or more observations during the algal bloom period were available for a year, the individual observations were plotted along with the mean and the standard error. When only one observation was available, that value was simply plotted as a point. Data for fecal coliform bacteria and sulfite waste liquor were plotted as the log of the geometric means, with the standard errors calculated on log-transformed data (Greenberg et al. 1985). Regression lines were included on these plots when significant temporal trends were detected by regression of a variable against year (see below).

Historical Causes of Changes in Water Quality--When a temporal change in the values of a variable plotted against year was evident from visual inspection, an attempt was made to determine whether an historical event could explain the apparent change. For example, if the amount of sulfite waste liquor dropped in an area, inquiries were made to determine when changes in pulp mill discharges might have occurred.

Exceedance of Water Quality Standards--Plots of water quality variables through time were examined visually to detect possible exceedances of water quality criteria for surface waters. Dissolved oxygen concentration and the concentration of fecal coliform bacteria are the two variables in the characterization study for which water quality standards have been established for Puget Sound by Washington State. The water quality standards applicable to the study areas are given in Table 4.2. These standards are included in the descriptions of each study area in Chapter 5.

TABLE 4.2. WATER QUALITY STANDARDS APPLICABLE TO THE CHARACTERIZATION STUDY AREAS

Classification of Water[a]	Dissolved Oxygen Standard (mg/L)	Fecal Coliform Bacteria Standard (organisms/100 mL)	Characterization Study Area
AA	7.0	14[b,c]	Bellingham Bay Point Jefferson Nisqually Reach Carr Inlet Dabob Bay Mid-Hood Canal South Hood Canal
A	6.0	14[b,c]	Sinclair Inlet Budd Inlet (northern portion of study area) Totten Inlet Port Gardner (University of Washington stations)
B	5.0	100[b,d]	Budd Inlet (southern portion of study area) Oakland Bay City Waterway Port Gardner (Ecology stations)

[a] AA = extraordinary; A = excellent; B = good.

[b] Geometric mean.

[c] No more than 10 percent of samples can exceed 43 organisms/100mL.

[d] No more than 10 percent of samples can exceed 200 organisms/100mL.

Reference: WAC 173-201-045(2) and WAC 173-201-085(2).

Statistical Analysis--

Nonparametric ANOVA and linear regression were used to detect temporal trends in water quality and climate.

Nonparametric ANOVA--A nonparametric ANOVA was conducted on the water quality data from each of the study areas. The purpose of this analysis was to determine whether significant differences in the values of each variable existed through time. Data collected prior to 1973 were compared with data collected from 1973 through 1986. The choice of 1973 as the year dividing the earlier data from the more recent data was made primarily because Ecology updated their monitoring program in 1973.

The procedure used to calculate the ANOVA comparing early and recent data was to compute an analogue of the Kruskal-Wallis test (SAS 1985, p. 608). The entire data set for each variable was ranked within each study area. The set of ranked values was then divided into pre-1973 and 1973-1986 subsets. A one-way ANOVA was conducted comparing ranks in the two periods of time.

Linear Regression--Temporal trends were also analyzed by linear regressions of the values of each variable against year of collection. The minimum data requirement for conducting the regression analysis was 5 yr of data, including data through 1986. The reason for conducting the regressions was to provide a measurement of the rate of change of each variable. This rate of change is estimated by the slope of the line. Multiplication of the rate of change of a variable by the number of years that data have been collected gave an estimate of the amount the variable has changed over the time period that it has been measured. Statistically significant regressions ($P<0.05$) were plotted on the graphs of data values plotted against year (as described above).

Two regressions were conducted for each variable within each study area. One regression was used to detect changes in values over the whole time period sampled between 1932 and 1986. In that analysis, the actual period analyzed was dependent on the number of years sampled in a given study area. The second regression was used to detect significant changes in values over the more recent time period of 1973-1986. Again, the actual period analyzed was dependent on the number of years sampled in a given study area. A temporal trend was considered significant if the slope of the regression was statistically significant ($P<0.05$). A significant positive slope indicates increasing values of the variable, while a significant negative slope indicates decreasing values of the variable. A nonsignificant slope indicated that no overall trend was detected by regression.

Raw data values were used in the regressions of all variables except fecal coliform bacteria and sulfite waste liquor. The frequency distributions of the data for these two variables were positively skewed. Values for fecal coliform bacteria were log transformed (Greenberg et al. 1985). Values for sulfite waste liquor were transformed to log(X+1) because the database contained values of zero (Steel and Torrie 1960).

Because recent data are a subset of the long-term data, a recent change in the data could introduce an apparent long-term change that would be detected statistically by the long-term regression, even though the change actually occurred recently. For example, if dissolved oxygen concentration in an area averaged 8 mg/L from 1932 to 1980, and then averaged 4 mg/L from 1981 to 1986, a declining trend for the entire period of 1932 to 1986 might be detected statistically, even though the actual change would have occurred only in the 1981 to 1986 portion of the long-term data.

CHAPTER 5. RESULTS AND DISCUSSION

ORGANIZATION OF THE CHAPTER

A brief discussion of long-term weather patterns in Puget Sound precedes the discussion of results of the graphical, regression, and correlation analyses performed for this characterization study. The results are presented according to geographic regions of the sound: northern, central, and southern sound, and Hood Canal. Except for the northern sound, these regions correspond to the basins of Puget Sound as described in Chapter 2. Because neither long-term nor recent data were available for the Strait of Juan de Fuca, no results are presented for this area. Following the discussion of results within each geographic region, a summary of the major findings is provided.

As discussed in Chapter 3, the results for a particular study area are representative only of the immediate area in which the sampling stations were located. For example, trends in water quality detected in the Bellingham Bay study area may or may not be indicative of trends in water quality in all of Bellingham Bay.

Statistical statements in the text are based on the following conventions. Regressions of data against year were considered significant if the slope of the regression line was statistically significant at $P<0.05$. The nonparametric ANOVA also was considered statistically significant at $p<0.05$. Correlation coefficients were considered significant if $P<0.05$ after sealing with the Bonferroni inequality.

WEATHER DURING STUDY PERIOD

Plots of air temperature, percentage of possible sunshine, rainfall, runoff, and wind velocity data by year for the Puget Sound area are given in

Figures 5.1-5.3. These data provide general information on basic weather patterns in the central Puget Sound area during the study period.

Several long-term trends are evident. Between 1945 and 1985, a significant increase in mean air temperature was detected (slope=+0.3^{o} C per year). The temperature increase may be attributable to a cool period that occurred between 1948 and 1955. Total annual rainfall declined significantly between 1945 and 1985 (slope=-0.45 cm/yr). The decrease in rainfall may be attributable to a wet period that occurred during the 1950s and a dry period that occurred from 1976 through the 1980s. Some years had unusual weather. For example, 1955 was cool, while 1958 was warm. Similarly, 1950 was wet, while 1952, 1976, and 1985 were dry, and 1978 was cloudy, while 1982 was sunny.

NORTHERN SOUND

The northern sound is defined in this study as the region encompassing the eastern end of the Strait of Juan de Fuca, the southern end of the Strait of Georgia, and the area around the San Juan Islands (see Figure 2.1). The northern sound is the only study region north of Admiralty Inlet, and is the region most subject to oceanic influences. The northern sound is typically over 100 m deep in the Straits of Juan de Fuca and Georgia. Extensive tidelands and sheltered embayments are located along the mainland shore. Water movements are complicated by an abundance of islands. Approximately 60 percent of the flow of the Skagit River, the largest river in the Puget Sound basin (see Table 2.1), discharges into the eastern end of the Strait of Juan de Fuca. The remaining volume flows into the Main Basin of Puget Sound through Skagit Bay and Possession Sound (NOAA 1984a). Major population centers are the Cities of Bellingham and Anacortes. The major historical sources of pollutants in the northern sound have been saw mills, pulp mills, and canneries near Anacortes and Bellingham, and a large oil refinery near Anacortes (Chasan 1981).

Bellingham Bay is the only study area in the characterization project that is located in the northern sound. Station locations are shown in Figure 5.4. Data sources are given in Table 5.1. The algal bloom season

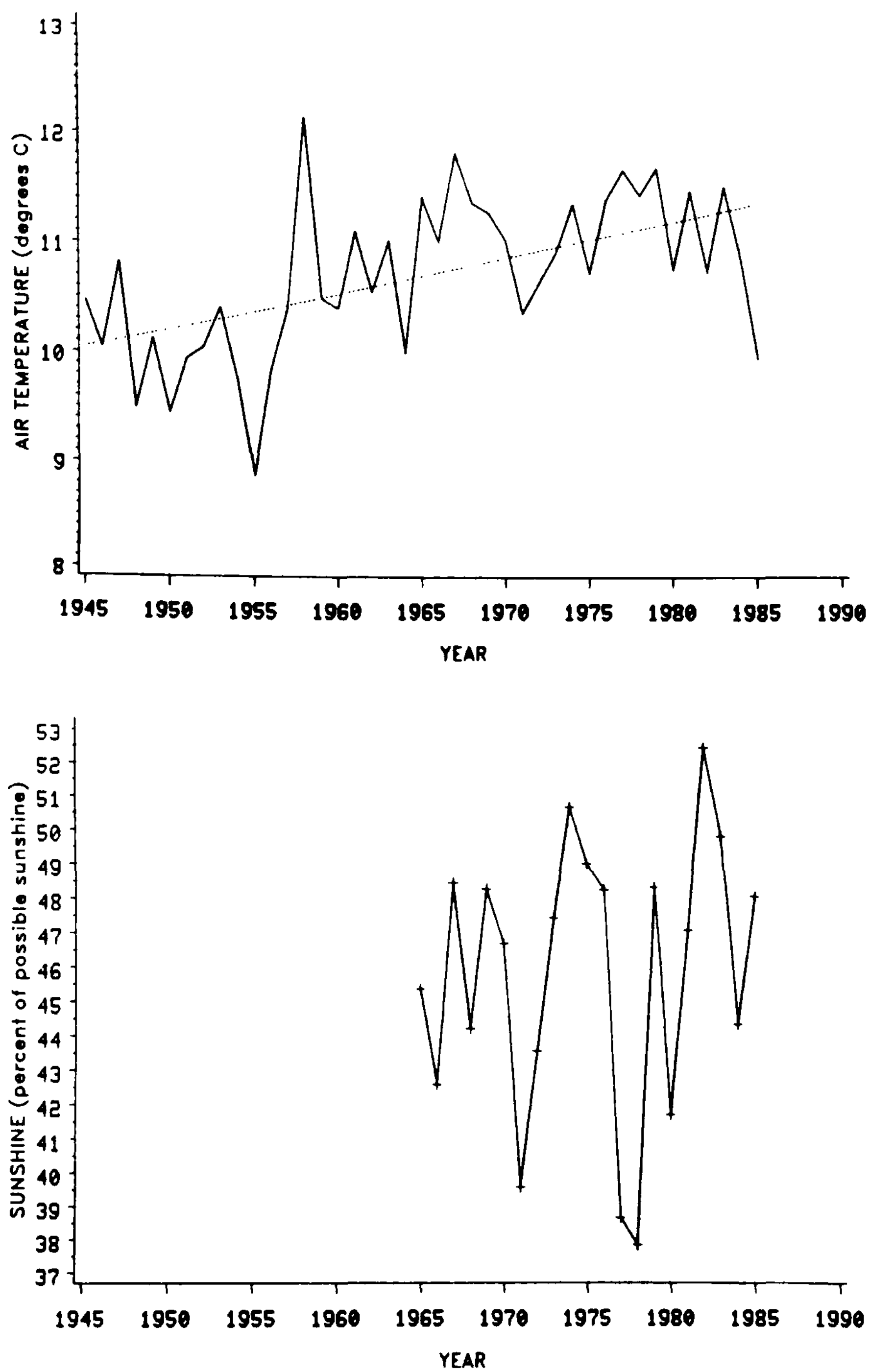


Figure 5.1. Annual means of air temperature and the percent of possible sunshine at Seattle-Tacoma International Airport.

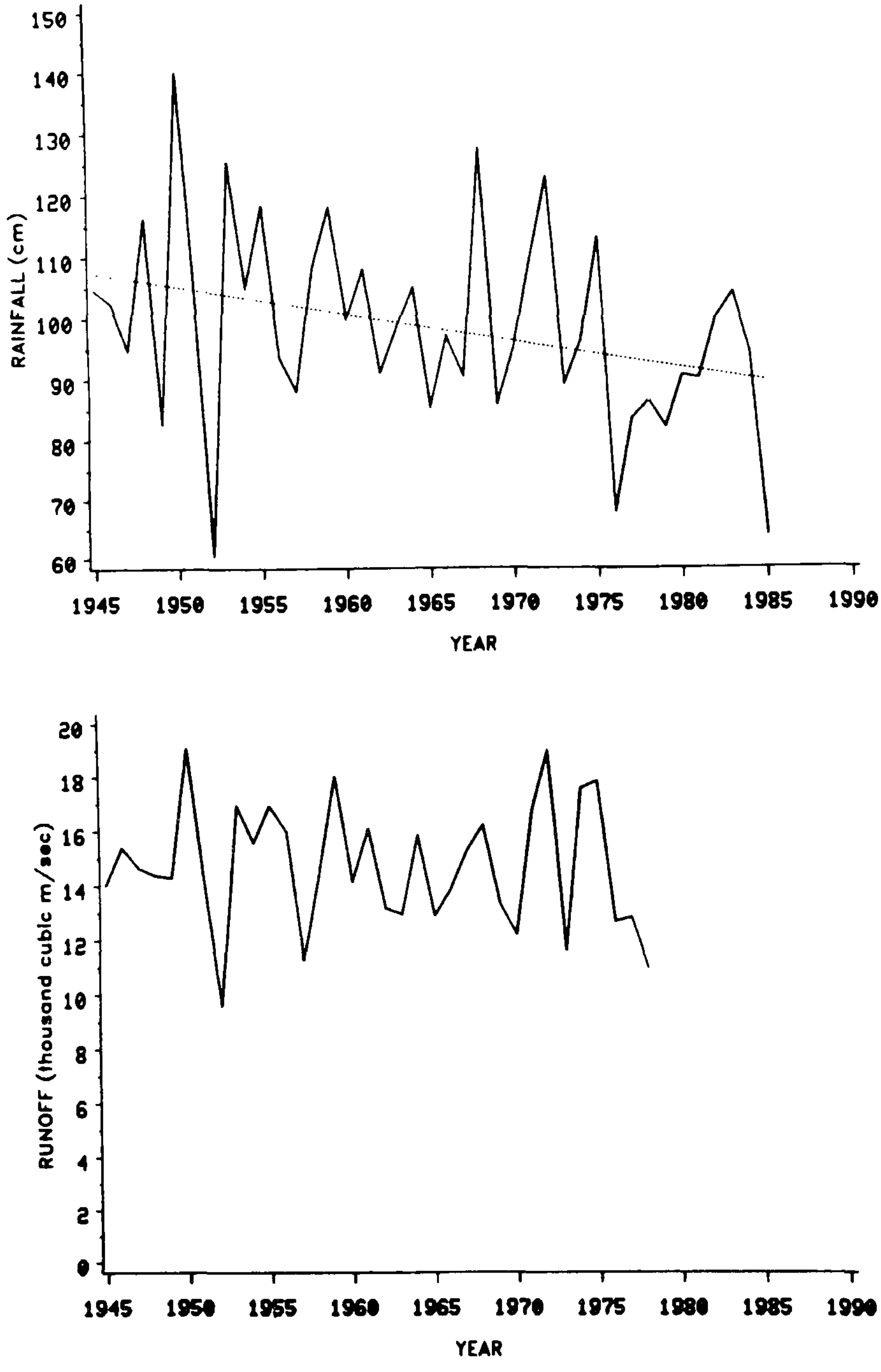


Figure 5.2. Annual totals of rainfall at Seattle-Tacoma International Airport and runoff to Puget Sound.

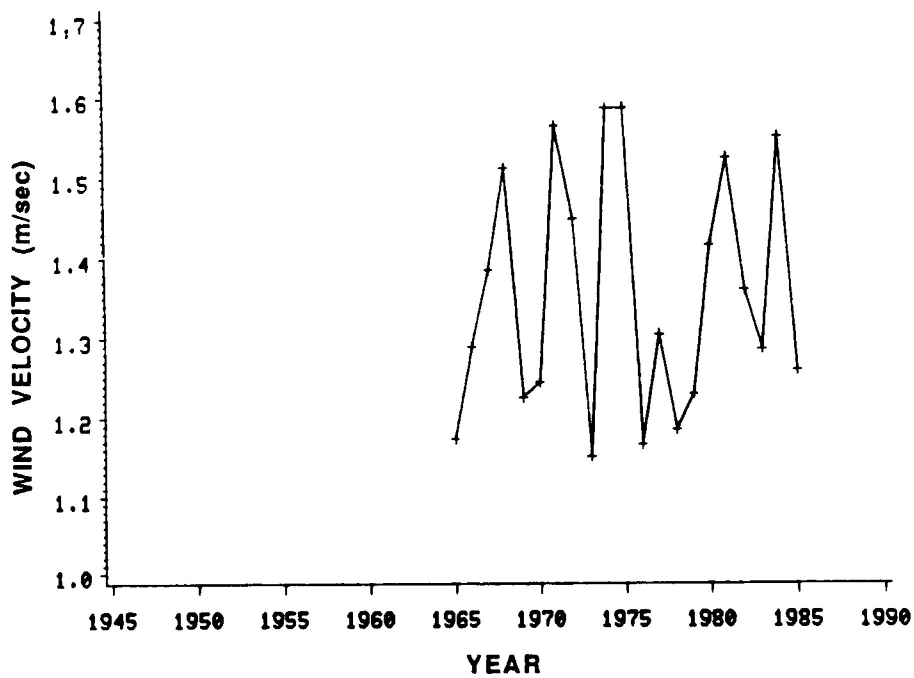


Figure 5.3. Annual mean wind velocity at Seattle-Tacoma International Airport.

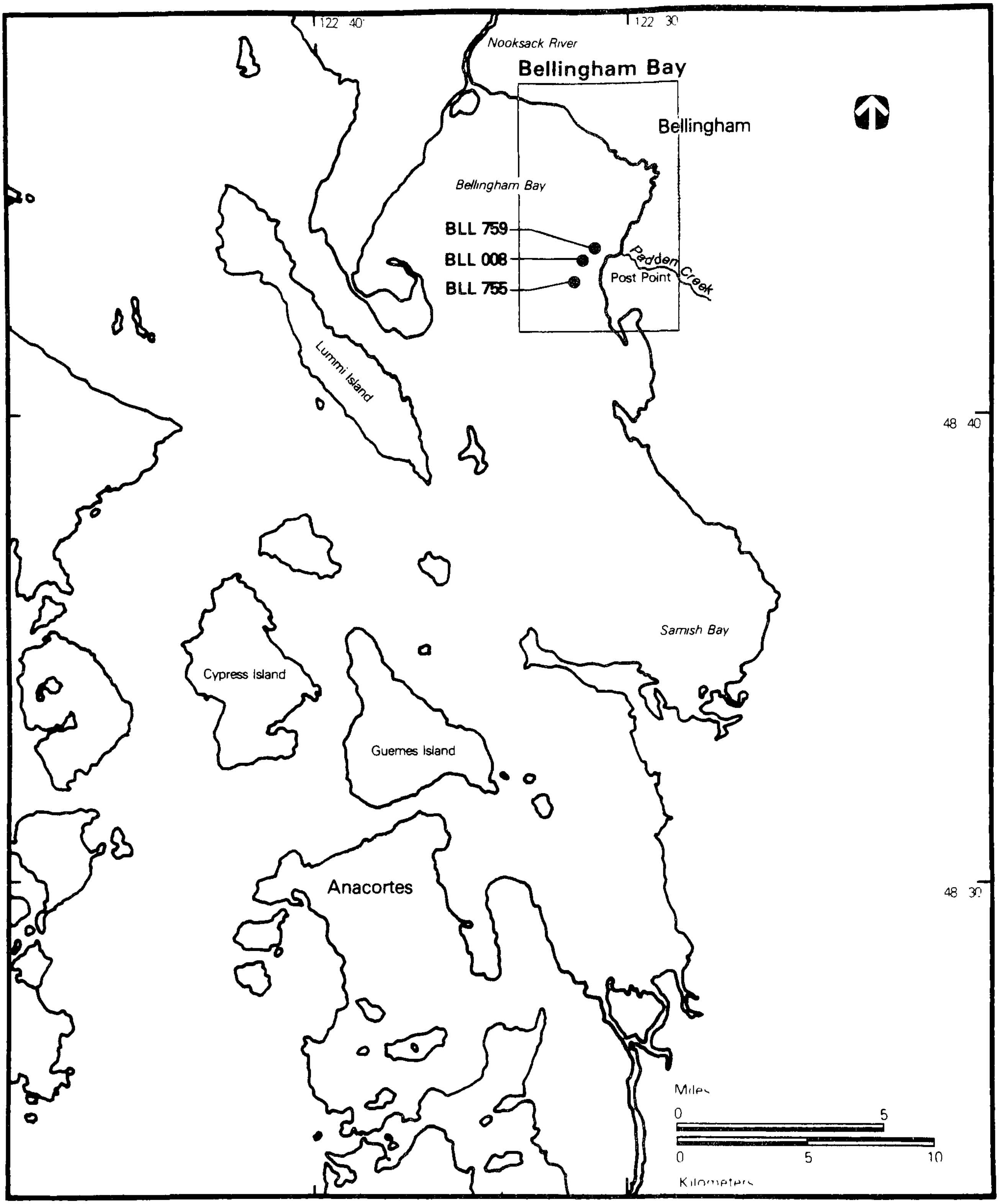


Figure 5.4. Locations of the study area and sampling stations in the northern sound.

TABLE 5.1. SAMPLING STATION NUMBERS, DATA SOURCES, AND SAMPLING PERIODS FOR THE STUDY AREA IN THE NORTHERN SOUND

Study Area	Station Number	Data Source	Sampling Period
Bellingham Bay	BLL755	UW[a]	1956-63 (includes data from WDF[b])
	BLL759	UW	1956-63 (includes data from WDF)
	BLL008	Ecology	1967-70, 1973-86

[a] UW = University of Washington.

[b] WDF = Washington Department of Fisheries.

is given in Table 5.2. Based on the percent dissolved oxygen saturation at the surface, algal blooms were most prevalent in Bellingham Bay from May through July.

Bellingham Bay

The study area is located off Post Point (Figure 5.4). The northern portion of Bellingham Bay is bordered by the City of Bellingham. Class A water quality standards apply at the site. Water depth at the study area is about 32 m. The Nooksack River discharges into the head of the bay, about 10 km northwest of the study area. The Nooksack is the fourth largest river flowing into Puget Sound and discharges approximately 7 percent of the total freshwater flow reaching the sound. Several creeks also flow into Bellingham Bay, including Padden Creek, which enters the bay approximately 1 km north of the study area. On a flooding tide, low salinity water from the Nooksack River is recirculated to the northeast, toward Post Point (City of Bellingham 1984).

A series of improvements have been made to the waste treatment facilities in the Bellingham Bay area. A primary sewage treatment plant began operating near the study site at Post Point in 1974. It replaced the old City of Bellingham plant that discharged into the Whatcom Waterway in the inner harbor north of Post Point (City of Bellingham 1984). The Post Point plant treats municipal wastes, including discharges from vegetable and seafood processors from July through December. When the Post Point plant became operational, at least two outfalls near the study area that discharged raw sewage from a service population of over 6,000 in South Bellingham were closed (Thomas, K., 27 October 1987, personal communication). From 1979 through the 1980s, several combined sewage overflows that drained into Bellingham Bay were also closed. One remains open within the City of Bellingham, well north of the study area. The Georgia-Pacific pulp mills in Bellingham reduced the biological oxygen demand (BOD) in their effluents by more than 1 order of magnitude during the 1970s. These mills upgraded to secondary effluent treatment in 1979 (NOAA 1985).

TABLE 5.2. ALGAL BLOOM SEASONS IN THE NORTHERN SOUND STUDY AREA, AS DEFINED BY MONTHLY MEAN AND STANDARD ERROR OF PERCENT DISSOLVED OXYGEN SATURATION IN SURFACE WATER

	Percent Dissolved Oxygen Saturation
Month	Bellingham Bay
April	98 +/- 2
May	114 +/- 2[a]
June	115 +/- 4[a]
July	121 +/- 3[a]
August	100 +/- 4
September	100 +/- 5

[a] Months included in the algal bloom season.

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.5. Summary statistics are given in Appendix E. Data are available from 1958 through 1986, with limited coverage from the mid-1960s through the mid-1970s. Substantial vertical gradients in both salinity and water temperature values indicated that density stratification was well developed in the study area. The mean salinity value at the surface was 4.2 ppt lower than the mean at 10-m depth, while the mean water temperature at the surface was 3.4^{o} C higher than the mean at 10-m depth. The negative correlation between salinity values and water temperature values at the surface (Appendix F) indicates that warm water tended to be low in salinity and that cold water tended to be high in salinity. This correlation probably reflects fluctuating freshwater inputs from the Nooksack River. During periods of density stratification and relative stability of the water column, solar heating of the surface would be most effective in heating up the low salinity surface water.

The vertical distributions of dissolved oxygen and nutrients appear to have been strongly influenced by density stratification of the water column (Figures 5.6 and 5.7). The concentration of dissolved oxygen was approximately 10 percent higher at the surface than at 10-m depth. The concentration of nitrate was only about 40 percent as high at the surface as at 10-m depth, while the concentration of phosphate was 60 percent as high the surface as at 10-m depth. Although considerable, these depth gradients were less developed than those in more sheltered embayments that lacked substantial inputs of fresh water, such as Sinclair and Carr Inlets.

Correlations for surface waters (see Appendix F) suggest that when dissolved oxygen concentrations were low, salinity values were also low and water temperature values were high. Freshwater sources in the area probably have lower concentrations of dissolved oxygen than does the seawater in the area.

The moderate elevation of the percent dissolved oxygen saturation at the surface (i.e., 115 percent) suggests that only moderate algal blooms

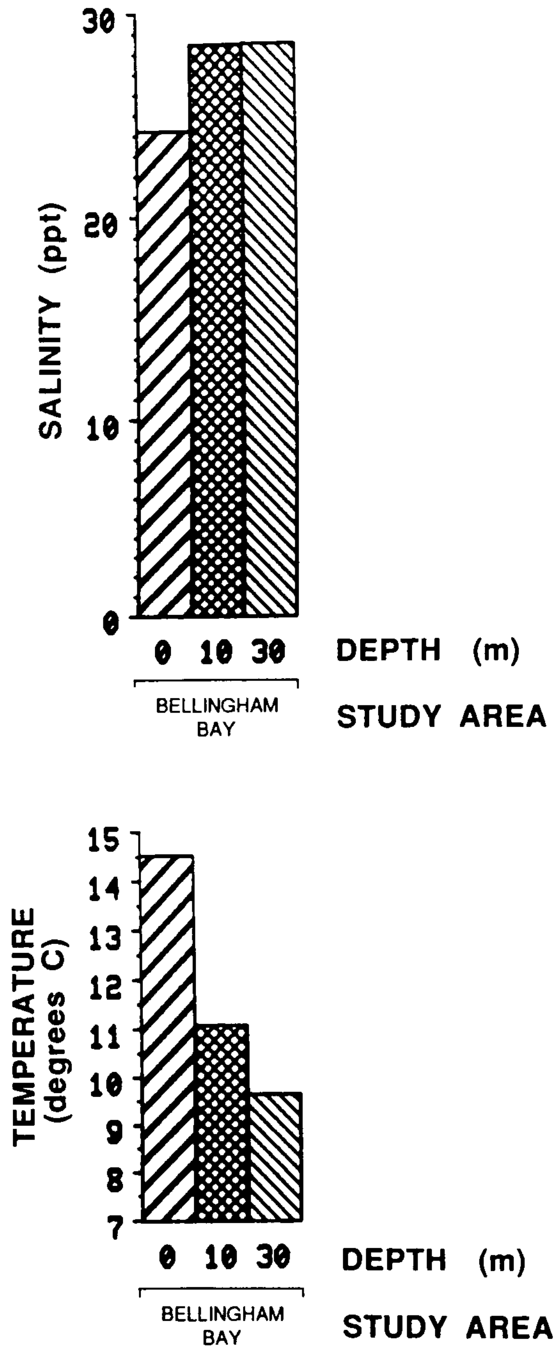
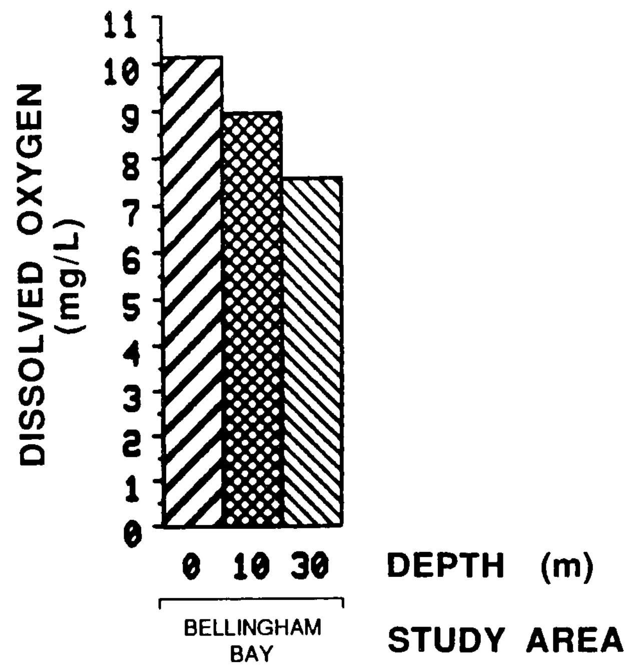


Figure 5.5. Mean salinity and water temperature values in the northern sound study area during the algal bloom season.



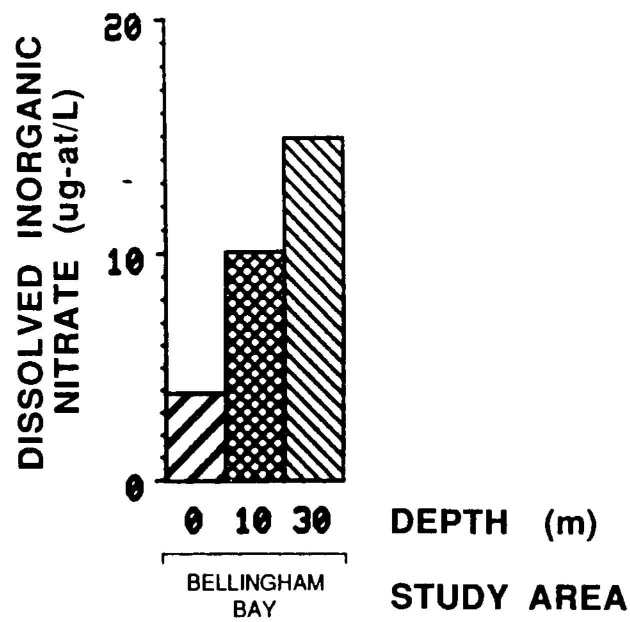
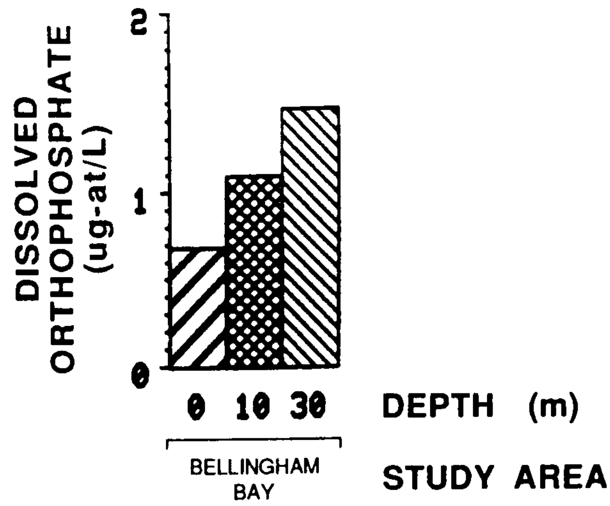


Figure 5.6. Mean concentrations of dissolved oxygen and dissolved inorganic nitrate in the northern sound study area during the algal bloom season.



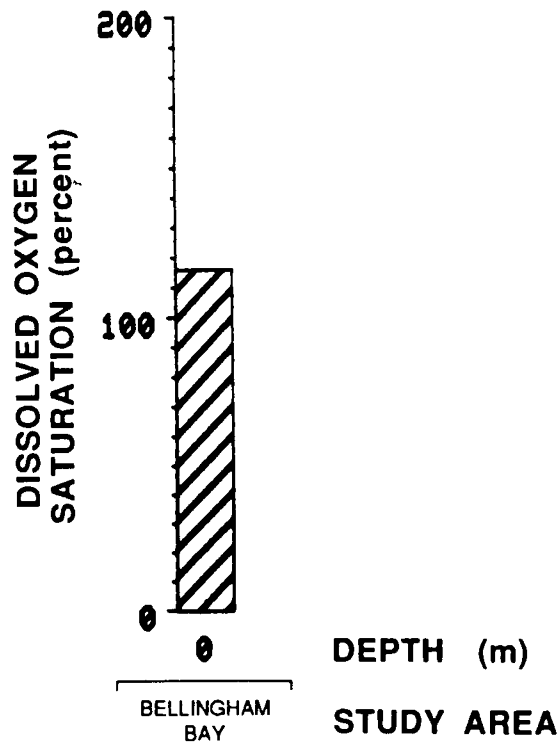


Figure 5.7. Mean concentrations of dissolved orthophosphate and the mean percent saturation of dissolved oxygen at the surface in the northern sound study area during the algal bloom season.

occurred in the study area (Figure 5.7). Secchi disk depth readings (Figure 5.8) were relatively low (i.e., 3 m) compared with areas such as Point Jefferson, presumably because of suspended particulate material carried into Bellingham Bay by the Nooksack River. The limited photic zone and relatively rapid flushing of upper Bellingham Bay, which averages about 4 days (City of Bellingham 1984), may limit the growth rates of phytoplankton.

The geometric mean concentration of sulfite waste liquor was high (22.1 Pearl Benson Index) in the study area, particularly at the surface (Figure 5.8). Historically, two Georgia-Pacific pulp mills discharged sulfite waste liquor into Whatcom Waterway in inner Bellingham Harbor. Generally, the sulfite waste liquor remained in the top 6 m of the water column (Federal Water Pollution Control Administration and Washington State Pollution Control Commission 1967).

Concentrations of fecal coliform bacteria have remained low (geometric mean <2.5 organisms/100 mL) in the study area (Figure 5.8). The Federal Water Pollution Control Administration and the Washington State Pollution Control Commission (1967) reported that fecal coliform concentrations were markedly elevated in the vicinity of Whatcom Waterway before the City of Bellingham sewage treatment plant was replaced by the Post Point Pollution Control Plant.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.3. Slopes of statistically significant long-term and recent regressions of the values of water quality variables by year are given in Table 5.4.

Physical Conditions--Plots of salinity and water temperature data by year are shown in Figures 5.9-5.11. Significant long-term declines ($P<0.05$) in salinity values were detected at the surface and at 10-m depth. These declines in salinity values were detected by both the ANOVA comparisons of the data reported before and after 1973 (Table 5.3) and the long-term

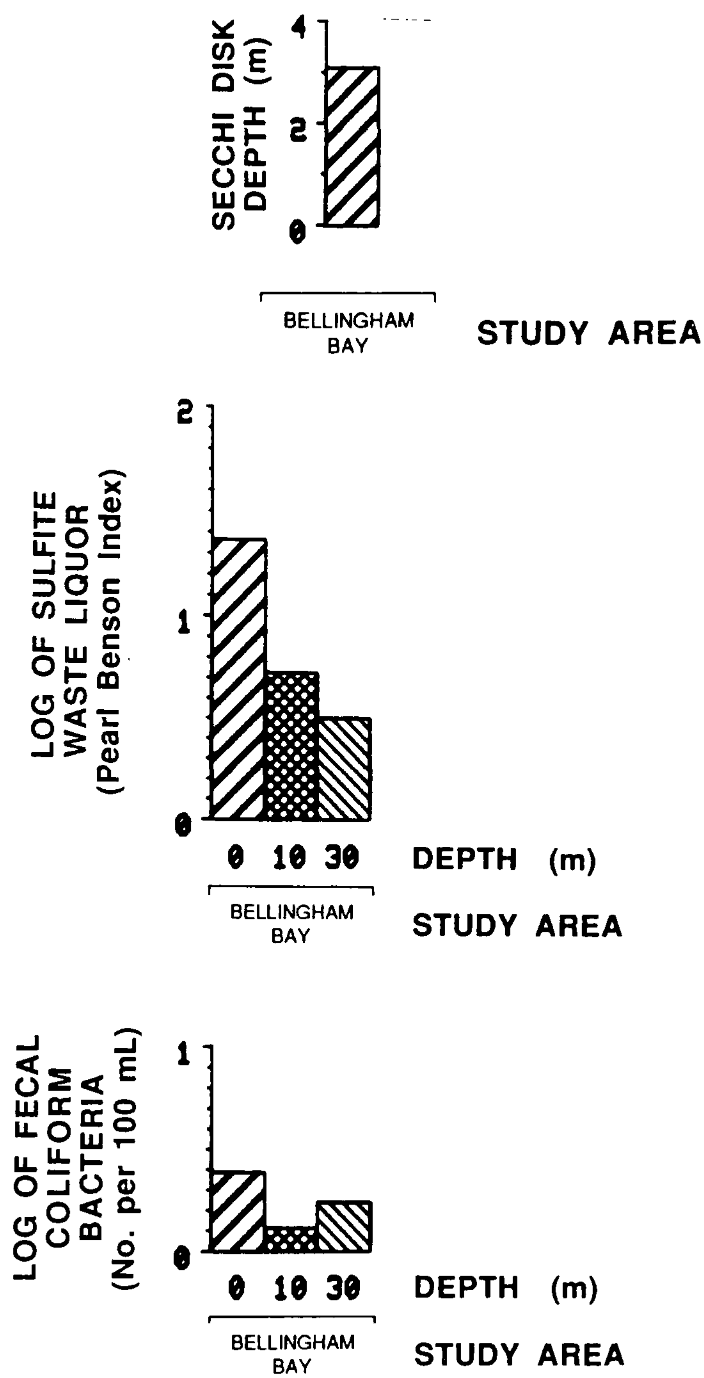


Figure 5.8. Mean Secchi disk depth and log of geometric mean concentrations of sulfite waste liquor and fecal coliform bacteria in the northern sound study area during the algal bloom season.

TABLE 5.3. NET CHANGE AND PERCENT CHANGE IN THE MEAN VALUES OF WATER QUALITY VARIABLES IN THE NORTHERN SOUND, BASED ON ANOVA COMPARISONS OF DATA TAKEN BEFORE 1973 WITH DATA TAKEN FROM 1973 TO 1986

Depth (m)	Bellingham Bay Change Net	Bellingham Bay Change Percent
	Salinity (ppt)	
0	-3.35	13.2
10	-1.11	3.8
30	na[a]	
	Water Temperature (^{o} C)	
0	-1.57	10.4
10	NS[b]	
30	na	
	Dissolved Oxygen (mg/L)	
0	NS	
10	NS	
30	na	
	Nitrate (ug-at/L)	
0	na	
10	na	
30	na	
	Phosphate (ug-at/L)	
0	NS	
10	NS	
30	na	
	Chlorophyll a (ug/L)	
0	na	
10	na	
30	na	
	Surface Dissolved Oxygen Saturation (Percent)	
0	NS	
	Secchi Disk Depth (m)	
	NS	
	Sulfite Waste Liquor (Pearl Benson Index)	
0	-39.94	68.7
10	+7.21	236.4
30	na	
	Fecal Coliform Bacteria (No./100 mL)	
0	na	
10	na	
30	na	

[a] na Results of the statistical test were not available because of a lack of data.

[b] NS - The pre-1973 and 1973-1986 values were not significantly different at P<0.05, based on a nonparametric one-way ANOVA.

TABLE 5.4. SLOPES OF STATISTICALLY SIGNIFICANT LONG-TERM AND RECENT REGRESSIONS OF WATER QUALITY VARIABLES AS A FUNCTION OF YEAR FOR THE NORTHERN SOUND

Depth (m)	Slopes: Bellingham Bay Long-term	Slopes: Bellingham Bay Recent
Salinity (ppt)		
0	-0.130	NS[a]
10	-0.060	NS
30	na[b]	NS
Water Temperature (° C)		
0	-0.086	0.194
10	NS	NS
30	na	0.148
Dissolved Oxygen (mg/L)		
0	NS	NS
10	NS	NS
30	na	NS
Nitrate (ug-at/L)		
0	na	NS
10	na	NS
30	na	NS
Phosphate (ug-at/L)		
0	NS	NS
10	NS	0.064
30	na	NS
Surface Dissolved Oxygen Saturation (Percent)		
0	NS	NS
Secchi Disk Depth (m)		
	NS	NS
Sulfite Waste Liquor[c] (Pearl Benson Index)		
0	-0.037	-0.068
10	0.025	NS
30	NS	NS
Fecal Coliform Bacteria[d] (No./100mL)		
0	na	-0.061
10	na	na
30	na	na

[a] NS - Not significant at $P<0.05$.

[b] na = Results of the statistical test were not available because of a lack of data.

[c] Data were subjected to a log(X+1) transformation for the regressions.

[d] Data were subjected to a log transformation for the regressions.

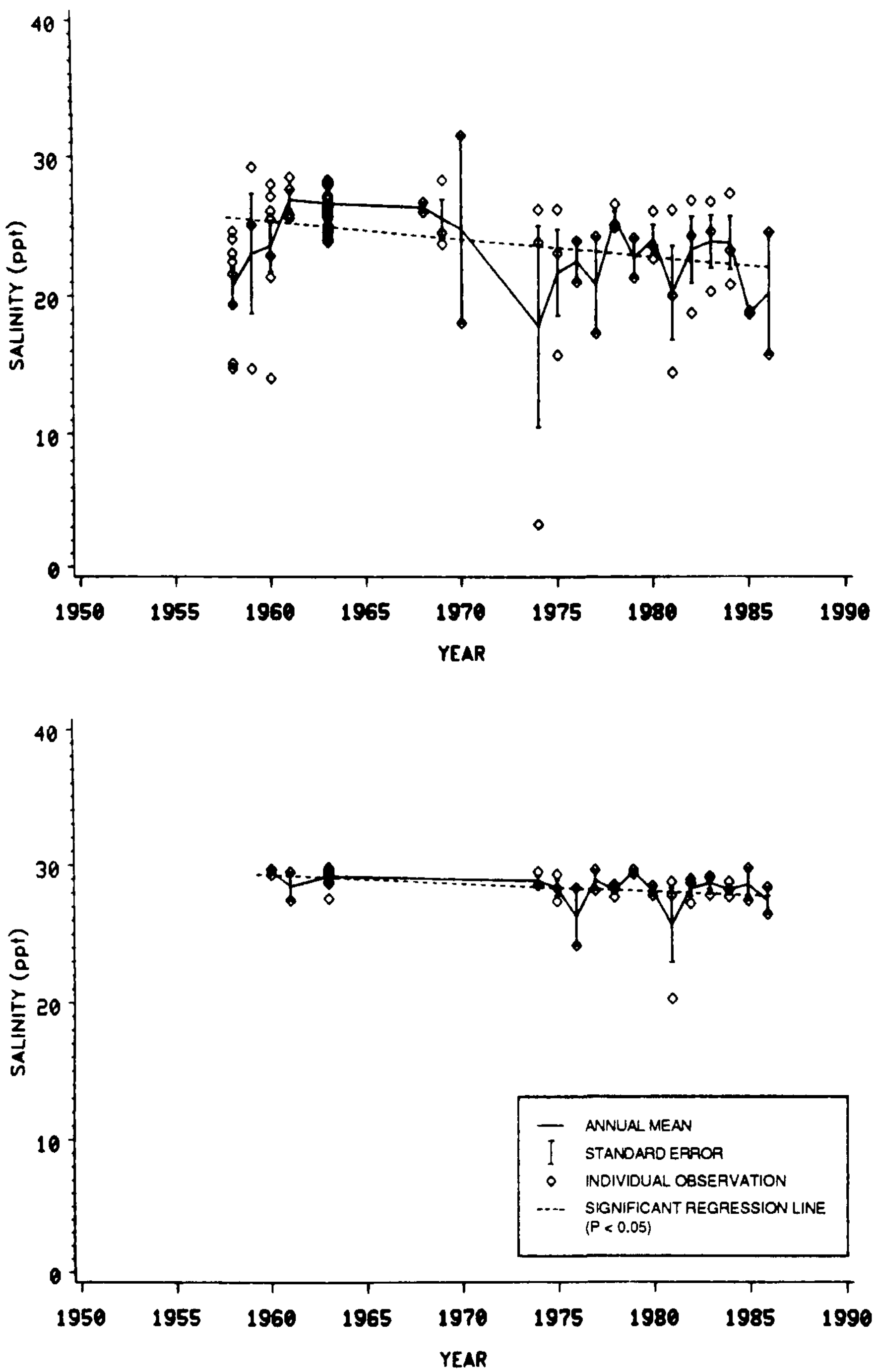


Figure 5.9. Salinity values at the surface and at 10-m depth in the Bellingham Bay study area during the algal bloom season.

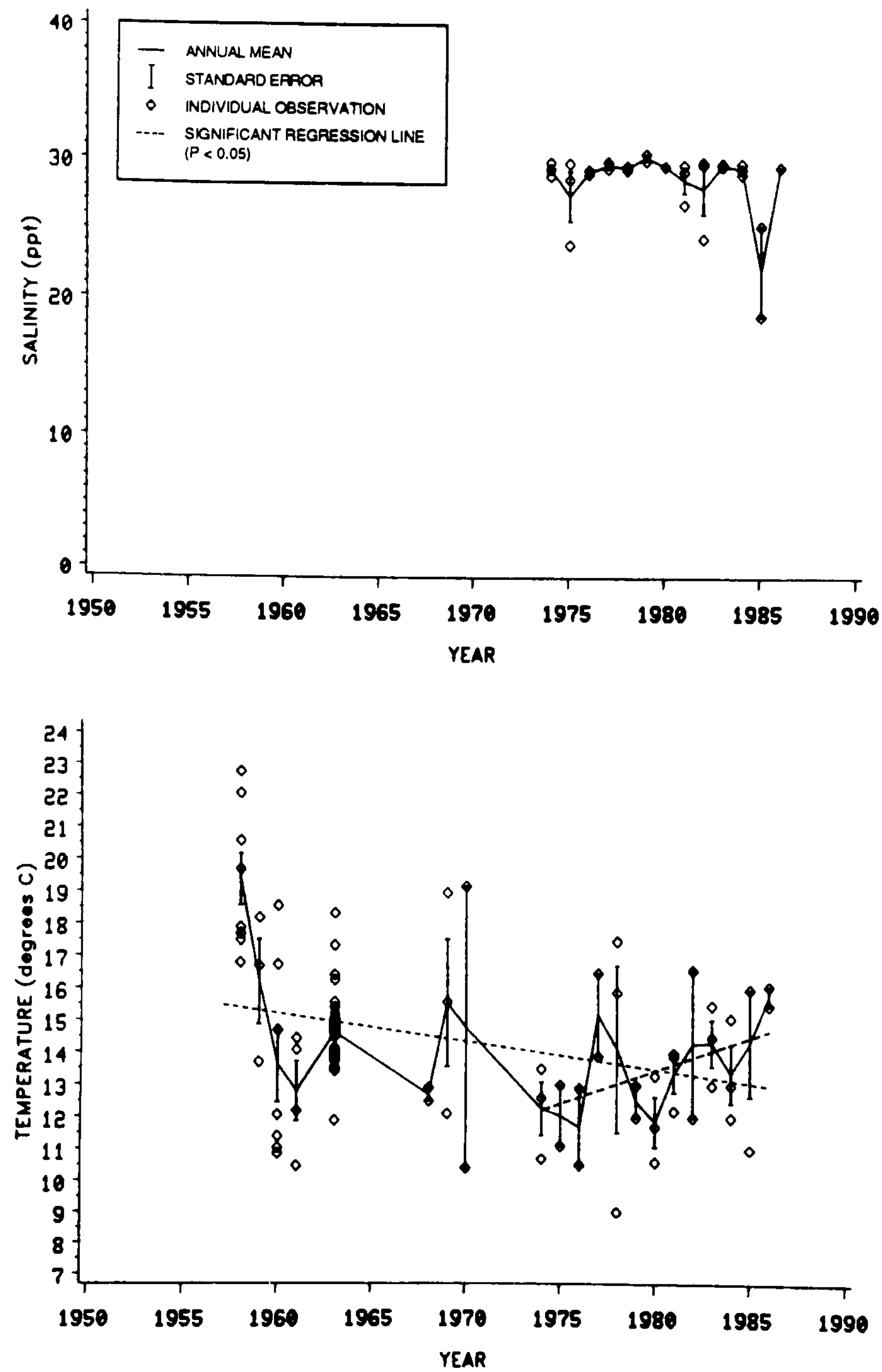


Figure 5.10. Salinity values at 30-m depth and water temperatures at the surface in the Bellingham Bay study area during the algal bloom season.

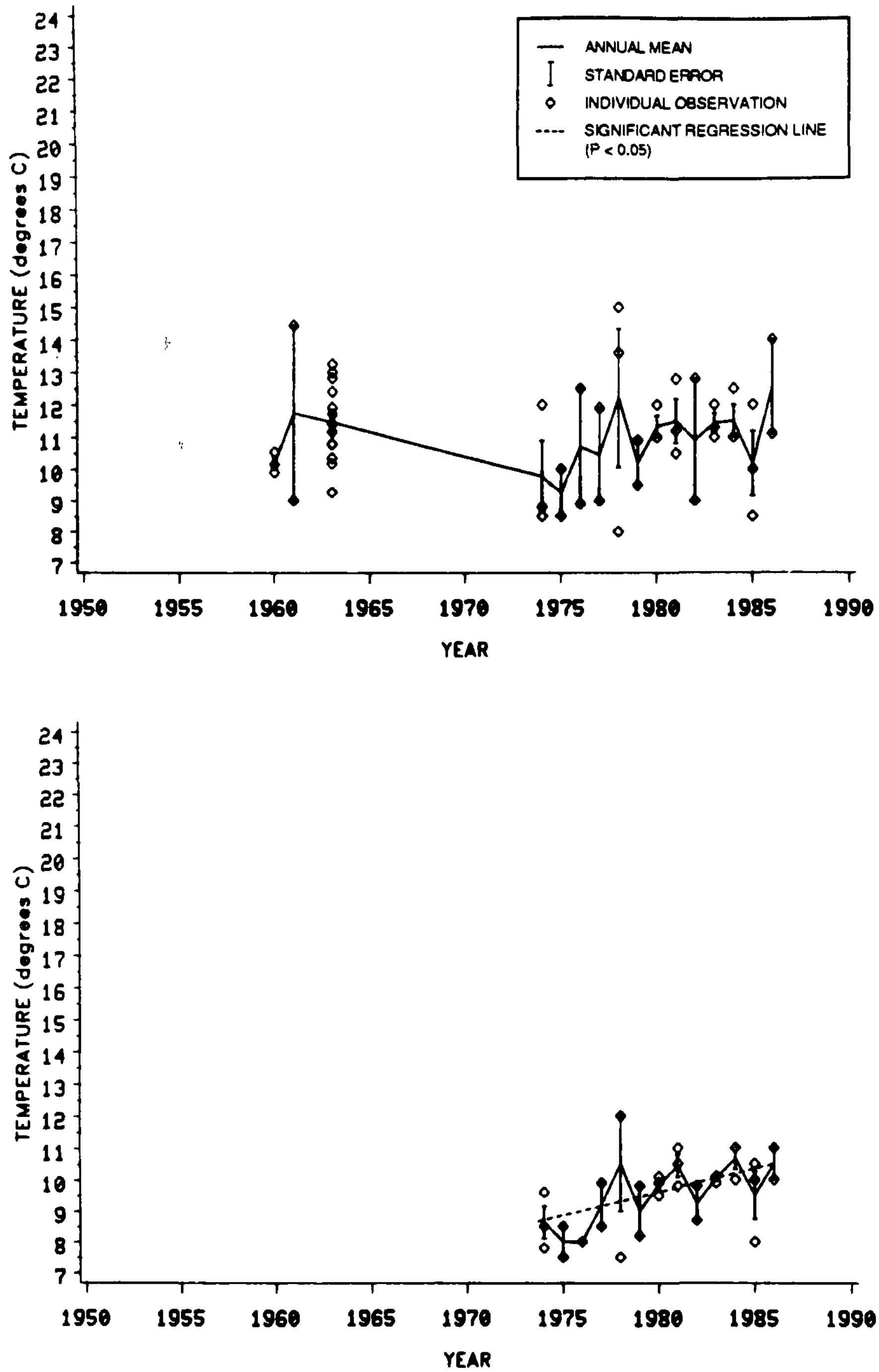


Figure 5.11. Water temperatures at 10- and 30-m depths in the Bellingham Bay study area during the algal bloom season.

regressions of salinity values by year (Table 5.4). No explanation is available for the apparent declines in salinity values. Based on the declines in total annual rainfall values at the Seattle-Tacoma International Airport (Figure 5.2), increases in salinity values, rather than decreases, would be expected.

A significant long-term decline in surface water temperatures, detected by both ANOVA (Table 5.3) and regression (Table 5.4), appears to have been driven by the high values recorded in 1958. The highest annual mean and temperature of Seattle-Tacoma International Airport for the period of 1945-1985 was recorded in 1958 (Figure 5.1). Recent increasing trends (Table 5.4) appear to have been associated with cool periods in 1974 through 1976 and warm periods in 1985 and 1986 (Figure 5.1).

Dissolved Oxygen--Plots of dissolved oxygen concentration by year are shown in Figures 5.12 and 5.13. Violations of the Class A water quality standard (see Table 4.2) were recorded only in 1960 at 10-m depth. No significant changes in dissolved oxygen concentrations were detected.

Nutrients--Plots of nitrate concentrations by year are given in Figures 5.13 and 5.14. Because data are only available since 1974, comparisons between data from before 1973 and data from 1973 through 1986, and long-term regressions of nitrate concentration by year, were not possible. Recent regressions against year were not significant (Table 5.4). Concentrations at the surface were low, often near the analytical detection limit (0.7 ug-at/L) and highly variable.

Plots of phosphate concentration by year are given in Figures 5.15 and 5.16. One point is available from 1960, along with data from 1974 through 1986. A positive slope in the regression for data from 10-m depth since 1974 was the only significant ($P<0.05$) trend detected (Table 5.4). Although the underlying cause of the rise in phosphate concentrations is unclear, the decline in sulfite waste liquor discharges from the Georgia-Pacific pulp mills that occurred when the mills adopted secondary treatment in 1979 (NOAA 1985) may have contributed to this trend. As noted in Chapter 3, sulfite waste liquor causes the inorganic phosphate contained

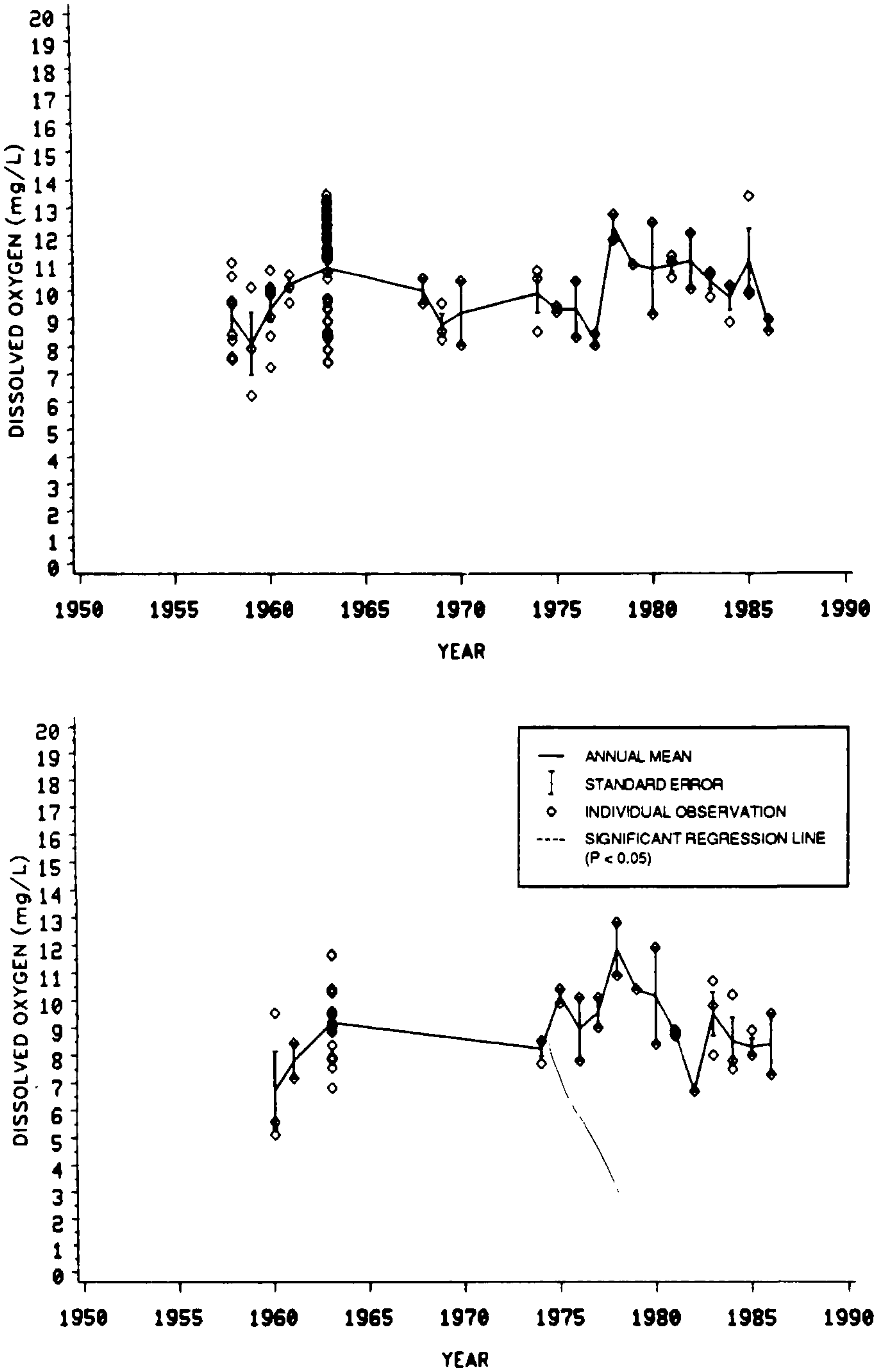


Figure 5.12. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Bellingham Bay study area during the algal bloom season.

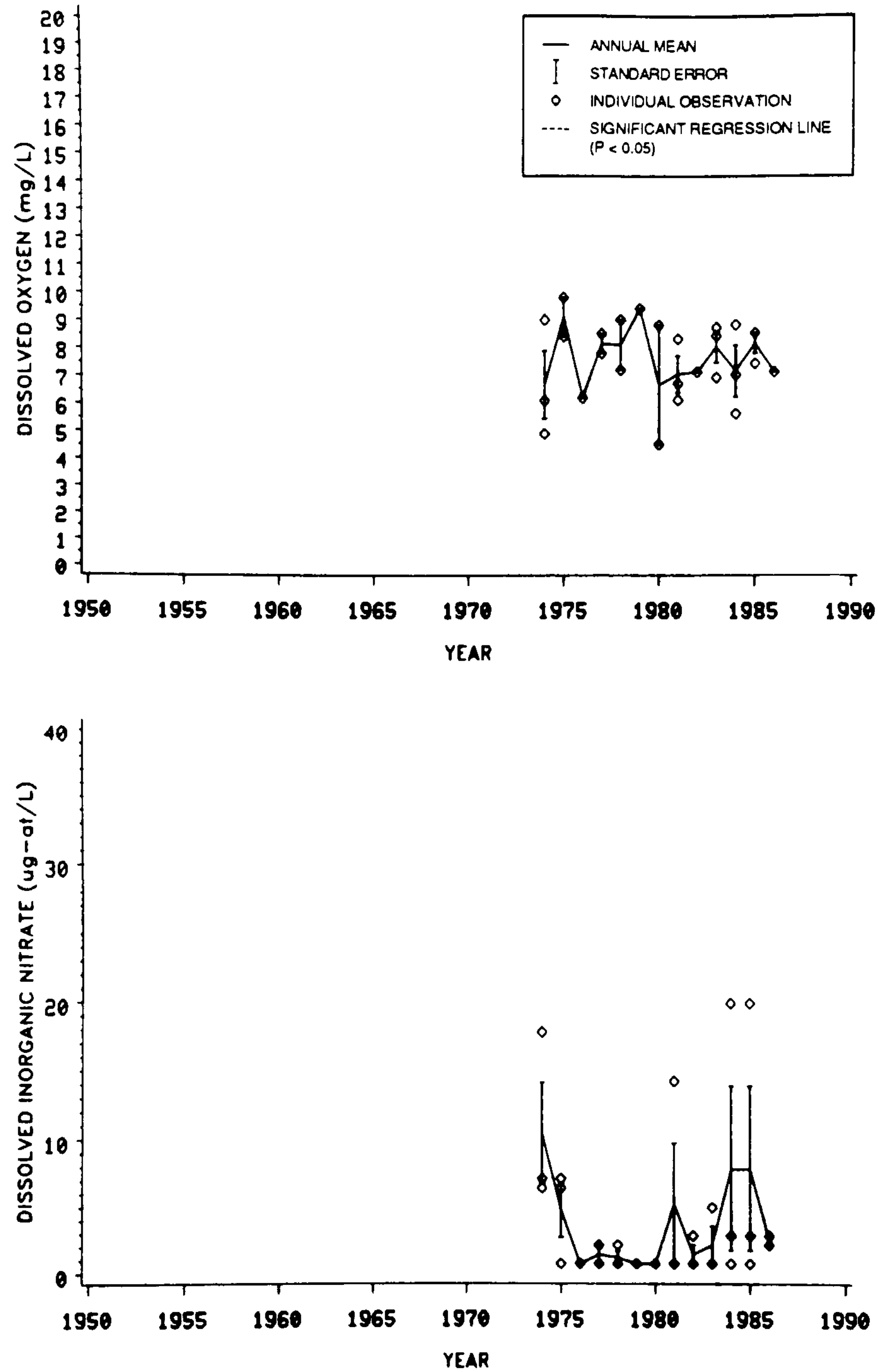


Figure 5.13. Concentrations of dissolved oxygen at 30-m depth and dissolved inorganic nitrate at the surface in the Bellingham Bay study area during the algal bloom season.

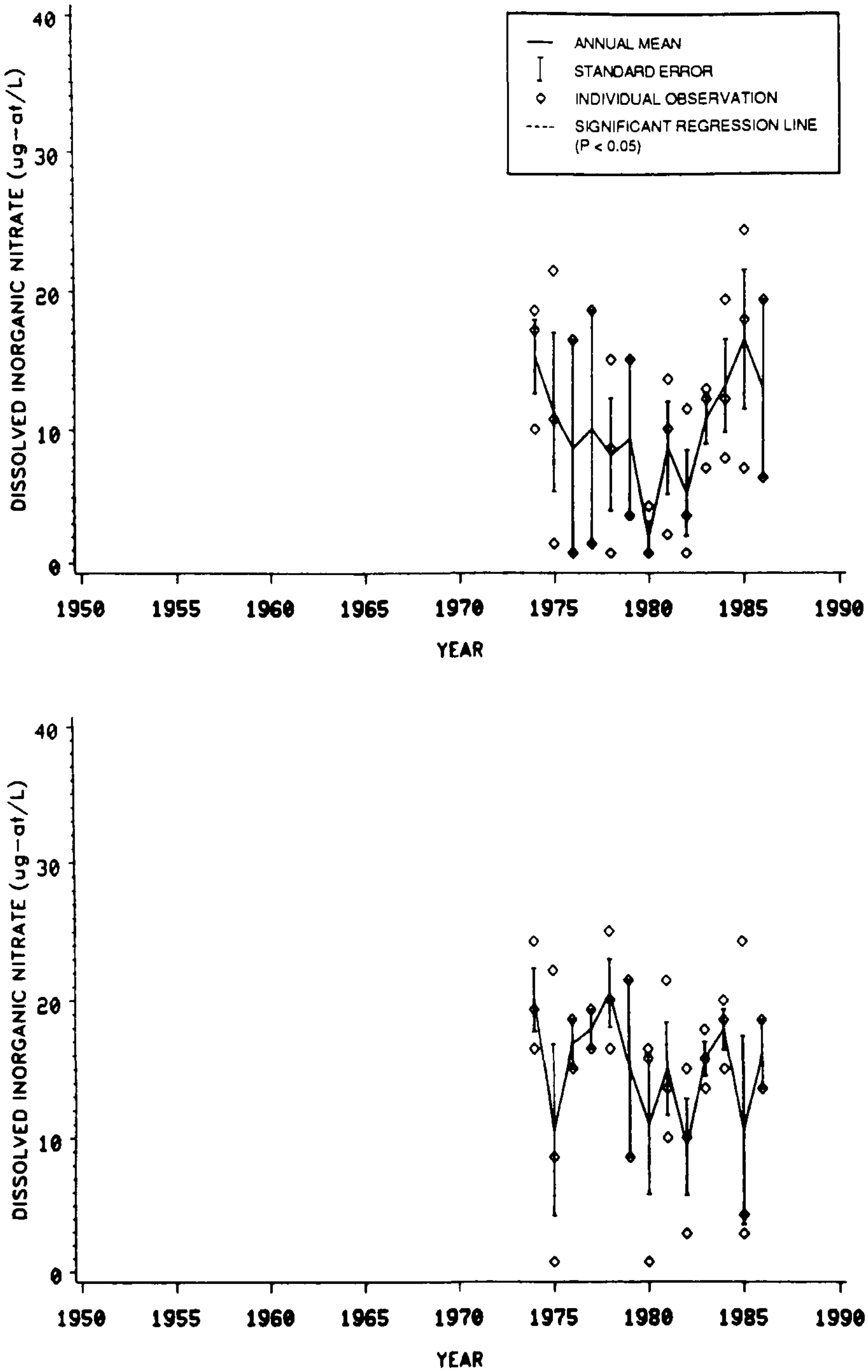


Figure 5.14. Concentrations of dissolved inorganic nitrate at 10- and 30-m depths in the Bellingham Bay study area during the algal bloom season.

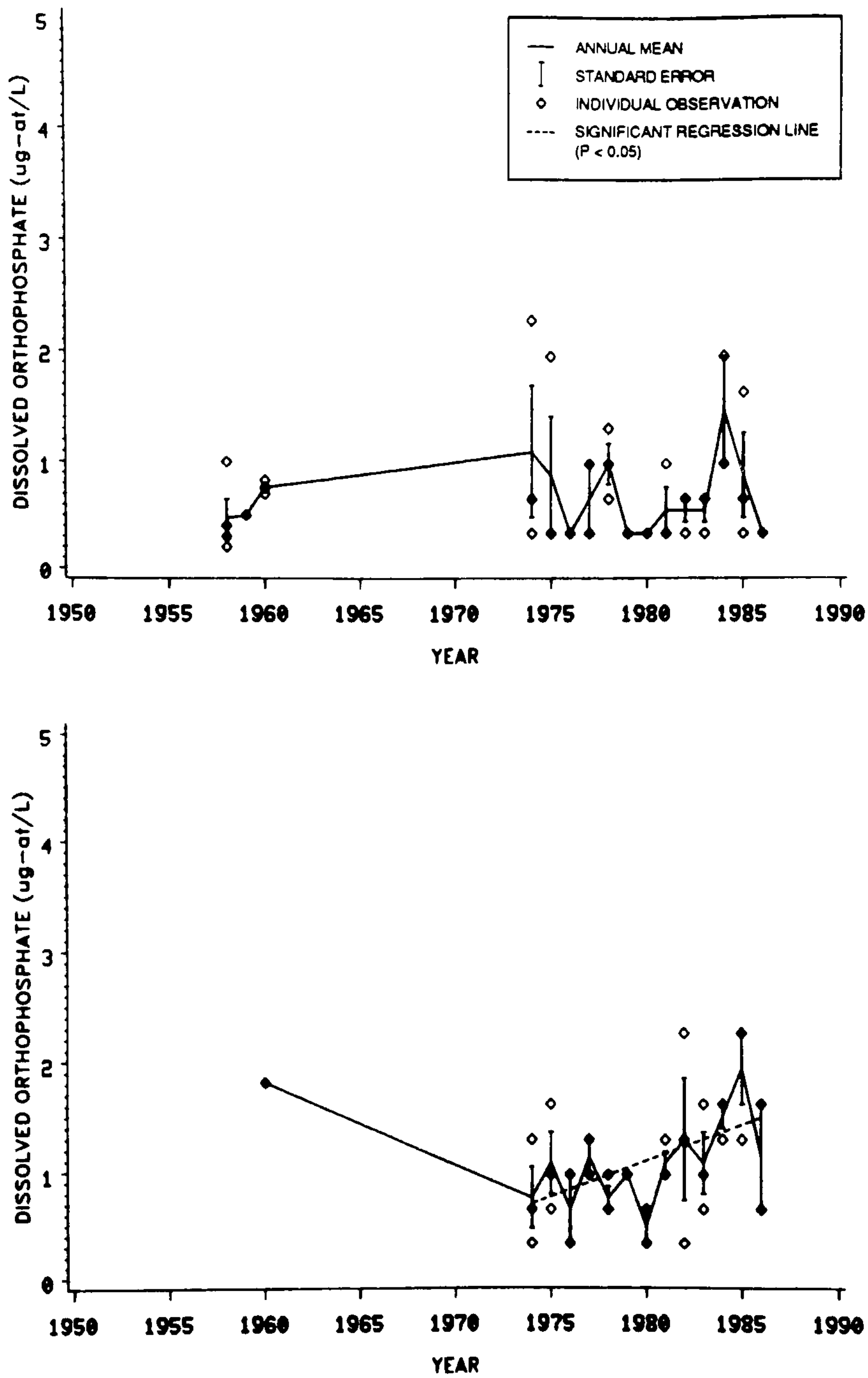


Figure 5.15. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Bellingham Bay study area during the algal bloom season.

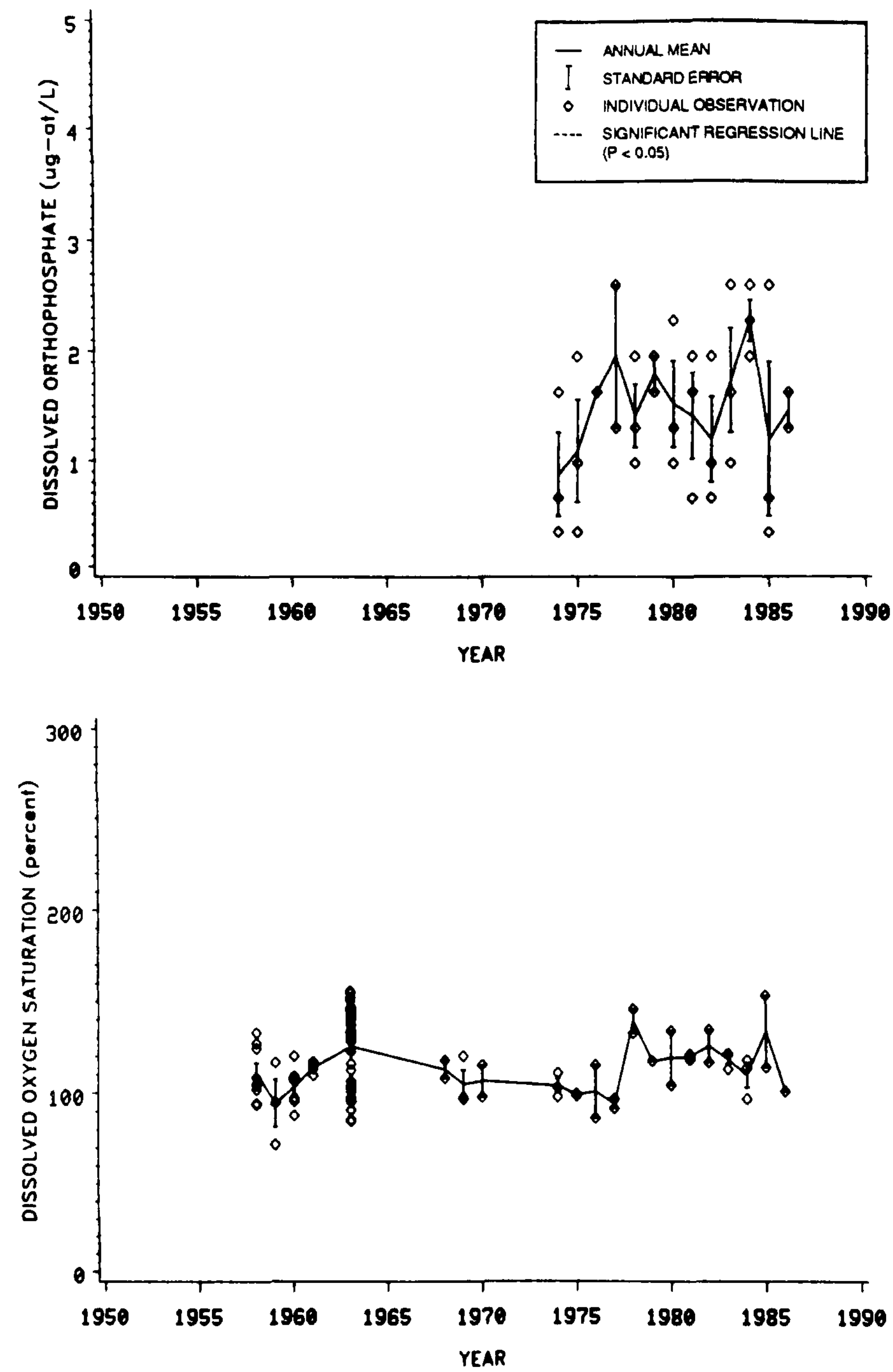


Figure 5.16. Concentrations of dissolved orthophosphate at 30-m depth and percent dissolved oxygen saturation at the surface in the Bellingham Bay study area during the algal bloom season.

in seawater to precipitate (Westley and Tarr 1978). The decline in sulfite waste liquor emissions might have allowed dissolved inorganic phosphate concentrations to recover over time. Alternatively, the increase in phosphate concentrations may have been influenced by changes in other anthropogenic sources or oceanic sources.

Indicators of Phytoplankton Growth--Data on chlorophyll a concentrations are not available. Percent dissolved oxygen saturation at the surface and Secchi disk depth are plotted against year in Figures 5.16 and 5.17. No significant changes were detected for either variable.

Pollutants--Plots of sulfite waste liquor concentrations by year are shown in Figures 5.17 and 5.18. The most important change was a substantial decline in sulfite waste liquor concentration at the surface (Tables 5.3 and 5.4). This decline appears to have coincided with the onset of secondary treatment by the Georgia-Pacific pulp mill in 1979. A statistically significant long-term increase in sulfite waste liquor was detected at 10-m depth. No explanation is available for this increase.

Concentrations of fecal coliform bacteria in surface water are plotted by year in Figure 5.19. Class A water quality standards were not violated after 1978. A significant decline in the concentrations of fecal coliform bacteria since 1974 was detected by regression (Table 5.4). High values were reported in 1974 and 1978, but values reported in 1985 and 1986 represented "undetected" concentrations. The data from 1974 were obtained before the Post Point plant became operational, and probably reflect conditions that existed when raw sewage was still discharged near the study area. Subsequent declines in coliform concentrations may have reflected closures of combined sewer overflows that occurred in the early 1980s (Thomas, K., 27 October 1987, personal communication).

Summary of Results for the Northern Sound

Because only one area was investigated, summaries of environmental conditions and trends in water quality would simply repeat the foregoing

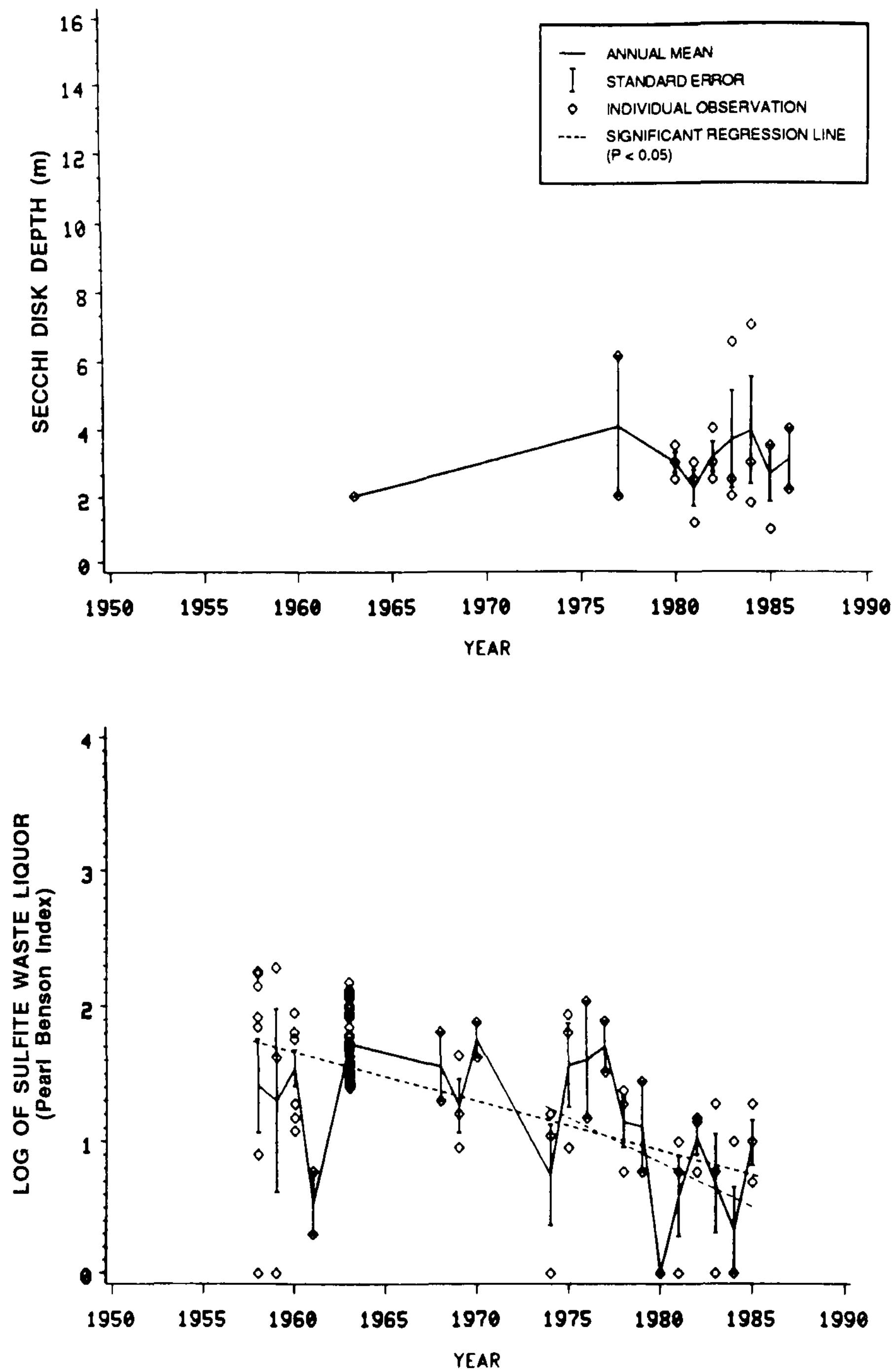


Figure 5.17. Secchi disk depth and log of concentrations of sulfite waste liquor at the surface in the Bellingham Bay study area during the algal bloom season.

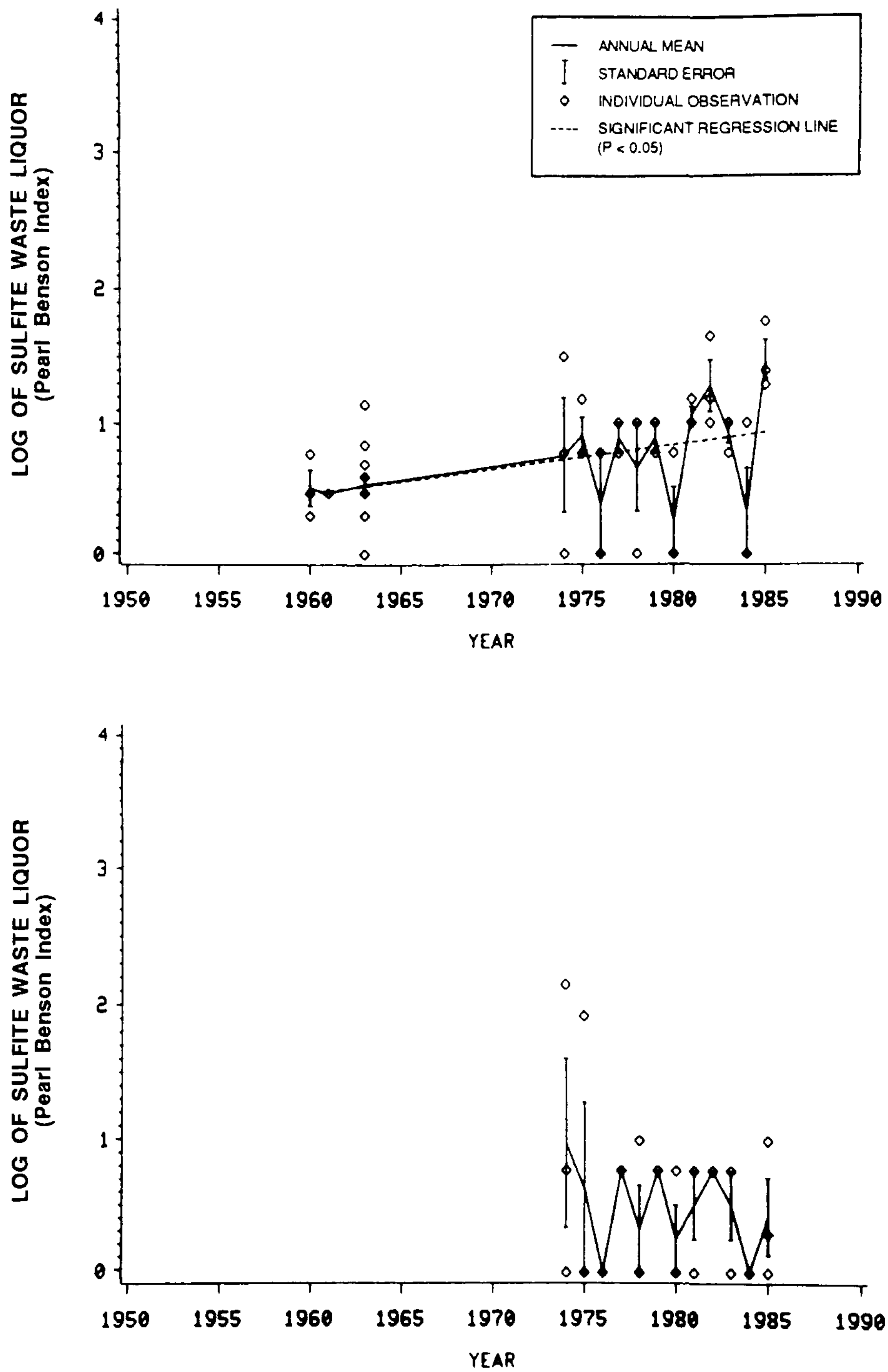


Figure 5.18. Log of concentrations of sulfite waste liquor at 10- and 30-m depths in the Bellingham Bay study area during the algal bloom season.

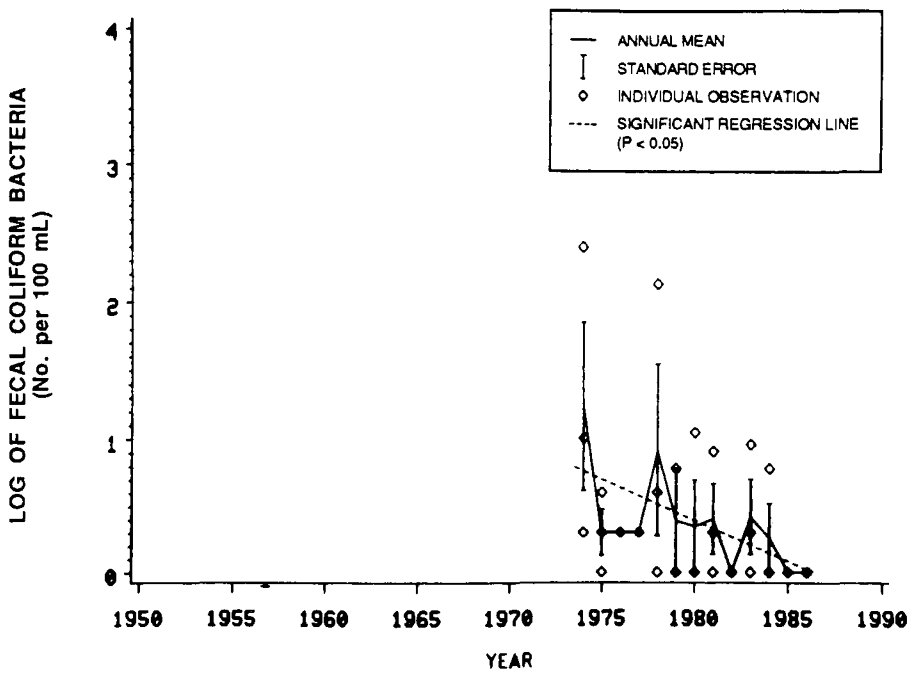


Figure 5.19. Log of concentrations of fecal coliform bacteria at the surface in the Bellingham Bay study area during the algal bloom season.

information. Hence, summaries of these topics are not presented for northern Puget Sound.

Sensitivity to Nutrient Enrichment--

The capacity of Bellingham Bay to export or assimilate pollutants without deleterious effects is probably higher than the capacities of the more sheltered embayments of Puget Sound that lack substantial freshwater inputs (e.g., Sinclair and Carr Inlets). The range of estimated flushing times for the bay, 1-10 days (City of Bellingham 1984), and the moderate depths of the bay (considerable portions of the bay are deeper than 100 m), suggest that nutrients would be removed or diluted more effectively than in the more sheltered areas mentioned above. However, the flushing rate and dilution capability of Bellingham Bay are lower than those found in open, mid-channel areas, such as Point Jefferson and Nisqually Reach.

CENTRAL SOUND

The central sound is defined herein as the area encompassing the Main Basin of Puget Sound from Admiralty Inlet to Tacoma Narrows, including the embayments west of Bainbridge Island (see Figure 2.1). Virtually all oceanic waters enter the central sound over the sill at Admiralty Inlet. Much of the central sound is relatively deep and well flushed, except for some urban waterways and the embayments west of Bainbridge Island. Substantial inputs of fresh water enter the central sound from the Skagit River (via Possession Sound) and from the Snohomish, Duwamish, and Puyallup Rivers (see Table 2.1). The central sound contains approximately 60 percent of the volume, 46 percent of the surface area, 33 percent of the shoreline, and 22 percent of the tidelands that occur within Puget Sound south of Admiralty Inlet (Burns 1985). Most of the original tidelands in the urban and agricultural areas of the central sound have been diked or filled (Shapiro and Associates 1983).

Most of the population of the Puget Sound basin lives in the vicinity of the central sound. Consequently, most of the pollutant loadings (nutrients, toxic substances) that reach Puget Sound are discharged into the central sound (PSWQA 1986b). The major cities and industrial centers in this region are Everett, Seattle, Bremerton, and Tacoma.

Four study areas included in the characterization project are located in the central sound: Port Gardner, Point Jefferson, Sinclair Inlet, and City Waterway in Commencement Bay. Station locations are shown in Figure 5.20. Data sources are given in Table 5.5. Algal bloom seasons for the study areas are given in Table 5.6. Histograms summarizing the water quality variables are given in Figures 5.21-5.27. Back-up tables of summary data are provided in Appendix E. The ANOVAs comparing the water quality variables before and after 1973 are summarized in Table 5.7. Long-term and recent regressions are summarized in Table 5.8.

The study areas in the central sound are all in urbanized areas. They represent a wide range of environments. The Port Gardner study area is located in a fairly large, deep embayment that is affected by significant inputs of fresh water. However, tidal volumes are low and tidal currents are weak in the area (Federal Water Pollution Control Administration and Washington State Pollution Control Commission 1967). The Point Jefferson study area is in an open, deep part of the Main Basin. It is characterized by a large volume and substantial flux of water. The Sinclair Inlet study area is in a sheltered, shallow embayment, with little freshwater input and a low flushing rate. The City Waterway study area is at the mouth of a manmade waterway in the southeastern corner of Commencement Bay, a deep and relatively open embayment. Although the Puyallup River influences the circulation of Commencement Bay, the study area is approximately 1.2 km south of the mouth of the river. Previously, Dames and Moore (1981) reported that the study area was not greatly influenced by the freshwater plume of the Puyallup River.

Based on the percent dissolved oxygen saturation at the surface, algal blooms occurred in all the central sound study areas during May and June (Table 5.6). The bloom period began and ended early in Port Gardner, and ended late (August) in Sinclair Inlet. The blooms appeared to be most intense in Sinclair Inlet and least intense in Port Gardner and City Waterway.

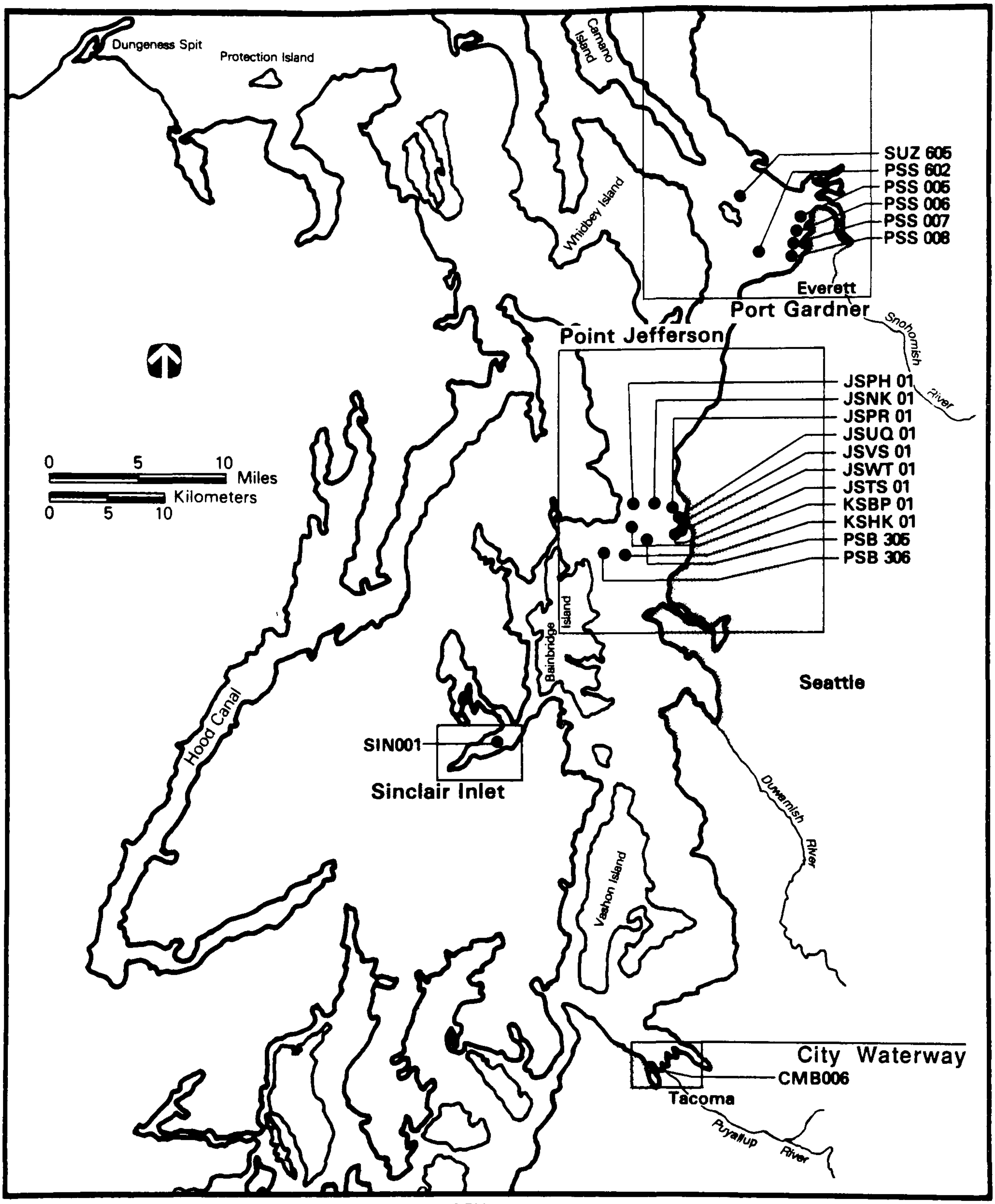


Figure 5.20. Locations of study areas and sampling stations in the central sound.

TABLE 5.5. SAMPLING STATION NUMBERS, DATA SOURCES, AND SAMPLING PERIODS FOR THE STUDY AREAS IN THE CENTRAL SOUND

Study Area	Station	Data Source	Sampling Period
Port Gardner	PSS602	UW[a]	1952-62
	SUZ605	UW	1952-53, 1956-57, 1960-62, 1969-71
	PSS005	Ecology	1967-70, 1973-76
	PSS006	Ecology	1967-70
	PSS007	Ecology	1967-70
	PSS008	Ecology	1967-70, 1980-86
Point Jefferson	PSB305	UW	1933-71
	PSB306	UW	1965-67
	JSVS01	Metro	1965-86
	JSWT01	Metro	1965-86
	JSUQ01	Metro	1965-86
	JSYS01	Metro	1965-86
	KSHK01	Metro	1965-86
	JSPH01	Metro	1966-67
	JSNK01	Metro	1966-86
	JSPR01	Metro	1965-67
	KSBP01	Metro	1966-75, 1985-86
Sinclair Inlet	SIN001	Ecology	1967-70, 1973-74, 1976, 1978-86
City Waterway	CMB006	Ecology	1967-70, 1973-86

[a] UW = University of Washington.

TABLE 5.6. ALGAL BLOOM SEASONS FOR THE CENTRAL SOUND STUDY AREAS, AS DEFINED BY MONTHLY MEAN AND STANDARD ERROR OF PERCENT DISSOLVED OXYGEN SATURATION IN SURFACE WATER

	Percent Dissolved Oxygen Saturation			
Month	Port Gardner	Point Jefferson	Sinclair Inlet	City Waterway
April	102 +/- 3[a]	103 +/- 2	116 +/- 4	95 +/- 2
May	115 +/- 3[a]	116 +/- 2[a]	140 +/- 3[a]	103 +/- 8[a]
June	102 +/- 3[a]	118 +/- 2[a]	123 +/- 7[a]	99 +/- 4[a]
July	98 +/- 5	122 +/- 2[a]	129 +/- 7[a]	110 +/- 6[a]
August	93 +/- 6	102 +/- 2	143 +/- 13[a]	88 +/- 6
September	72 +/- 6	86 +/- 1	119 +/- 4	88 +/- 4

[a] Months included in the algal bloom season.

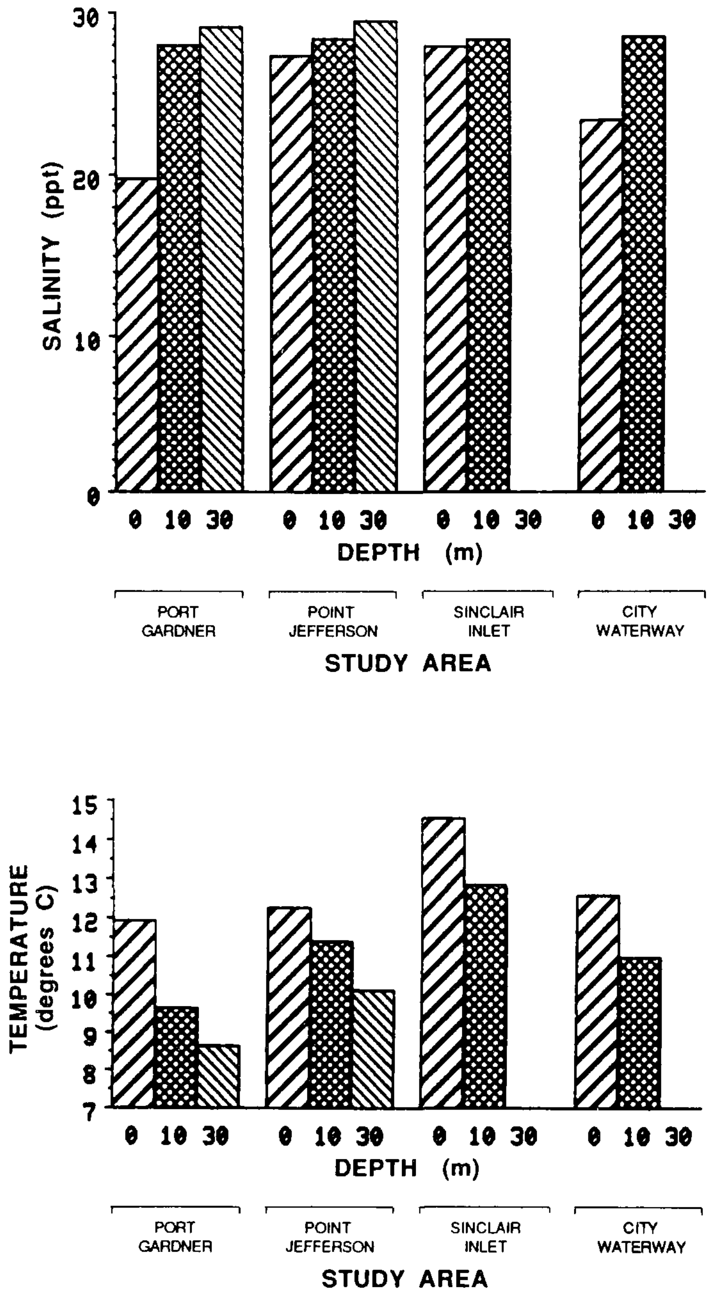


Figure 5.21. Mean salinity and water temperature values in the central sound study areas during the algal bloom season.

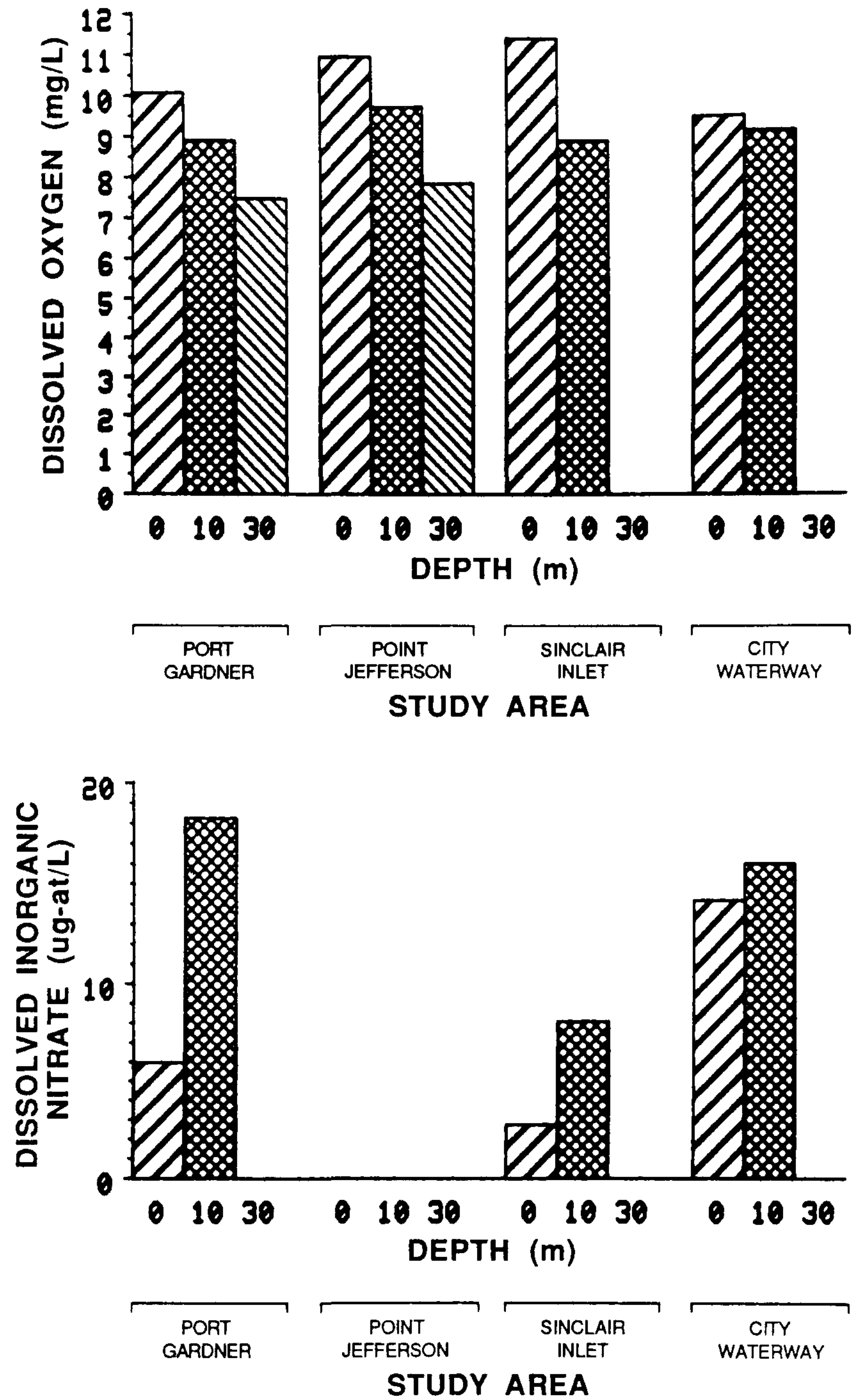


Figure 5.22. Mean concentrations of dissolved oxygen and dissolved inorganic nitrate in the central sound study areas during the algal bloom season.

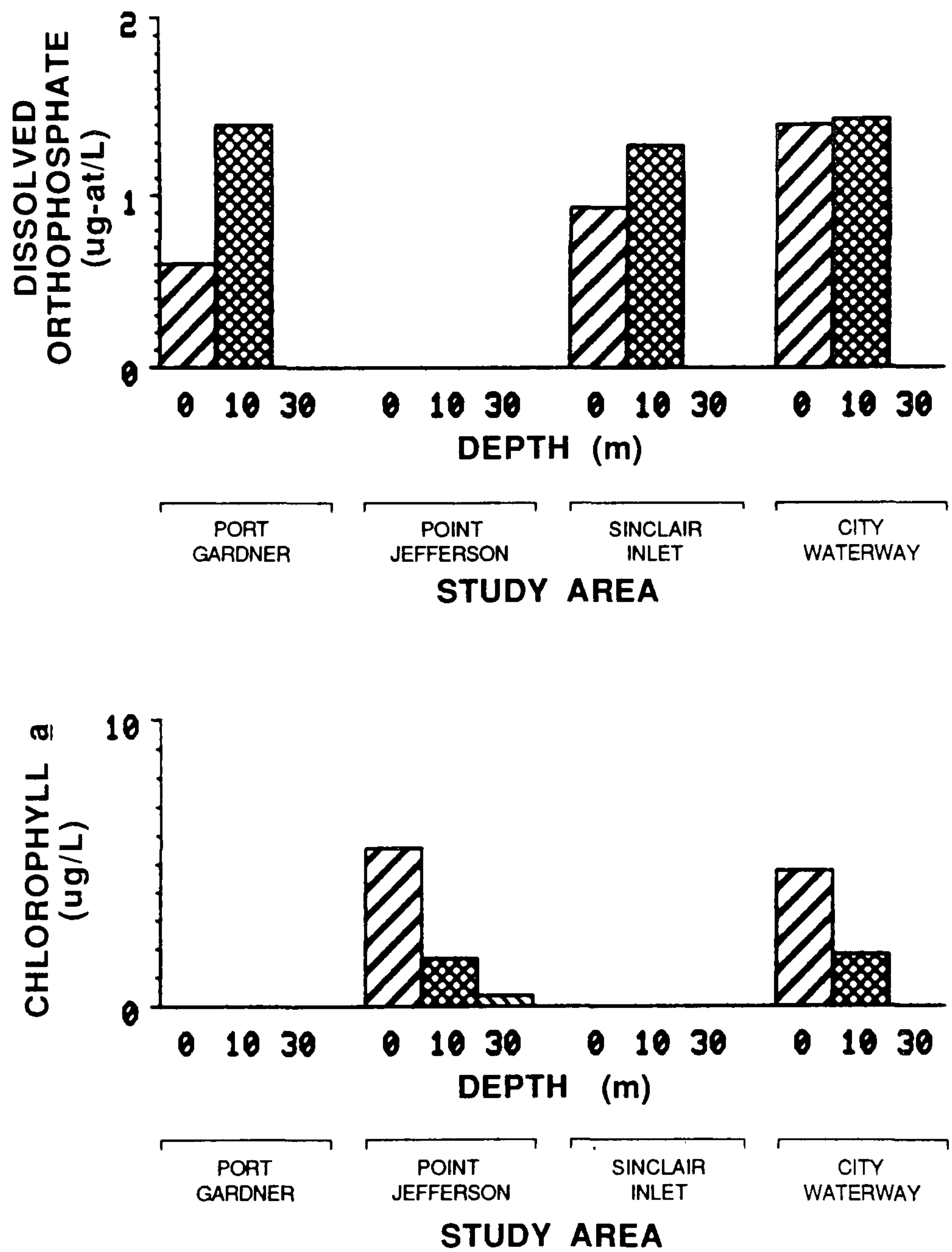


Figure 5.23. Mean concentrations of dissolved orthophosphate and chlorophyll a in the central sound study areas during the algal bloom season.

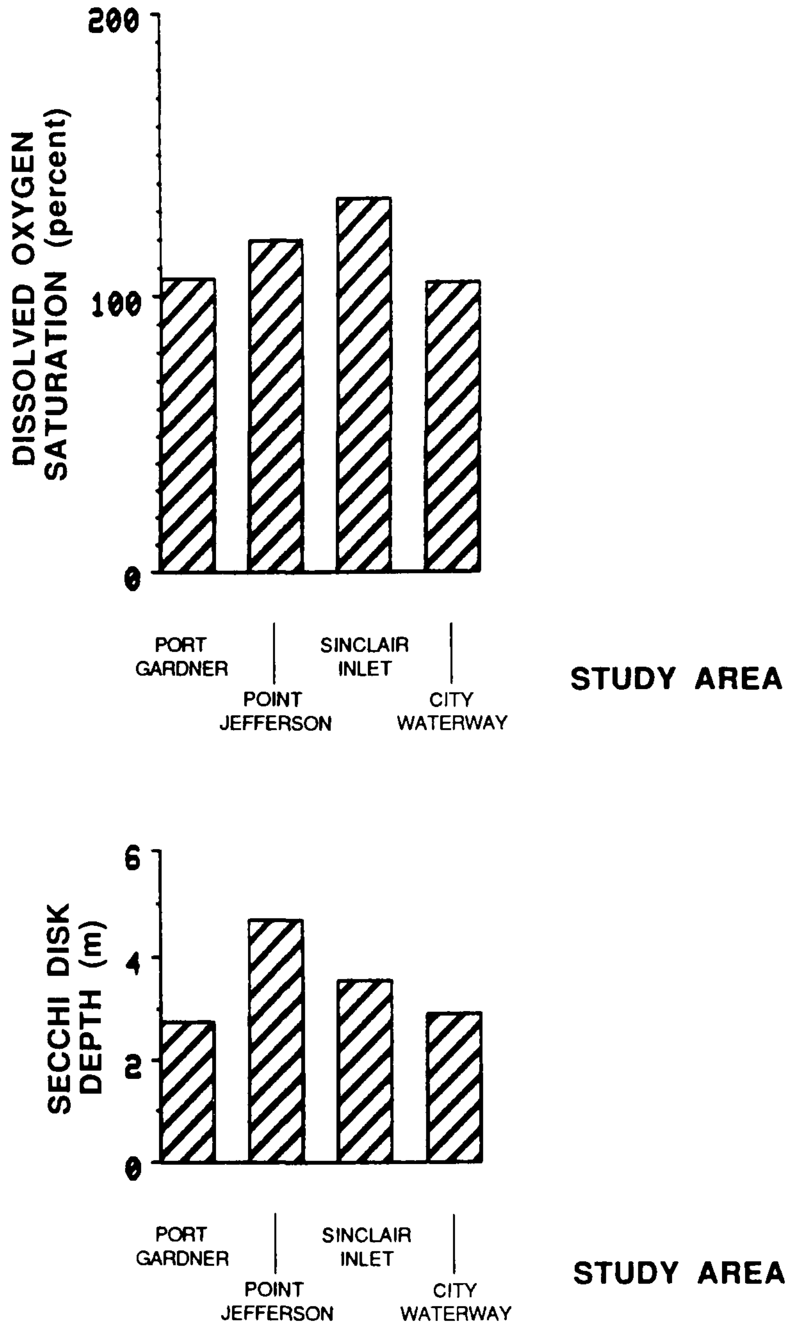


Figure 5.24. Mean percent dissolved oxygen saturation at the surface and Secchi disk depth in the central sound study areas during the algal bloom season.

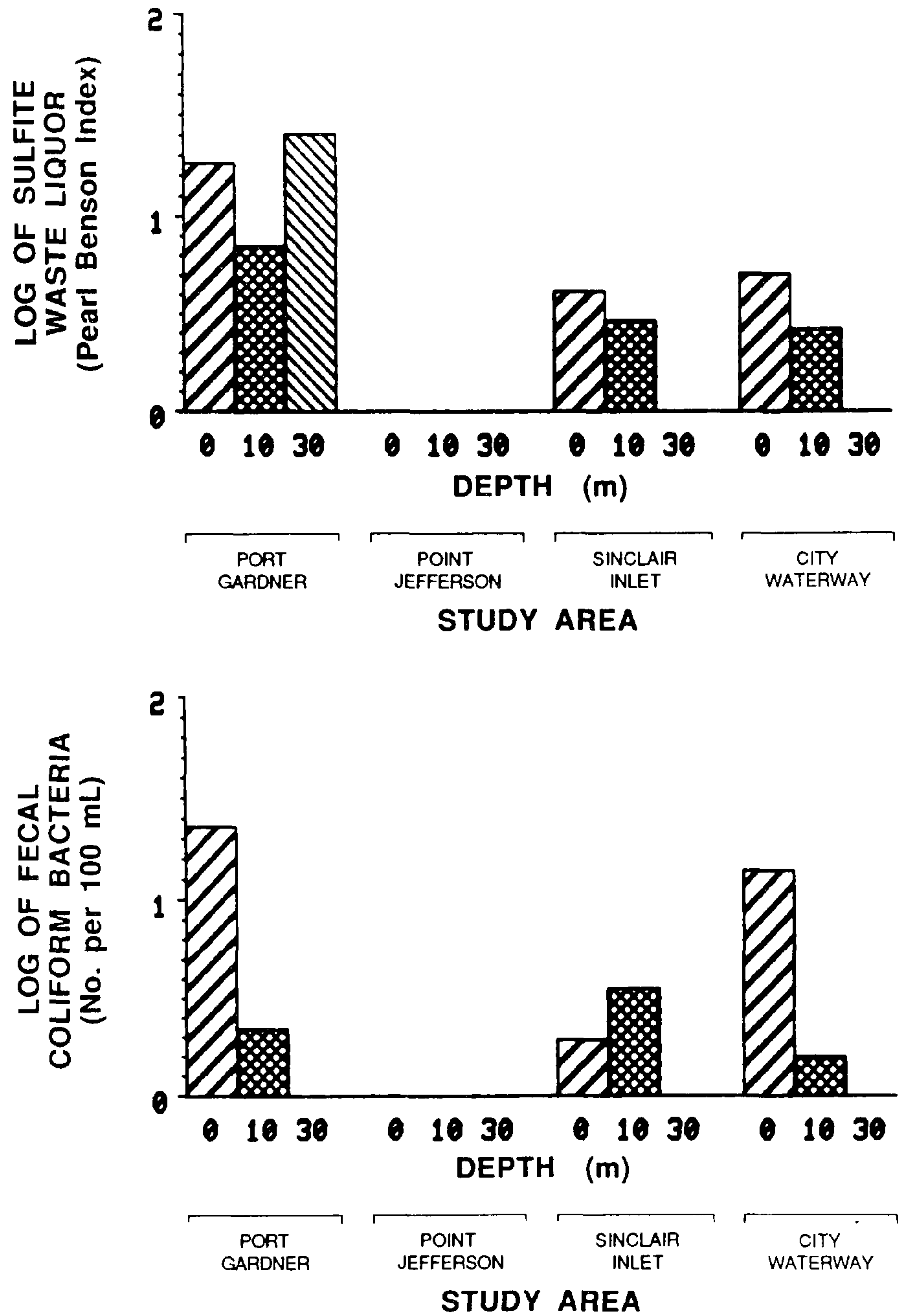


Figure 5.25. Log of geometric mean concentrations of sulfite waste liquor and fecal coliform bacteria in the central sound study areas during the algal bloom season.

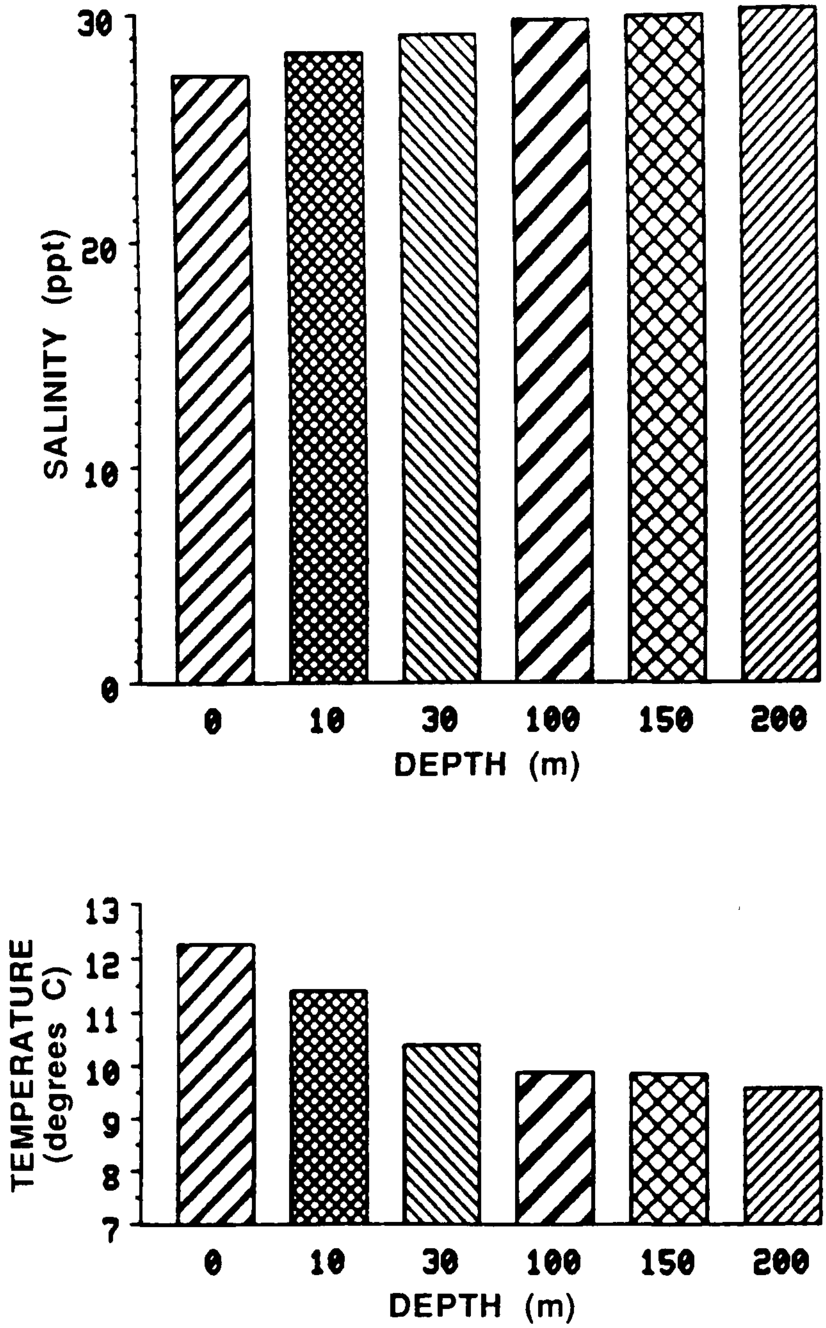


Figure 5.26. Depth profiles of mean salinity and water temperature values in the Point Jefferson study area during the algal bloom season.

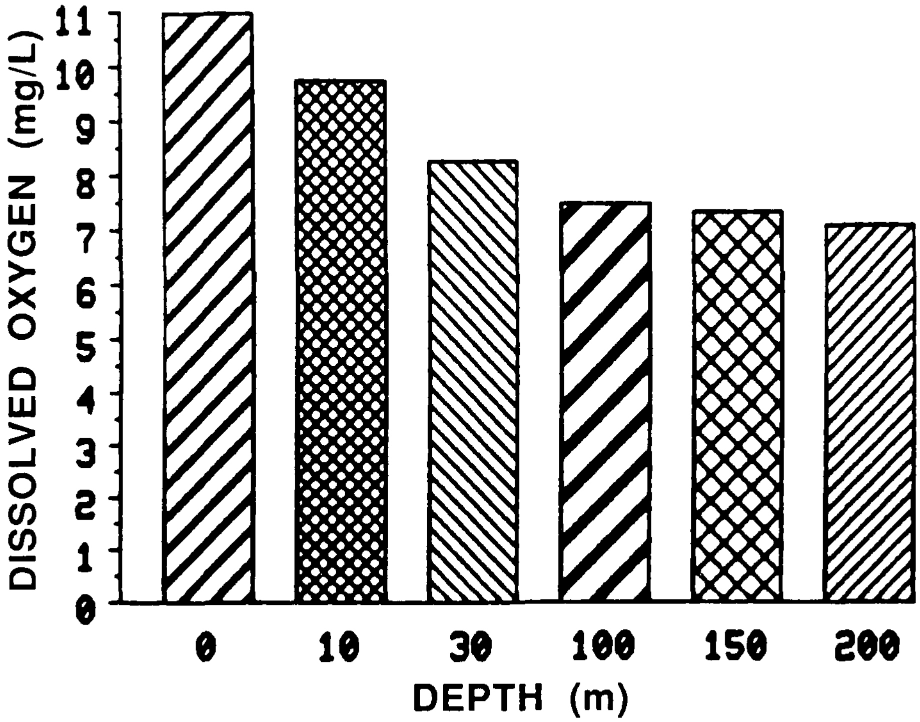


Figure 5.27. Depth profiles of mean concentrations of dissolved oxygen in the Point Jefferson study area during the algal bloom season.

TABLE 5.7. NET CHANGE AND PERCENT CHANGE IN THE MEAN VALUES OF WATER QUALITY VARIABLES IN THE CENTRAL SOUND, BASED ON ANOVA COMPARISONS OF DATA TAKEN BEFORE 1973 WITH DATA TAKEN FROM 1973 TO 1986

Depth (m)	Port Gardner Change Net	Port Gardner Change Percent	Point Jefferson Change Net	Point Jefferson Change Percent	Sinclair Inlet Change Net	Sinclair Inlet Change Percent	City Waterway Change Net	City Waterway Change Percent
				Salinity (ppt)				
0	-3.11	15.0	+0.53	2.0	NS[a]		NS	
10	-0.81	2.8	NS		na[b]		na	
30	na		NS		na		na	
100	na		NS		na		na	
150	na		NS		na		na	
200	na		na		na		na	
				Water Temperature (° C)				
0	NS		NS		NS		NS	
10	NS		+0.46	4.1	na		na	
30	na		+0.73	7.2	na		na	
100	na		+0.72	7.4	na		na	
150	na		NS		na		na	
200	na		na		na		na	
				Dissolved Oxygen (mg/L)				
0	NS		NS		NS		NS	
10	NS		NS		na		na	
30	na		NS		na		na	
100	na		NS		na		na	
150	na		NS		na		na	
200	na		na		na		na	
				Nitrate (ug-at/L)				
0	na		na		na		na	
10	na		na		na		na	
30	na		na		na		na	
				Phosphate (ug-at/L)				
0	-0.16	20.9	na		na		na	
10	-0.55	28.3	na		na		na	
30	na		na		na		na	
				Chlorophyll a (ug/L)				
0	na		NS		na		na	
10	na		NS		na		na	
30	na		na		na		na	
				Surface Dissolved Oxygen Saturation (Percent)				
0	NS		NS		NS		NS	
				Secchi Disk Depth (m)				
	NS		NS		na		na	
				Sulfite Waste Liquor (Pearl Benson Index)				
0	-35.38	76.4	na		NS		-7.32	51.8
10	NS		na		na		na	
30	na		na		na		na	
				Fecal Coliform Bacteria (No./100 mL)				
0	na		na		na		na	
10	na		na		na		na	
30	na		na		na		na	

[a] NS The pre-1973 and 1973-1986 values were not significantly different at $P<0.05$, based on a nonparametric one-way ANOVA.

[b] na - Results of the statistical test were not available because of a lack of data.

TABLE 5.8. SLOPES OF STATISTICALLY SIGNIFICANT LONG-TERM AND RECENT REGRESSIONS OF WATER QUALITY VARIABLES AS A FUNCTION OF YEAR FOR THE CENTRAL SOUND

Depth (m)	Slopes: Port Gardner Long-term	Port Gardner Recent	Point Jefferson Long-term	Point Jefferson Recent	Sinclair Inlet Long-term	Sinclair Inlet Recent	City Waterway Long-term	City Waterway Recent
				Salinity (ppt)				
0	NS[a]	0.450	NS	NS	NS	NS	NS	NS
10	-0.027	0.085	-0.017	NS	na[b]	NS	NS	NS
30	na	na	NS	-0.077	na	na	na	na
100	na	na	NS	-0.115	na	na	na	na
150	na	na	-0.009	-0.165	na	na	na	na
200	na	na	NS	na	na	na	na	na
				Water Temperature (° C)				
0	NS	NS	NS	-0.068	NS	NS	NS	NS
10	0.035	0.150	0.028	NS	na	NS	na	na
30	na	na	0.027	NS	na	na	na	na
100	na	na	NS	NS	na	na	na	na
150	na	na	NS	NS	na	na	na	na
200	na	na	NS	na	na	na	na	na
				Dissolved Oxygen (mg/L)				
0	NS	NS	NS	-0.078	NS	NS	NS	NS
10	NS	NS	NS	NS	na	NS	na	NS
30	na	na	NS	NS	na	na	na	na
100	na	na	NS	NS	na	na	na	na
150	na	na	NS	NS	na	na	na	na
200	na	na	na	na	na	na	na	na
				Nitrate (ug-at/L)				
0	na	NS	na	na	na	NS	na	NS
10	na	-0.709	na	na	na	NS	na	0.452
30	na	na	na	na	na	na	na	na
				Phosphate (ug-at/L)				
0	NS	NS	na	na	na	NS	na	0.090
10	-0.017	0.063	na	na	na	0.056	na	0.086
30	na	na	na	na	na	na	na	na
				Chlorophyll _a_ (ug/L)				
0	na	na	NS	na	na	na	na	NS
10	na	na	NS	na	na	na	na	NS
30	na	na	na	na	na	na	na	na
				Surface Dissolved Oxygen Saturation (Percent)				
0	NS	NS	-0.285	-2.091	NS	NS	NS	NS
				Secchi Disk Depth (m)				
	-0.086	NS	NS	0.102	na	NS	na	NS
				Sulfite Waste Liquor[c] (Pearl Benson Index)				
0	-0.044	NS	na	na	NS	na	-0.059	-0.079
10	-0.052	-0.099	na	na	na	na	-0.047	-0.047
30	na	na	na	na	na	na	na	na
				Fecal Coliform Bacteria[d] (No./100 mL)				
0	na	0.122	na	na	na	NS	na	NS
10	na	na	na	na	na	na	na	na
30	na	na	na	na	na	na	na	na

[a] NS Not significant at P<0.05.

[b] na - Results of the statistical test were not available because of a lack of data.

[c] Data were subjected to a log(X+1) transformation for the regressions.

[d] Data were subjected to a log transformation for the regressions.

Port Gardner

The Port Gardner study area is located in the Whidbey Basin (Figure 5.20). It is near the industrialized City of Everett and is relatively close to shore. Historically, several pulp mills have discharged wastes into the area (NOAA 1985). The earlier University of Washington sampling stations were farther from shore than the more recently sampled Ecology stations. Depths range from 100 to 150 m for the University of Washington stations and average about 90 m for the Ecology stations. Class A water quality standards apply in the area of the University of Washington stations, while Class B water quality standards apply in the area of the Ecology stations.

Tidal currents are weak in the Port Gardner area. The Snohomish River flows into Possession Sound about 4.5 km north of the study area. This river is the second largest river discharging into Puget Sound, contributing approximately 18 percent of the total volume of fresh water that enters the sound (see Table 2.1). A net southward surface flow is caused by the input from the Snohomish River. Net motion is generally northward at mid-depths and generally southward near the bottom (Federal Water Pollution Control Administration and the Washington State Pollution Control Commission 1967).

The quantity of wastes discharged from pulp and paper mills in the Everett area decreased progressively through the 1960s and 1970s (Ecology 1976; NOAA 1985; Loehr, L., 21 July 1987, personal communication). These changes reduced discharges of both chemical wastes and BOD. Major discharge reductions were achieved by both the Scott and Weyerhaeuser sulfite mills in 1975. In 1978, the Weyerhaeuser mill closed. The Scott sulfite mill adopted secondary effluent treatment beginning in 1980, replacing a system that had discharged approximately half of the plant's effluent without treatment and half of the plant's effluent after primary clarification (Bechtel, T., 22 March 1988, personal communication).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.21. Data are available for surface water from the early 1950s through 1986, but less coverage is available for deeper water. The depth gradients for both salinity and water temperature were substantial (Appendix E). At the surface, the mean salinity value was approximately 8 ppt lower than at the 10-m depth, while the mean water temperature value was approximately 2.3^{o} C higher than at the 10-m depth. The reduced salinities observed at the surface presumably were caused by the inputs of fresh, low density water from the Snohomish River. The negative correlation between salinity and water temperature at the surface (Appendix F) suggests that the fresh water from the Snohomish River tended to be warmer than the salt water from the sound.

A vertical gradient in dissolved oxygen concentrations was also detected. Average dissolved oxygen concentration was approximately 10.1 mg/L at the surface and 8.9 mg/L at the 10-m depth (Figure 5.22). Data from deeper than 30 m are not available for the characterization study, but anoxic sediments containing material from log yards and pulp mills have been reported in the past (Federal Water Pollution Control Administration and Washington State Pollution Control Commission 1967).

Average surface concentrations of nitrate and phosphate were approximately one-third as high at the surface (6.0 ug-at/L and 0.7 ug-at/L, respectively) as they were at the 10-m depth (18.2 ug-at/L and 1.6 ug-at/L, respectively) (Figures 5.22 and 5.23). Negative correlations between water temperature and both nitrate and phosphate concentrations at the surface (Appendix F) may have been due to the seasonal rise in temperature and the seasonal decline in nutrient concentrations that occur during the spring and early summer. From April through June, the monthly mean water temperature rose by 4.8^{o} C, while the mean nitrate concentration fell by a factor of four and the mean phosphate concentration fell by a factor of nearly two. These seasonal drops in nutrient concentrations also probably caused the positive correlation between the nitrate and phosphate concentrations at the surface (Appendix F).

The relatively low mean percent dissolved oxygen saturation at the surface (106 percent) suggests that algal blooms in the Port Gardner study area were less intense than those in most of the other study areas (e.g., Point Jefferson and Sinclair Inlet). Although density stratification of the water column was well developed, the net southward drift of surface water probably does not allow intense blooms to develop around Port Gardner. The low value for mean Secchi disk depth (2.7 m) was probably due to suspended particulate materials from the Snohomish River, rather than to high concentrations of phytoplankton. Low transparency of the water column would restrict the depth of the photic zone, limiting the growth of algal blooms. Suspended material in pulp mill effluents did not have a major influence on the Secchi depth values because secondary treatment was instituted in the local mills by the time most of the Secchi depth data were collected.

The geometric mean of the concentrations of sulfite waste liquor (measured by the Pearl Benson Index) at the surface was higher in the Port Gardner study area (17.3) than in any other central sound study area (Figure 5.25). However, the geometric mean of the surface concentrations of sulfite waste liquor was higher in the Bellingham Bay study area (22.1) in the northern sound. At Port Gardner, the average sulfite waste liquor concentration at 10-m depth was less than half that of the surface, reflecting the tendency of sulfite waste liquor released in surface water in a density stratified system to remain in the surface layer. The high concentration detected at 30-m depth (geometric mean=22.0) was based on only three data points from the mid-1950s and early 1960s. During that period, the Scott and Weyerhaeuser mills both discharged highly concentrated sulfite wastes from a deep water diffuser off Port Gardner (Federal Water Pollution Control Administration and Washington State Pollution Control Commission 1967). However, substantial reductions of sulfite waste liquor discharges from this diffuser have occurred since those data were obtained (see above). Thus, this limited set of data for 30-m depth may have been correct for the time period during which sampling occurred. The concentration of sulfite waste liquor probably has been much lower at this depth during the 1980s.

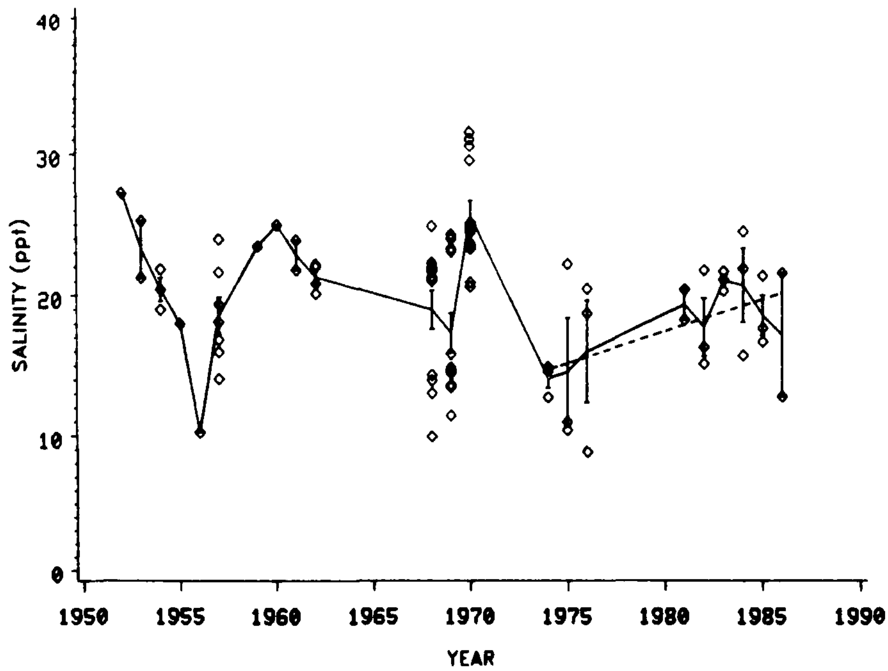
The mean concentration of fecal coliform bacteria at the surface appeared to be relatively high in the Port Gardner study area (geometric mean=22.9 organisms/100 mL) (Figure 5.25). As discussed in the next section on water quality trends, this result probably was not caused by detection of inadequately treated sewage. Instead, this apparent elevation in the concentration of fecal coliform bacteria probably was the result of detecting the bacterium, Klebsiella, which is often released in large quantities in secondary pulp mill effluent (Johnson, B., 21 July 1987, personal communication).

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected prior to and after 1973 is given in Table 5.7. Slopes from statistically significant regressions of long-term and recent water quality data by year are given in Table 5.8.

Physical Conditions--Plots of salinity and water temperature data by year are shown in Figures 5.28 and 5.29. A long-term decline in salinity values is evident, although salinity values increased after 1974 (see Tables 5.7 and 5.8). The long-term decline in salinity values was probably caused by a change in station locations from the offshore stations that were sampled by the University of Washington in the 1950s and early 1960s to the inshore stations (closer to the mouth of the Snohomish River) that were sampled by Ecology since the late 1960s. The apparent increase in salinity values since 1974 also may have been driven by changes in station location. The values from 1974 through 1976 were recorded at Station PSS005, while the values since 1981 were recorded at Station PSS008 (see Figure 5.20). The later samples came from a station at the mouth of a manmade waterway that was sheltered from the Snohomish River by an earthen breakwater.

The long-term increase in water temperature values at 10-m depth appears to have been driven by the recent increase in water temperature values at this depth. This recent increase also may have been caused by changes in the locations of sampling stations. The most recent data were taken from the mouth of the waterway mentioned above. The sheltering effect



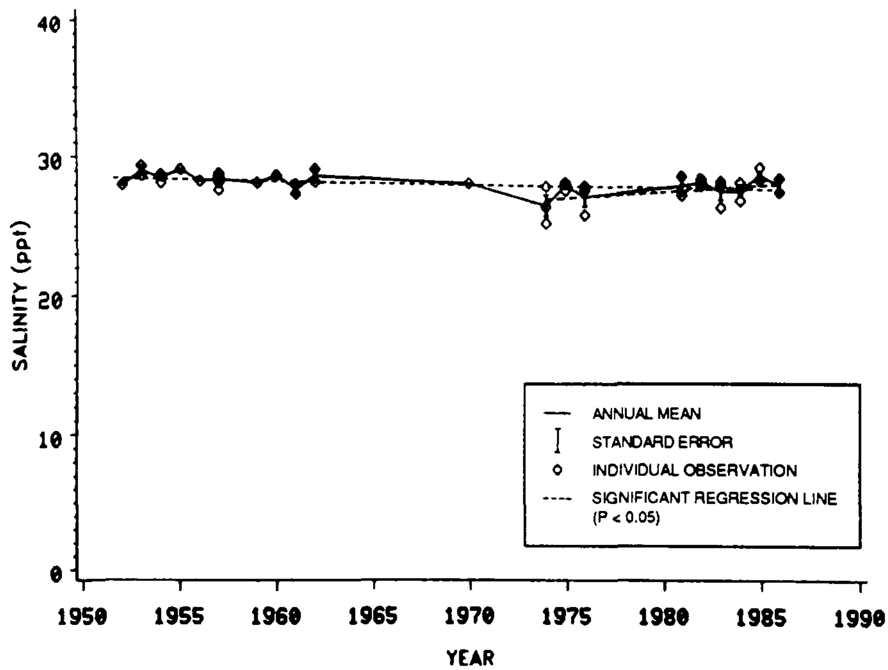


Figure 5.28. Salinity values at the surface and at 10-m depth in the Port Gardner study area during the algal bloom season.

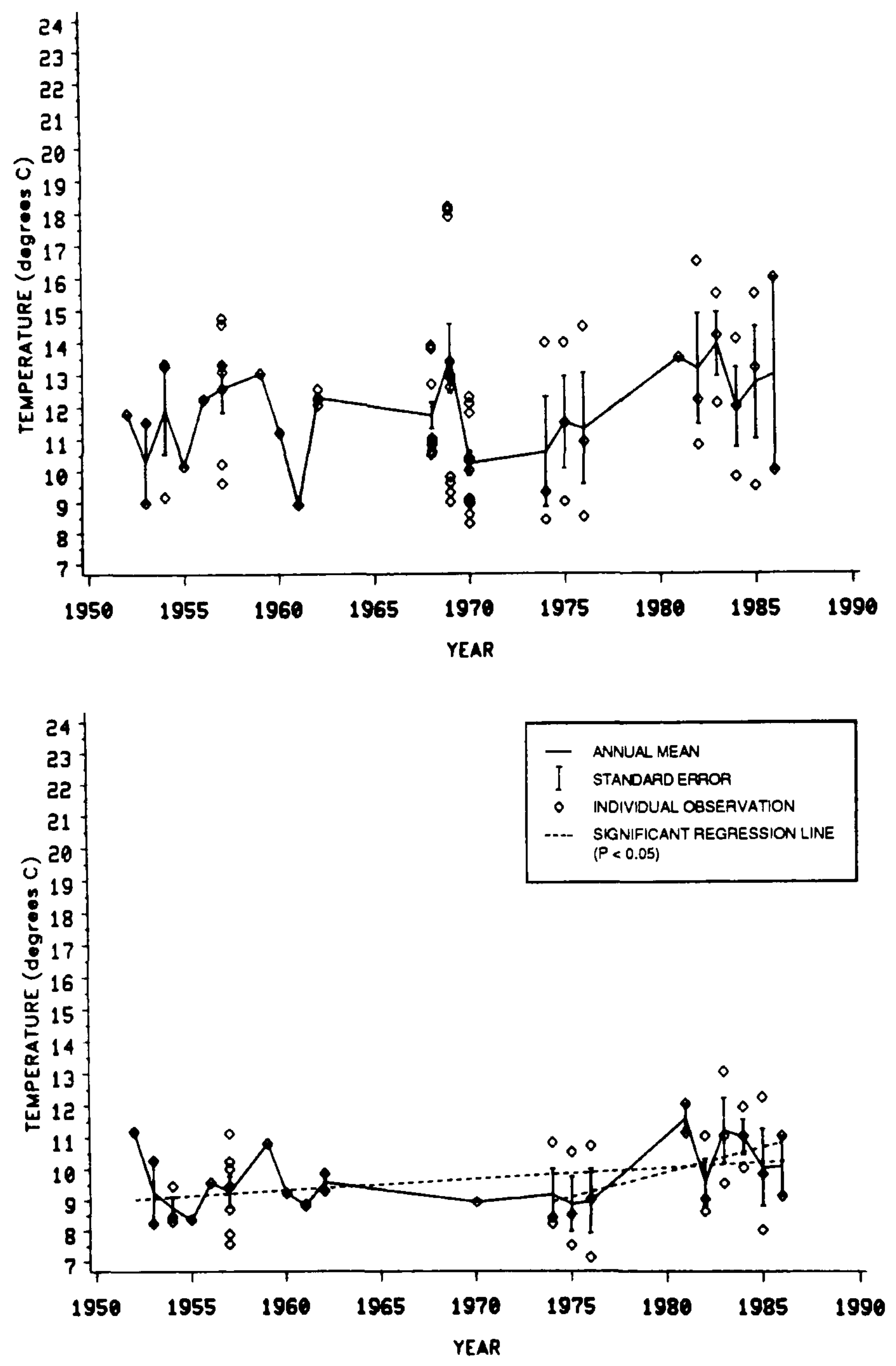


Figure 5.29. Water temperatures at the surface and at 10-m depth in the Port Gardner study area during the algal bloom season.

of the breakwater may reduce the rate of vertical mixing in the waterway, which could allow more effective solar heating of the near-surface water.

Dissolved Oxygen--Plots of dissolved oxygen concentration by year are shown in Figure 5.30. There is no evidence for violations of the Class A water quality standard (see Table 4.2). No significant temporal trends were detected in dissolved oxygen concentrations (see Tables 5.7 and 5.8) at the surface or at 10-m depth. The possibility that changes in station location influenced the dissolved oxygen data could not be assessed. As discussed above, anoxic sediments have been reported in the past, but long-term data for water column depths below 10 m are not available.

Nutrients--Plots of nitrate concentrations against year are shown in Figure 5.31. Data are available since 1974. Nitrate concentrations have declined significantly ($P<0.05$) at the 10-m depth. Changes in nitrate concentration do not appear to have coincided with changes in station location that occurred between 1976 and 1981. No explanation is available for this decrease.

Statistically significant ($P<0.05$) declines in phosphate concentrations have occurred since the 1950s (Figure 5.32, Tables 5.7 and 5.8), although the apparent change was greater at 10-m depth than at the surface. The decline at 10-m depth could indicate that a long-term change has occurred in phosphate concentrations. This long-term decline is consistent with the declines detected in most other study areas. However, this apparent decline may have been influenced by changes in station locations or analytical techniques. Values averaged approximately 2 ug-at/L for the University of Washington samples, which were collected from offshore stations during the mid-1950s through the early 1960s. Values averaged approximately 1.5 ug-at/L for the Ecology samples, which were collected since 1968 from stations located closer to shore. Because it was not possible to calibrate the methods used for phosphate analyses by University of Washington and Ecology, the possibility that analytical differences between University of Washington and Ecology introduced changes in phosphate concentrations into the data cannot be assessed. However, the University of

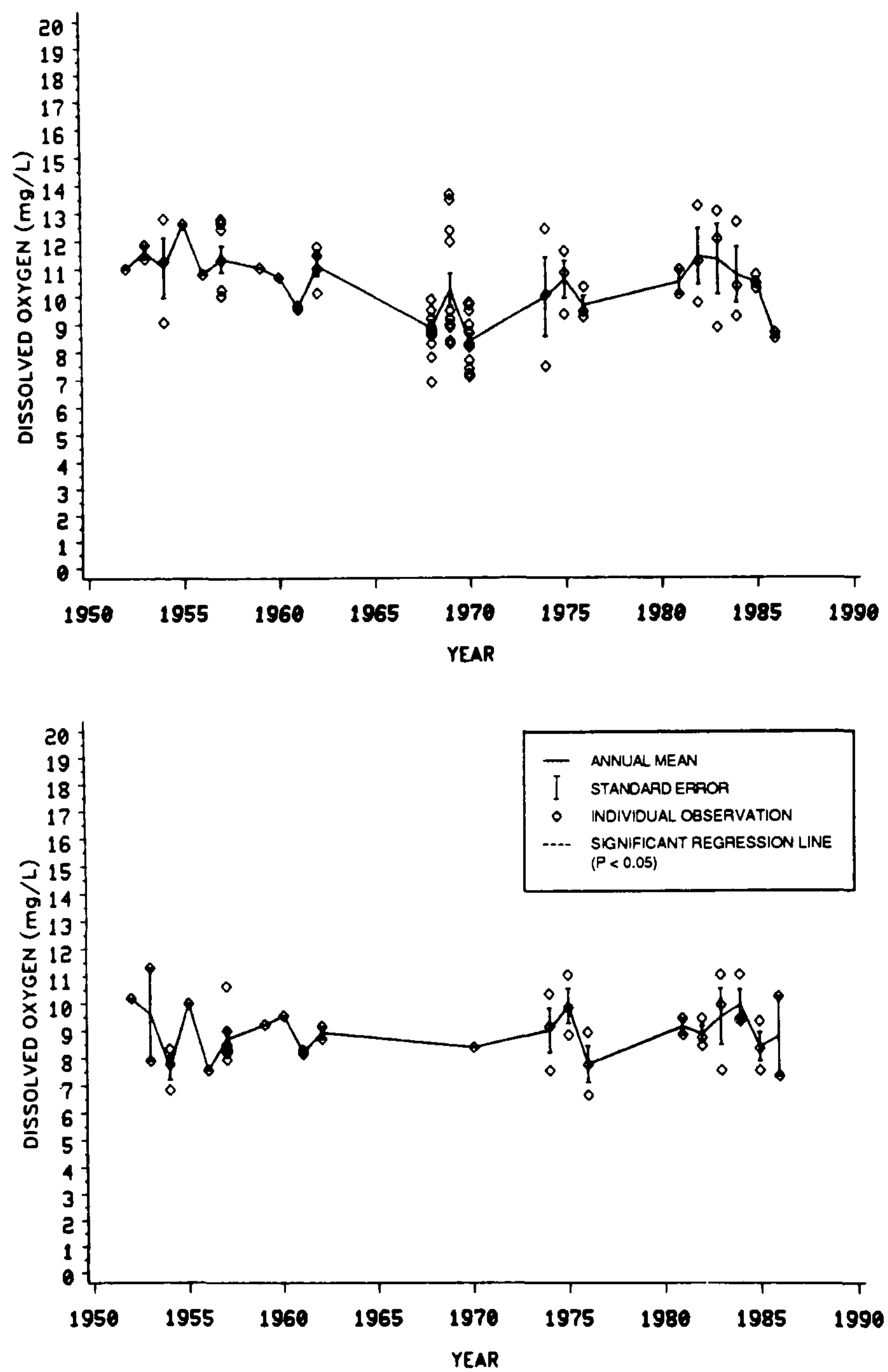


Figure 5.30. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Port Gardner study area during the algal bloom season.

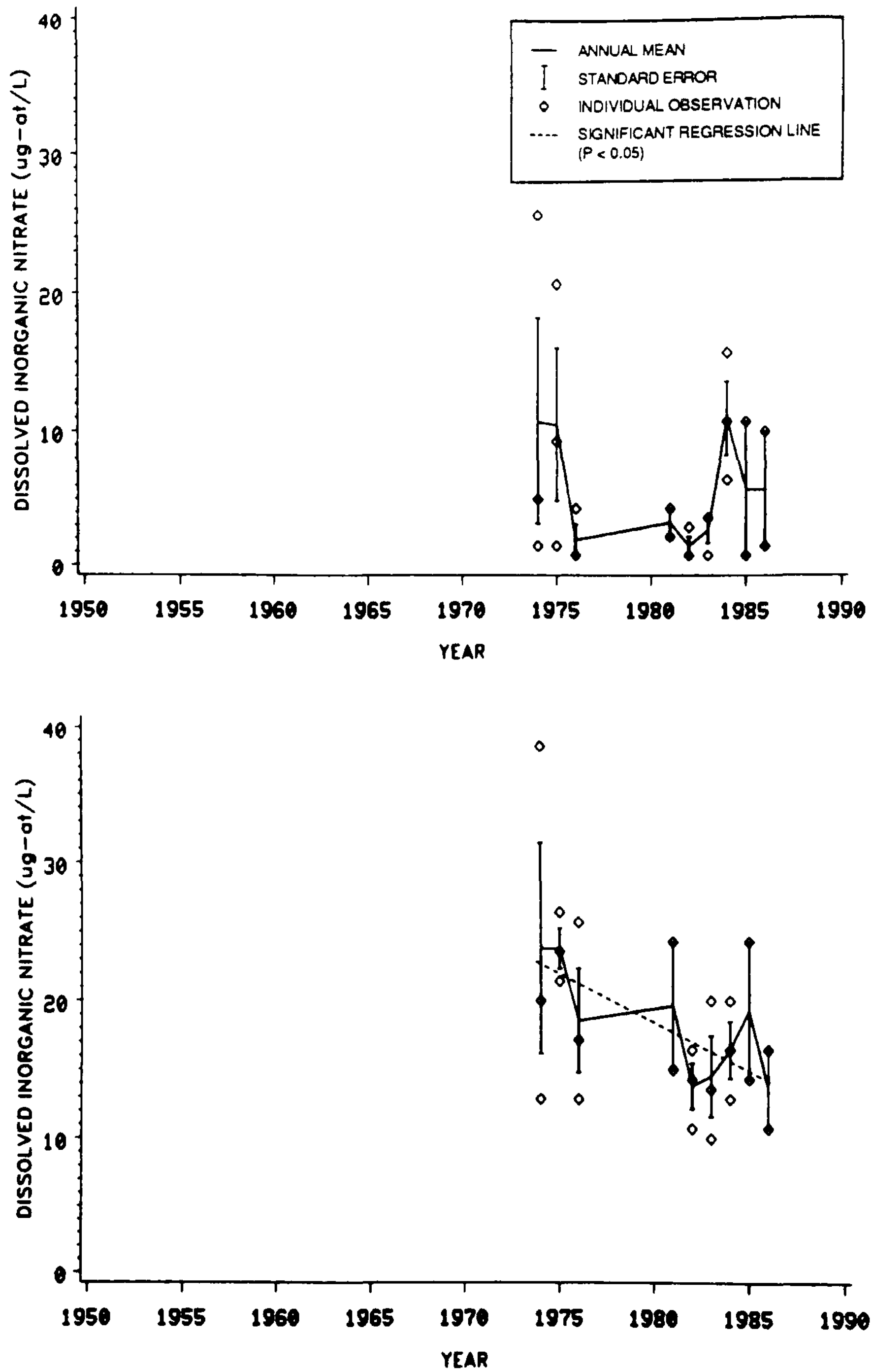


Figure 5.31. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the Port Gardner study area during the algal bloom season.

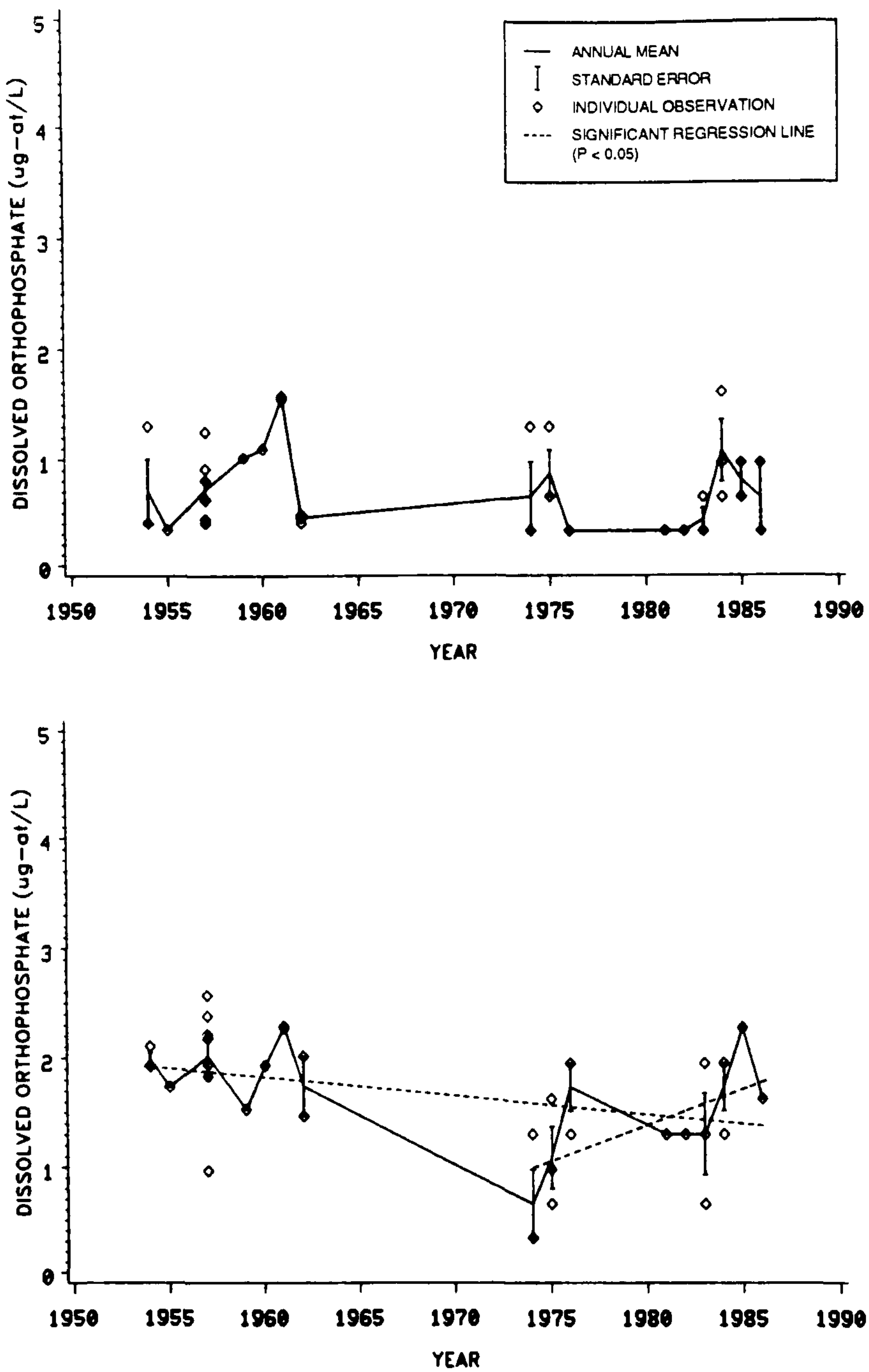


Figure 5.32. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Port Gardner study area during the algal bloom season.

Washington data were produced with a spectrophotometer (Appendix A), which probably yielded reasonably accurate results.

Phosphate concentrations at 10-m depth appear to have increased since 1974. This increase may have been affected by changes in station location in Ecology's monitoring program. However, changes in location that occurred since 1974 were less drastic than those that occurred when the data sources changed from University of Washington to Ecology (see Table 5.5 and Figure 5.20). As discussed in Chapter 3, sulfite waste liquor removes dissolved orthophosphate from seawater, and secondary pulp mill waste treatment facilities came on line in the Port Gardner area in 1980. The negative correlation between the concentrations of phosphate and sulfite waste liquor at 10 m ($r=-0.41$), while not statistically significant ($P<0.05$) when scaled with the Bonferroni inequality, suggests that reductions in the discharge of sulfite waste liquor may have contributed to the increase in phosphate concentrations detected since 1974. Alternatively, changes in other anthropogenic factors or oceanic inputs may have influenced the phosphate data.

Indicators of Phytoplankton Growth--No substantial changes were detected in the indicators of phytoplankton growth. Data on chlorophyll *a* concentrations are not available. No trends were detected in the percent saturation of dissolved oxygen in the surface water (Figure 5.33). A statistically significant long-term decline in Secchi disk depth since 1961 was detected (Figure 5.33, Table 5.8), but this decline was driven by one very high value recorded in 1961. This observation was obtained at an offshore station located relatively far from the influence of the Snohomish River. Because observations obtained since 1968 were from inshore stations relatively close to the mouth of the Snohomish River and the influences of the Port of Everett, the apparent decline in Secchi disk depth probably was an artifact of changes in the location of sampling stations.

Pollutants--Significant temporal declines ($P<0.05$) in the concentration of sulfite waste liquor were detected (Figure 5.34, Tables 5.7 and 5.8). The sharp declines in concentrations that occurred in the mid-1970s and early 1980s coincided with the discharge changes mentioned above.

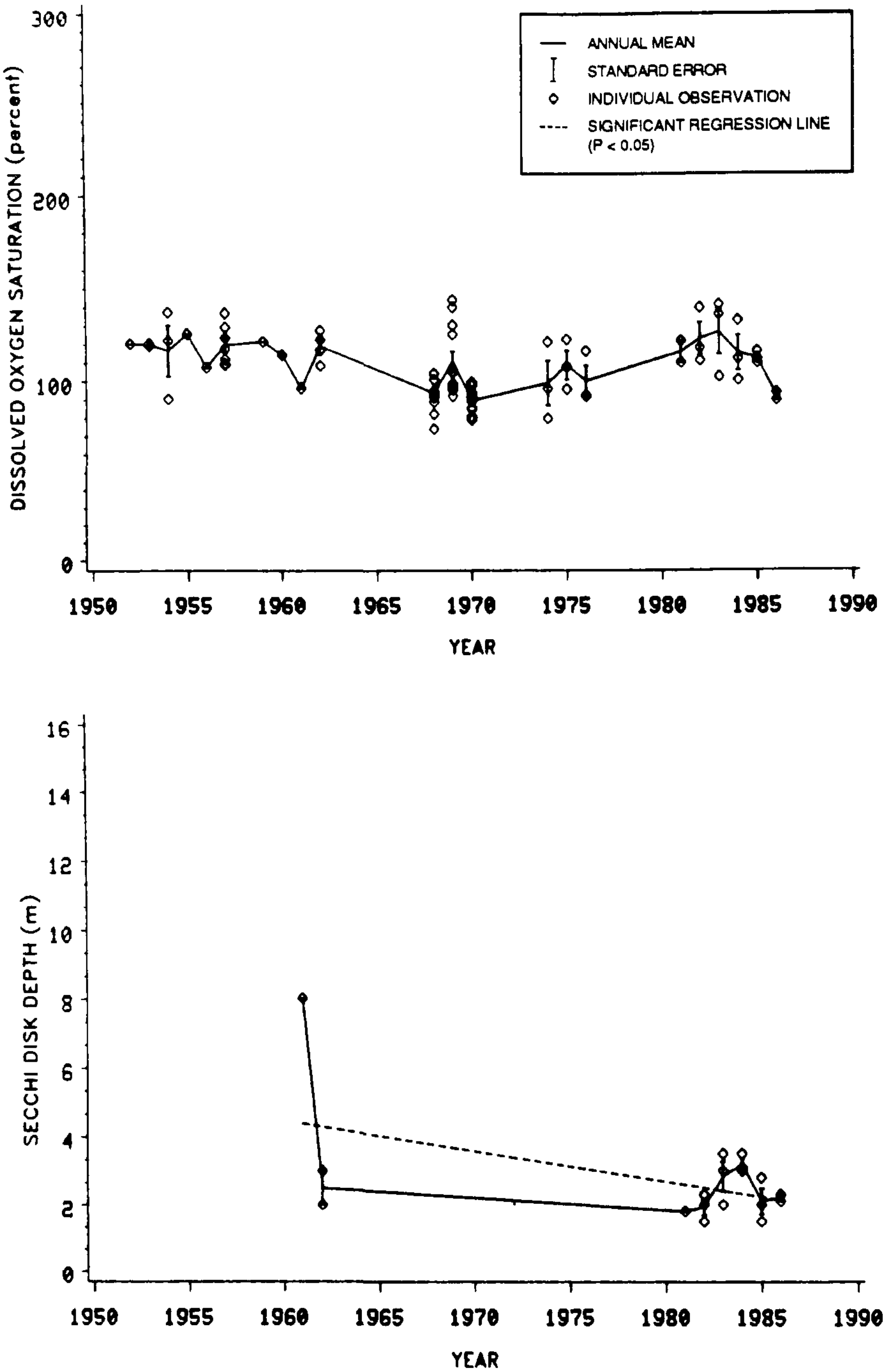
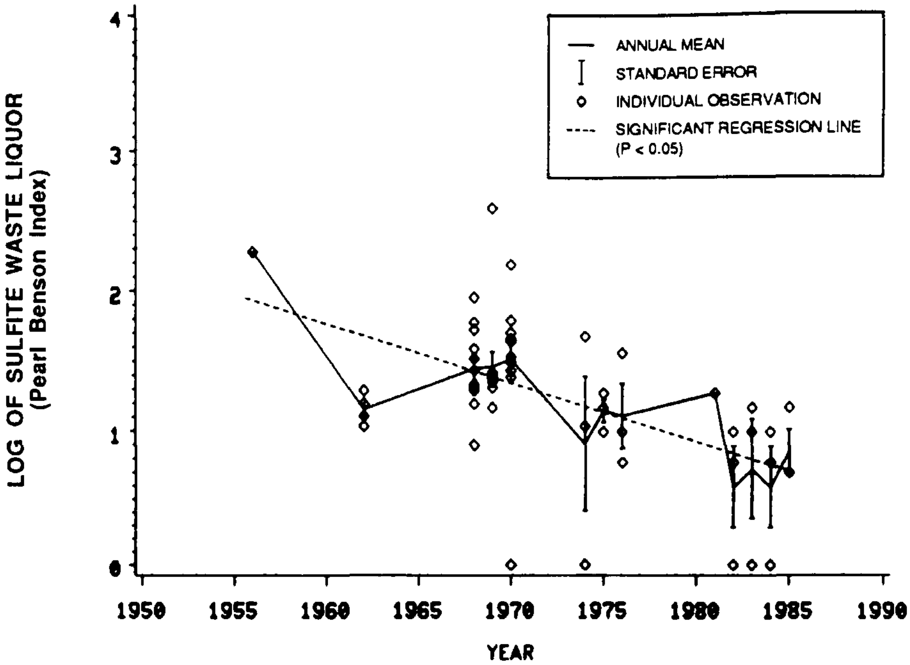


Figure 5.33. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Port Gardner study area during the algal bloom season.



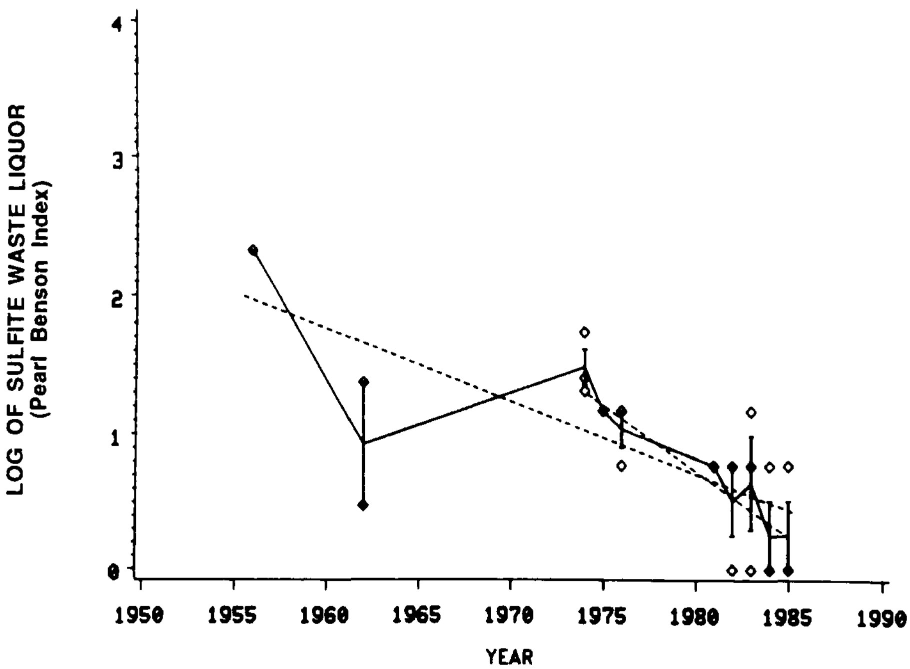


Figure 5.34. Log of concentrations of sulfite waste liquor at the surface and at 10-m depth in the Port Gardner study area during the algal bloom season.

The actual magnitude of the decrease in sulfite waste liquor concentrations in the Port Gardner area may have been greater than the decrease detected in the characterization database because the samples taken before 1968 were collected farther offshore (and farther from the discharge point) than the samples taken after 1968. Changes in station location probably biased the database to show increasing concentrations of sulfite waste liquor. Therefore, the improvements in sulfite waste liquor discharges were very substantial in the Port Gardner area.

A significant increase ($P<0.05$) was detected in the concentration of fecal coliform bacteria since 1974 (Figure 5.35, Table 5.8). Two distinct periods were evident in the data, as concentrations observed from 1974 through 1976 were much lower than concentrations observed since 1981. This change coincides with the conversion of the Scott sulfite pulp mill to secondary waste treatment in 1980. The fecal coliform bacteria detected after this conversion probably were of the genus Klebsiella (Bechtel, T., 22 March 1988, personal communication). This organism can be detected in fecal coliform tests (Johnson, B., 21 July 1987, personal communication). Klebsiella grows rapidly in secondary treatment facilities of sulfite pulp mills, which contain high concentrations of complex polysaccharides that Klebsiella can metabolize rapidly. Concentrations of Klebsiella as high as 2.1×10^{15}/100 mL have been reported in discharges from pulp mill treatment ponds (Knittel 1975). Thus, the fecal coliform bacteria detected recently in the Port Gardner study area probably were not indicative of contamination by sewage effluent. Increases in seal and sea lion populations may also have influenced fecal coliform bacteria concentrations, but no data are available to investigate this possibility in the study area.

Although Klebsiella is a known human pathogen that can exist in the guts of warm blooded animals, the presence of Klebsiella is probably not a substantial environmental concern. Storm (1981) conducted a literature review to determine whether dredging of sediments containing Klebsiella in Gray's Harbor, Washington represented a serious threat to human health. Storm (1981) concluded that Klebsiella was not a high risk human pathogen in that situation. Moreover, because the reproductive capacity of Klebsiella

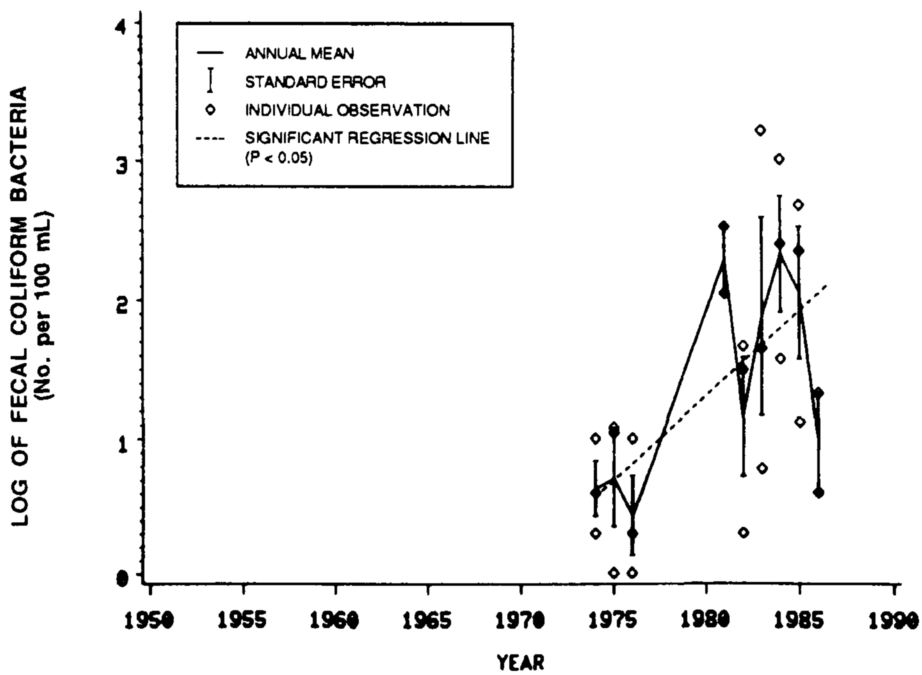


Figure 5.35. Log of concentrations of fecal coliform bacteria at the surface in the Port Gardner study area during the algal bloom season.

is dependent on the availability of high concentrations of organic wastes, this organism would be unlikely to persist in high concentrations in the marine environment. However, because current Ecology regulations do not distinguish Klebsiella from other fecal coliform bacteria, fecal coliform guidelines for marine waters in Classes A and B (see Table 4.2) frequently were violated in the Port Gardner area during the 1980s.

Point Jefferson

The study area for Point Jefferson is near the middle of the Main Basin of Puget Sound, approximately even with the northern border of the City of Seattle (see Figure 5.20). Class AA water quality standards apply in the area. The sound is quite deep in this region, ranging from 37 to 285 m. Although a substantial volume of water moves through the study area, current velocities are only moderate because flow is not restricted by geographic features. Thus, the currents do not cause substantial mixing of the water column (Lincoln and Collias 1975). Wind stress can increase mixing and retard the development of algal blooms in the area. Alternatively, an extended period of calm winds and sunshine allows density stratification to occur and enhance the development of algal blooms (Winter et al. 1975).

The Point Jefferson study area is not strongly affected by freshwater inputs. The nearest large source of fresh water is the Duwamish River, which contributes approximately 2 percent of the total flow of fresh water to the sound. The Duwamish River empties into Elliott Bay approximately 22 km southeast of the study area. The West Point sewage treatment plant, which has provided primary treatment for most of the sewage from the City of Seattle since the mid-1960s, discharges approximately 10 km south of the study area. Neither of these major sources of fresh water greatly influence water quality in the Point Jefferson study area.

Because of the absence of major pollutant sources, Point Jefferson is a reference area in this study. All the water that transits the sound south of Point Jefferson must pass by the study area. The discharges from the major urban areas on the sound south of the City of Everett also pass through the study area. In addition, the study area is in the middle of the

Main Basin of Puget Sound, well removed from local, small-scale influences. Because circulation is not restricted at Point Jefferson, the area does not appear to be particularly sensitive to excess nutrient enrichment. A substantial data set exists for this site, providing coverage from the surface to 200-m depth as far back as 1932.

Environmental Conditions in the Study Area--

Mean salinity and water temperature values for the surface and for depths of 10 and 30 m are plotted in Figure 5.21. This information is combined with data from depths of 100, 150, and 200 m in Figure 5.26. Data are available since 1932, although coverage decreases with depth (Appendix E).

Moderate changes of salinity and water temperature values were evident with depth. At the surface, the mean salinity value was approximately 1.0 ppt lower than at 10-m depth, while the mean water temperature value was approximately 0.9° C higher than at 10-m depth. Salinity varied less with depth at Point Jefferson than at several other areas with nearby sources of fresh water. For example, at Port Gardner the mean salinity value at the surface was over 8 ppt lower than the mean salinity value at 10-m depth. Water temperature varied less with depth at Point Jefferson than it did at sites with nearby sources of fresh water. For example, at Port Gardner, the mean water temperature value at the surface was approximately 2.3° C higher than the mean value at 10-m depth. Water temperatures also varied less with depth at Point Jefferson than at sites with more limited rates of circulation. For example, at Sinclair Inlet, the mean water temperature value at the surface was approximately 1.7° C higher than the mean value at 10-m depth. The rates of change of the salinity and temperature values were lower at depths below 100 m than at depths closer to the surface. For example, the mean salinity value at 150-m depth was only 0.2 ppt lower than the mean value at 200-m depth, and the mean water temperature value at 150-m depth was only 0.26° C higher than the mean value at 200-m depth.

The vertical distribution of dissolved oxygen concentrations (Figures 5.22 and 5.27) indicated that photosynthetic enhancement of dissolved oxygen was restricted to near-surface waters. The mean concentrations of dissolved oxygen were approximately 11.0 mg/L at the surface, 9.7 mg/L at 10-m depth, and 8.3 mg/L at 30-m depth. Mean dissolved oxygen concentrations dropped slowly below 100-m depth, remaining slightly above 7 mg/L at 200-m depth.

As discussed in Chapter 3, nutrient data for Point Jefferson, which would have been obtained from the University of Washington and Metro, were not analyzed because of inconsistencies in the variables measured. Algal blooms appear to have been moderately well developed at Point Jefferson (see Figures 5.23 and 5.24). Chlorophyll a concentrations were significantly higher (t-test, $P<0.001$) in the Point Jefferson study area than they were in the City Waterway study area, with highest concentrations occurring near the surface. Mean percent dissolved oxygen saturation at the surface (119.4 percent) was moderately elevated, although this value was less than in the Sinclair Inlet study area (134.0 percent). Mean Secchi disk depth was high (4.7 m) in the Point Jefferson study area. Secchi disk depth was negatively correlated with surface chlorophyll a concentration and with percent dissolved oxygen saturation at the surface (Appendix F). These correlations suggest that transparency at Point Jefferson is influenced primarily by phytoplankton growth. Because there is no nearby large source of fresh water, suspended particulates probably had a relatively small effect on Secchi disk depth.

It was not possible in this study to investigate pollutants in the Point Jefferson study area. Because no large pulp mill has existed in the area, it is unlikely that pollution by sulfite waste liquor has been a problem. However, data on sulfite waste liquor concentrations are not available for this study area. Data on the concentrations of fecal coliform bacteria have been recorded by Metro since 1966. However, the analytical techniques used to measure this variable changed from the Most Probable Number (MPN) Method to the Membrane Filtration Method in 1977, and the detection limit subsequently dropped from 10 organisms/100 mL to 1 organism/100 mL in 1980 (Hayward, A., 24 July 1987, personal communication). Therefore, incompatibility of analytical methods prevented the analysis of temporal trends in the concentrations of fecal coliform bacteria.

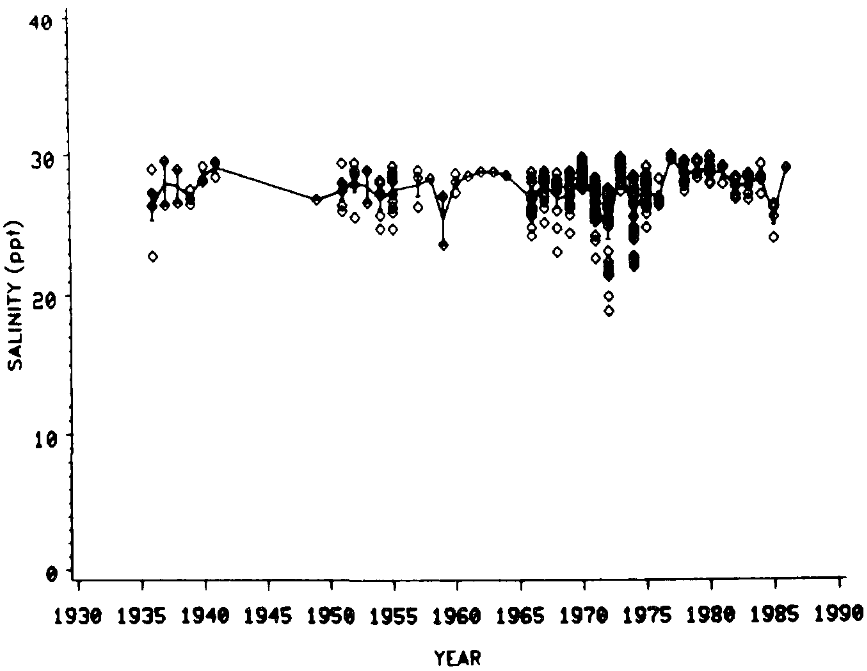
Water Quality Trends in the Study Area--

Temporal trends in water quality near Point Jefferson were evaluated by Duxbury (1975) and by Collias and Lincoln (1977). Duxbury (1975) concluded that changes in dissolved oxygen saturation and phosphate concentration that occurred at 10-m depth between 1933 and 1973 were related to oceanographic factors, rather than to increases in the amounts of waste discharged into the sound. Collias and Lincoln (1977) reached a similar conclusion in a more comprehensive study that used data collected through 1975.

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.7. Slopes from statistically significant long-term and recent regressions of values of the water quality variables by year are given in Table 5.8.

Physical Conditions--Plots of salinity and water temperature data by year are shown in Figures 5.36-5.41. The mean surface salinity from 1932 through 1972 was approximately 2 percent lower than the mean surface salinity from 1973 through 1986 (Table 5.7). However, a significant slope was not detected for the plot of this variable by year (Table 5.8). Increasing salinity is consistent with the rainfall data from the Seattle-Tacoma International Airport, which showed that total annual rainfall has declined since the late 1940s (see Figure 5.2). Although mean salinity values before and after 1973 were not significantly different ($P>0.05$) at depths below the surface (Table 5.7), most of the regressions of salinity against year had negative slopes. At 100- and 150-m depth, salinity values appear to have been higher in the 1930s and to have dropped in 1986.

The cause of the apparent declines in salinity values at depth is not known. Salinity changes may have been influenced by variations in oceanic inputs. Data on rainfall and runoff to Puget Sound do not explain these declines. The rainfall data show an overall decrease since 1945, which is



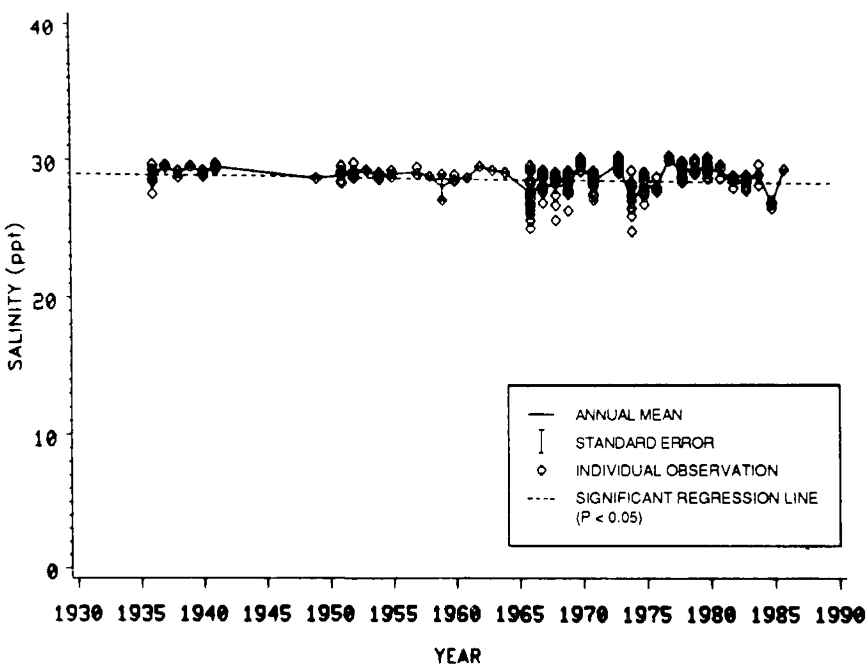


Figure 5.36. Salinity values at the surface and at 10-m depth in the Point Jefferson study area during the algal bloom season.

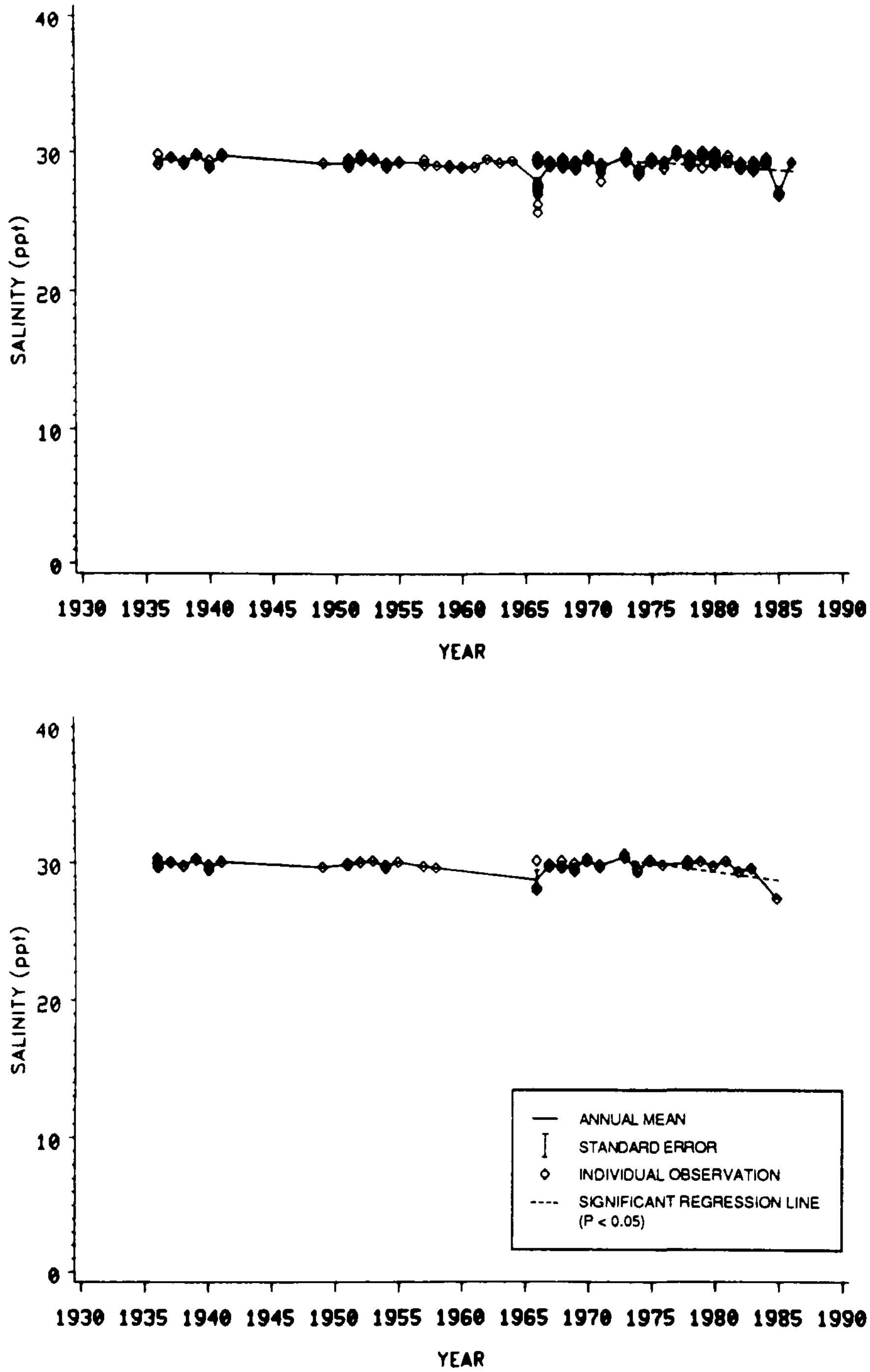


Figure 5.37. Salinity values at 30- and 100-m depths in the Point Jefferson study area during the algal bloom season.

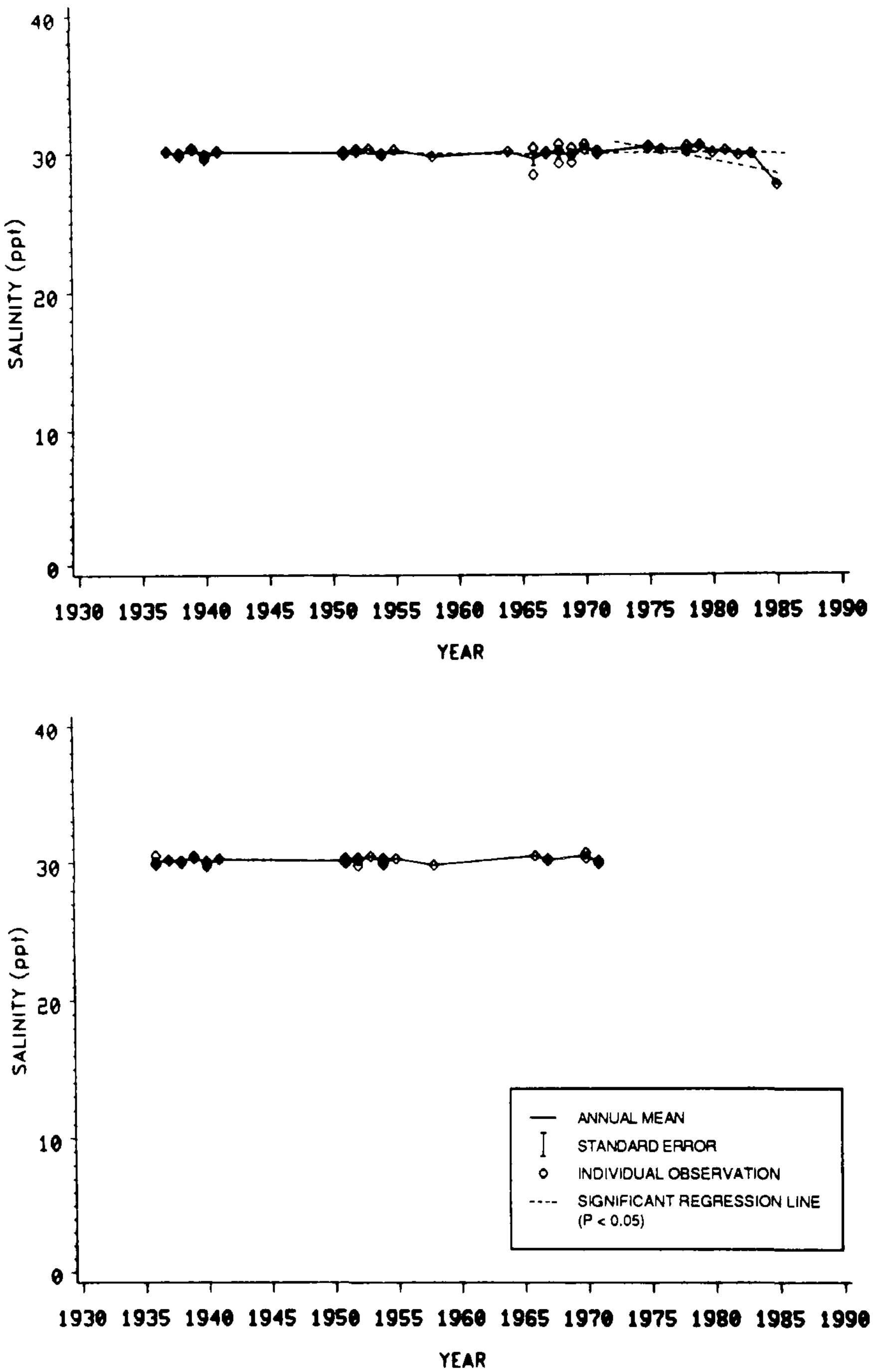


Figure 5.38. Salinity values at 150- and 200-m depths in the Point Jefferson study area during the algal bloom season.

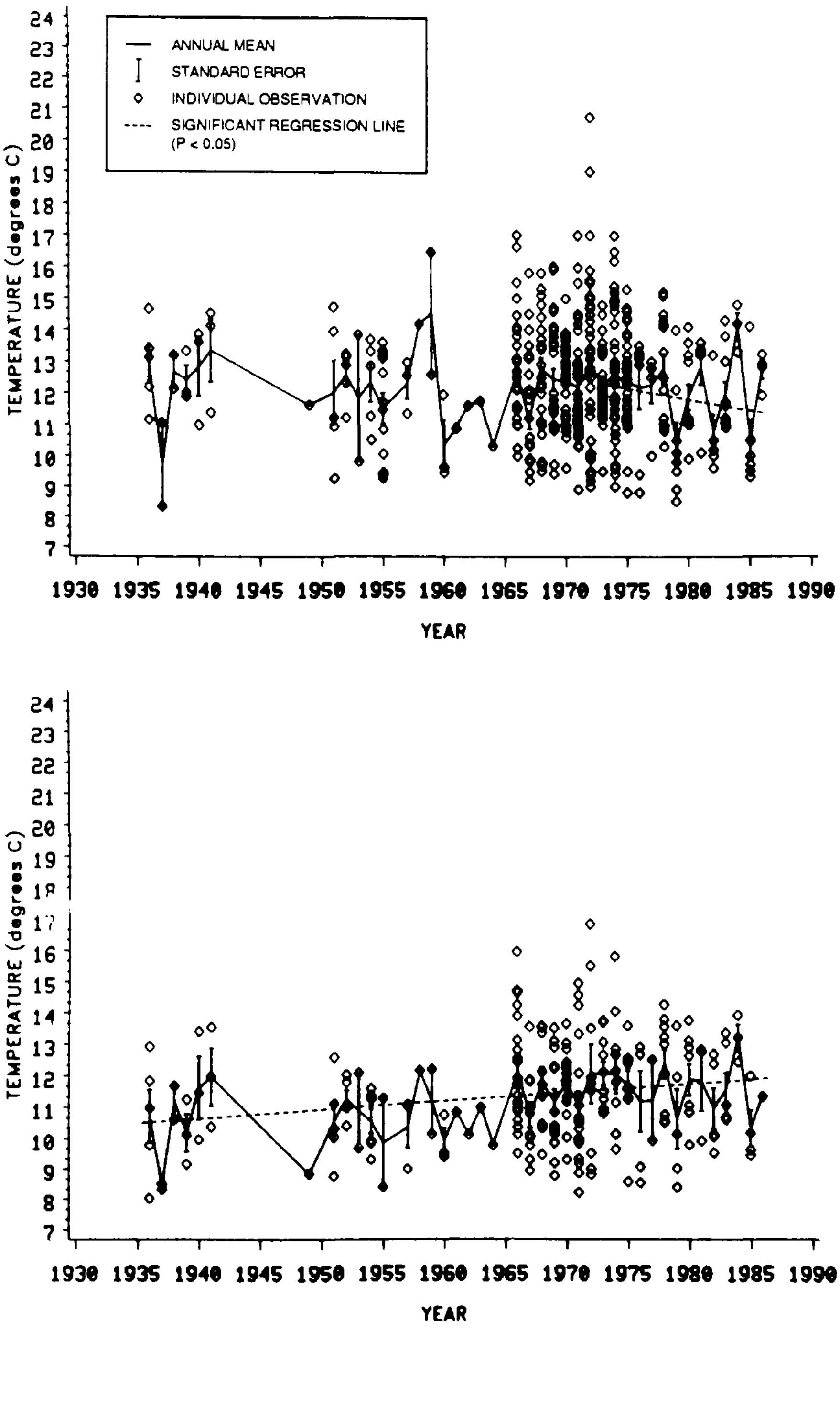
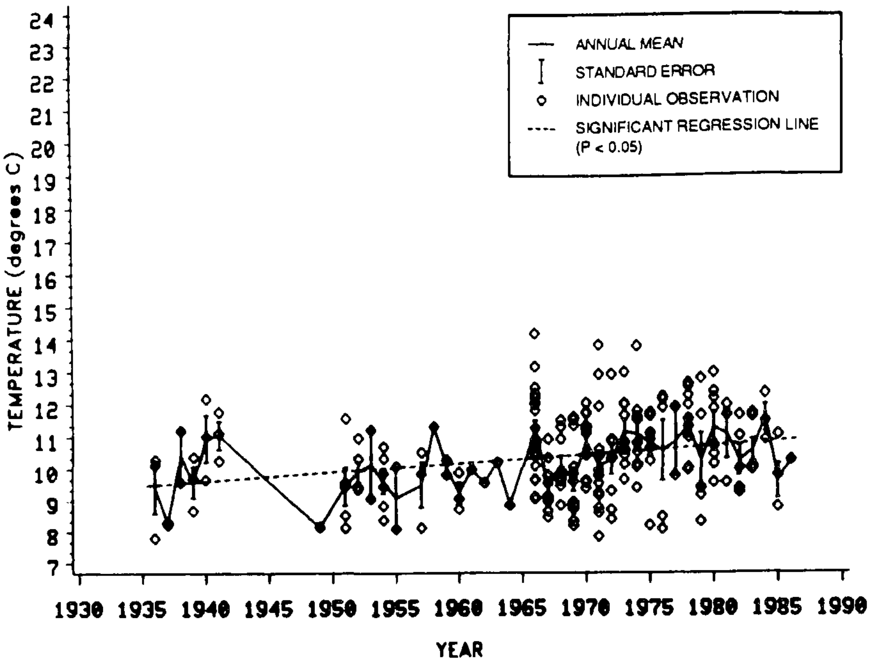


Figure 5.39. Water temperatures at the surface and at 10-m depth in the Point Jefferson study area during the algal bloom season.



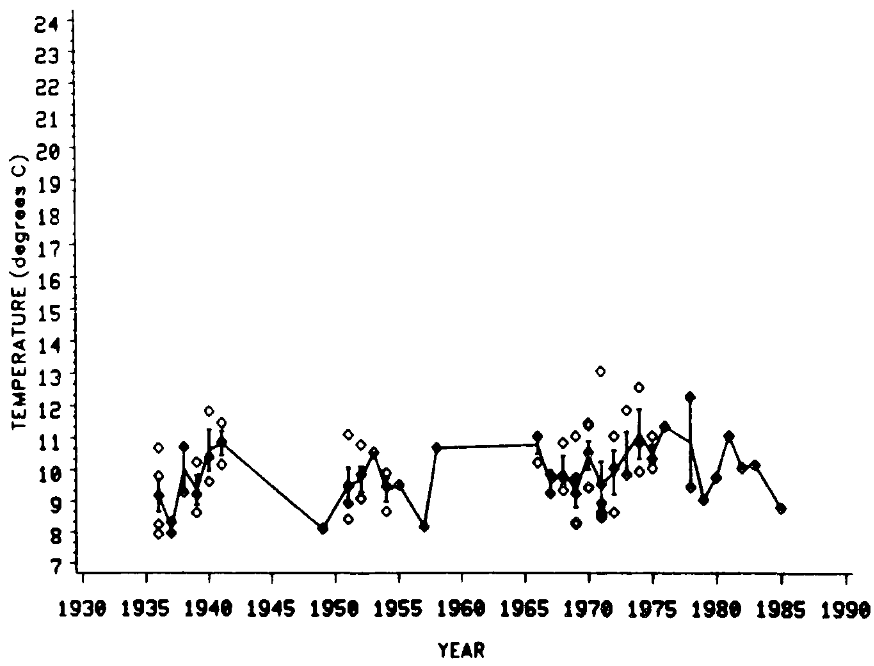


Figure 5.40. Water temperatures at 30- and 100-m depths in the Point Jefferson study area during the algal bloom season.

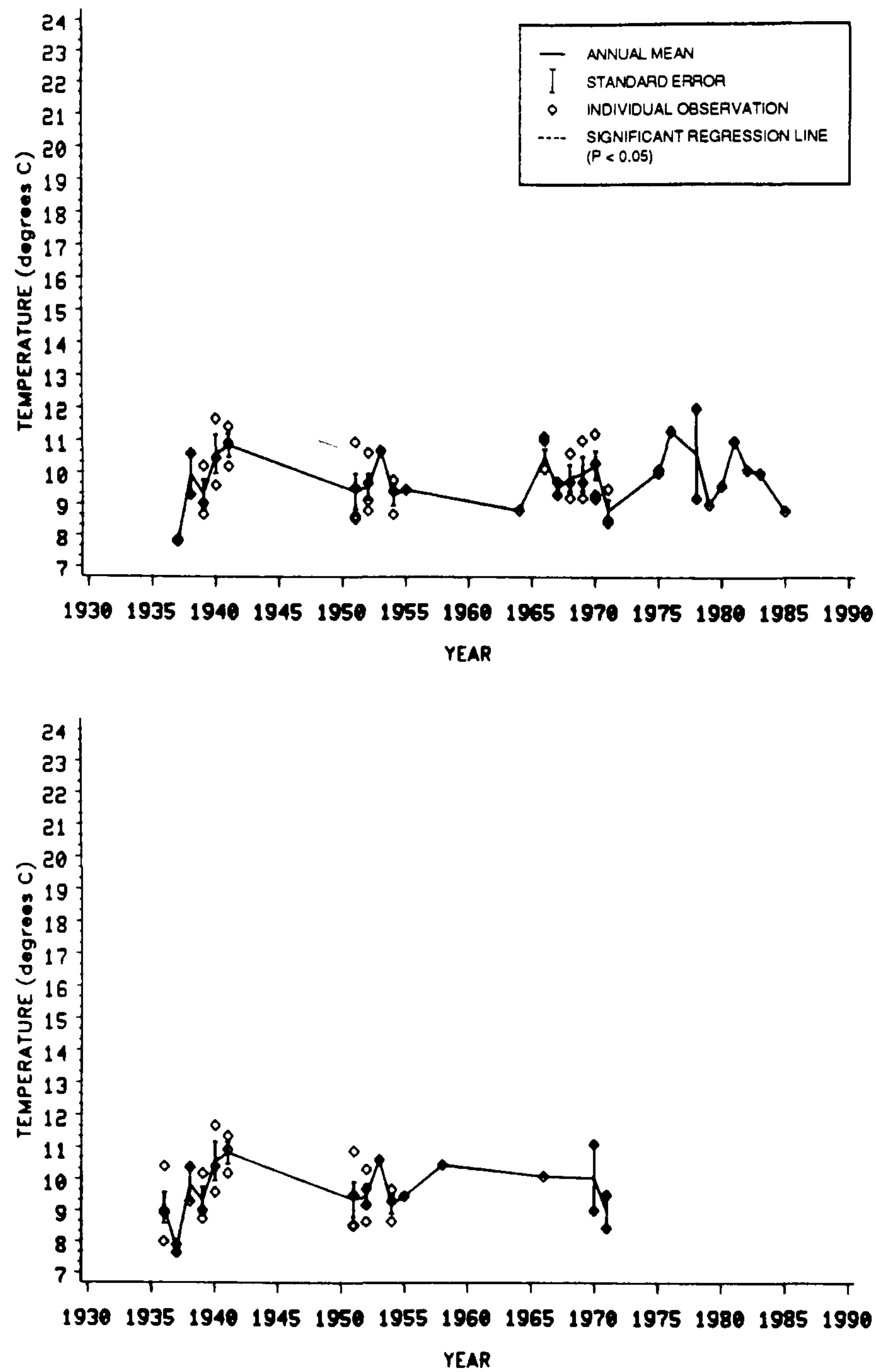


Figure 5.41. Water temperatures at 150- and 200-m depths in the Point Jefferson study area during the algal bloom season.

contrary to the apparent trend. Runoff data for 1930 through 1978 do not contain any statistically significant (P>0.05) temporal trend. Changes in station location probably did not influence these trends markedly because all data collected through the mid-1960s came from the same station (Station PSB305). However, for the station near Alki Point that was sampled during overlapping years and seasons by the University of Washington and Metro, the salinity values reported by Metro tended to be lower than the salinity values reported by the University of Washington (see Chapter 4). Thus, it is possible that differences in analytical technique between the University of Washington, which provided the older data, and Metro, which provided the recent data, could have introduced an apparent decline in salinity values into the data.

Some moderate changes were detected in water temperature. A negative slope of -0.07° C/yr was found for the regression of surface water temperature by year since 1973 (Table 5.8). However, mean surface water temperatures from before and after 1973 were not significantly different (P>0.05) (Table 5.7). The pattern of decreasing surface water temperatures in recent years was likely influenced by some high water temperatures reported in the early 1970s (Figure 5.39). Increases in water temperature were found at depths of 10, 30, and 100 m (Tables 5.7 and 5.8). These increases were likely influenced by low water temperatures at depth in the 1950s.

Dissolved Oxygen--Plots of dissolved oxygen concentration against year are shown in Figures 5.42-5.44. There is no evidence that the Class AA water quality standard (see Table 4.2) was violated. The only statistically significant change (P<0.05) in dissolved oxygen concentration was a decline in surface water since 1973 (Tables 5.7 and 5.8). However, this apparent decline appears to have been caused by some high values recorded from the mid-1970s and by erratic variations that have occurred since the mid-1970s, including some low values in 1986.

Nutrients--As discussed previously, temporal trends in nutrient concentrations were not analyzed due to the limited amount of available

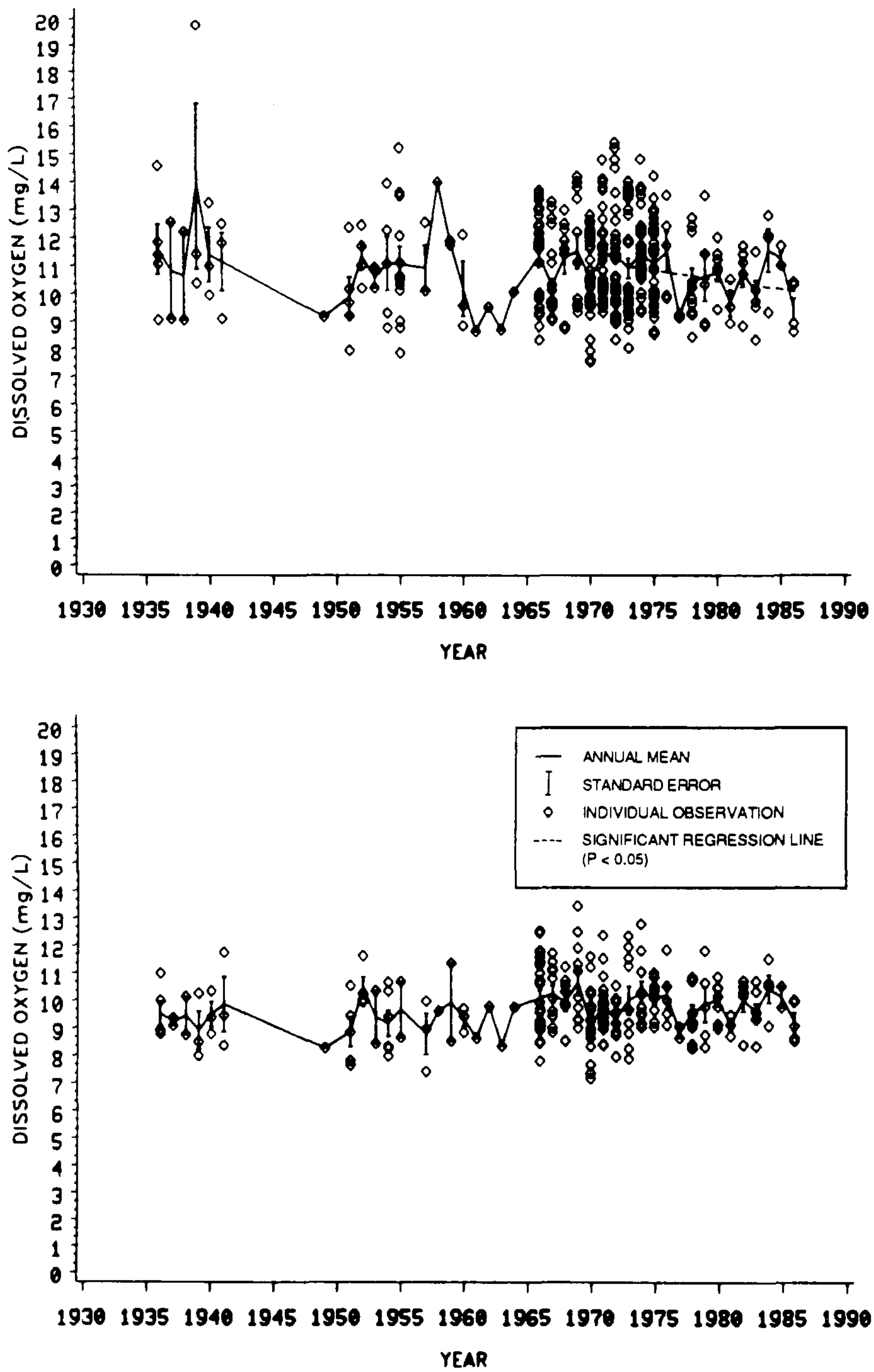


Figure 5.42. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Point Jefferson study area during the algal bloom season.

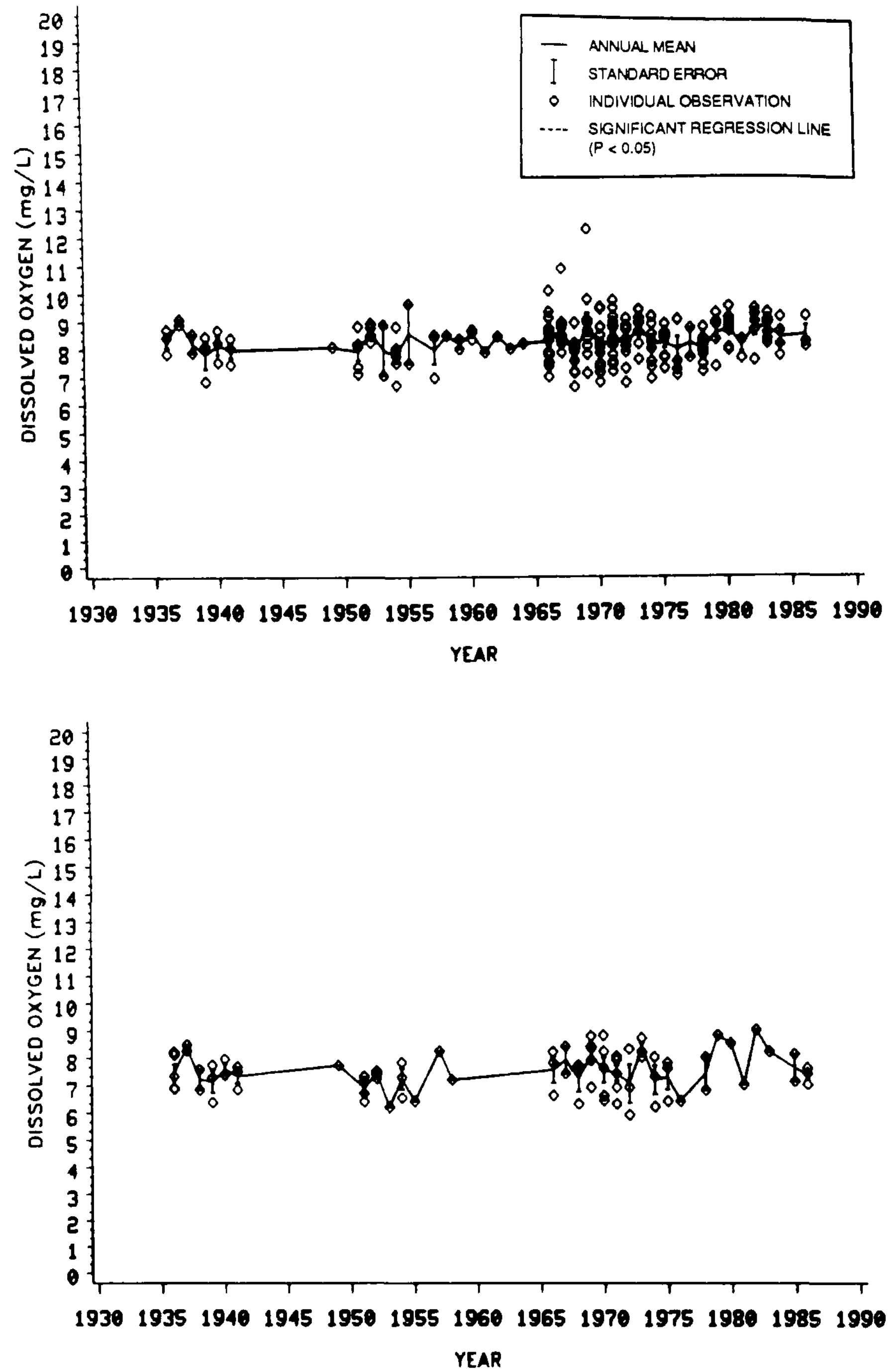
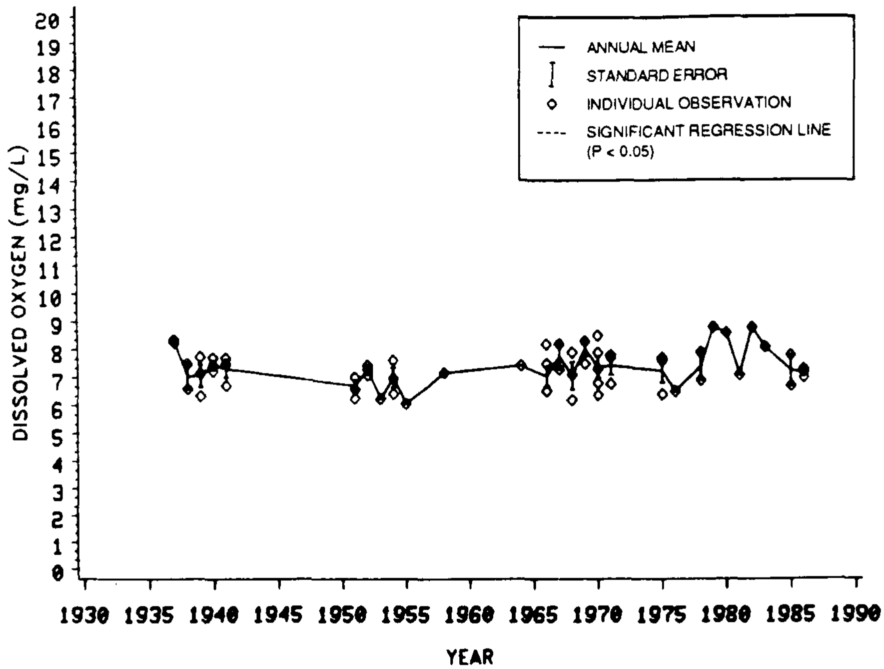


Figure 5.43. Concentrations of dissolved oxygen at 30- and 100-m depths in the Point Jefferson study area during the algal bloom season.



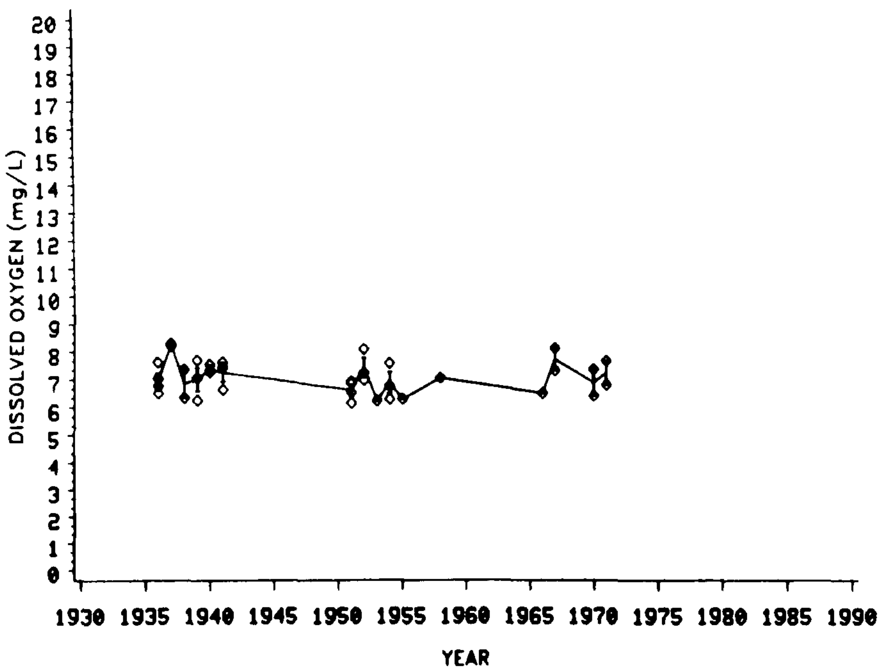


Figure 5.44. Concentrations of dissolved oxygen at 150- and 200-m depths in the Point Jefferson study area during the algal bloom season.

data and the incompatibility of the data collected by the University of Washington and Metro.

Indicators of Phytoplankton Growth--The evidence discussed below suggests that algal production has declined recently in the Point Jefferson study area. However, the evidence is somewhat weak and is not unequivocal. It appears that this decline, if it was a real phenomenon, was merely short-term variation within the normal range of production, and not a well-established, long-term trend.

Chlorophyll a concentrations are plotted against year in Figure 5.45. Unfortunately, data are available only for the years 1966 through 1975, and cannot be used to corroborate the tentative results discussed above. No temporal trends were detected in chlorophyll a concentrations from 1966 through 1975.

The percent dissolved oxygen saturation at the surface exhibited both long-term and recent declines (Figure 5.46, Table 5.8). However, the overall averages from before and after 1973 were not significantly different (Table 5.7). From examination of Figure 5.46, it appears that the values were highest in the 1930s (e.g., up to 220 percent saturation), and that the values recorded in 1985 and 1986 were low (averaging approximately 70 percent saturation). The recent statistically significant ($P<0.05$) increase in Secchi disk depth (Figure 5.46, Table 5.8) also suggests that the drop in percent dissolved oxygen saturation at the surface represented a decline in algal production. However, as with the dissolved oxygen saturation data, unusual Secchi disk depth data were reported in 1985 and 1986. The mean Secchi disk depth reported during the 1986 algal bloom season was approximately 9 m, which is the highest seasonal mean observed in the Point Jefferson study area. Thus, the changes in the percent dissolved oxygen saturation at the surface and Secchi disk depth appear to have been caused by unusual conditions in 1985 and 1986, rather than by systematic changes through time.

Pollutants--As discussed previously, analyses of concentrations of sulfite waste liquor and fecal coliform bacteria could not be conducted.

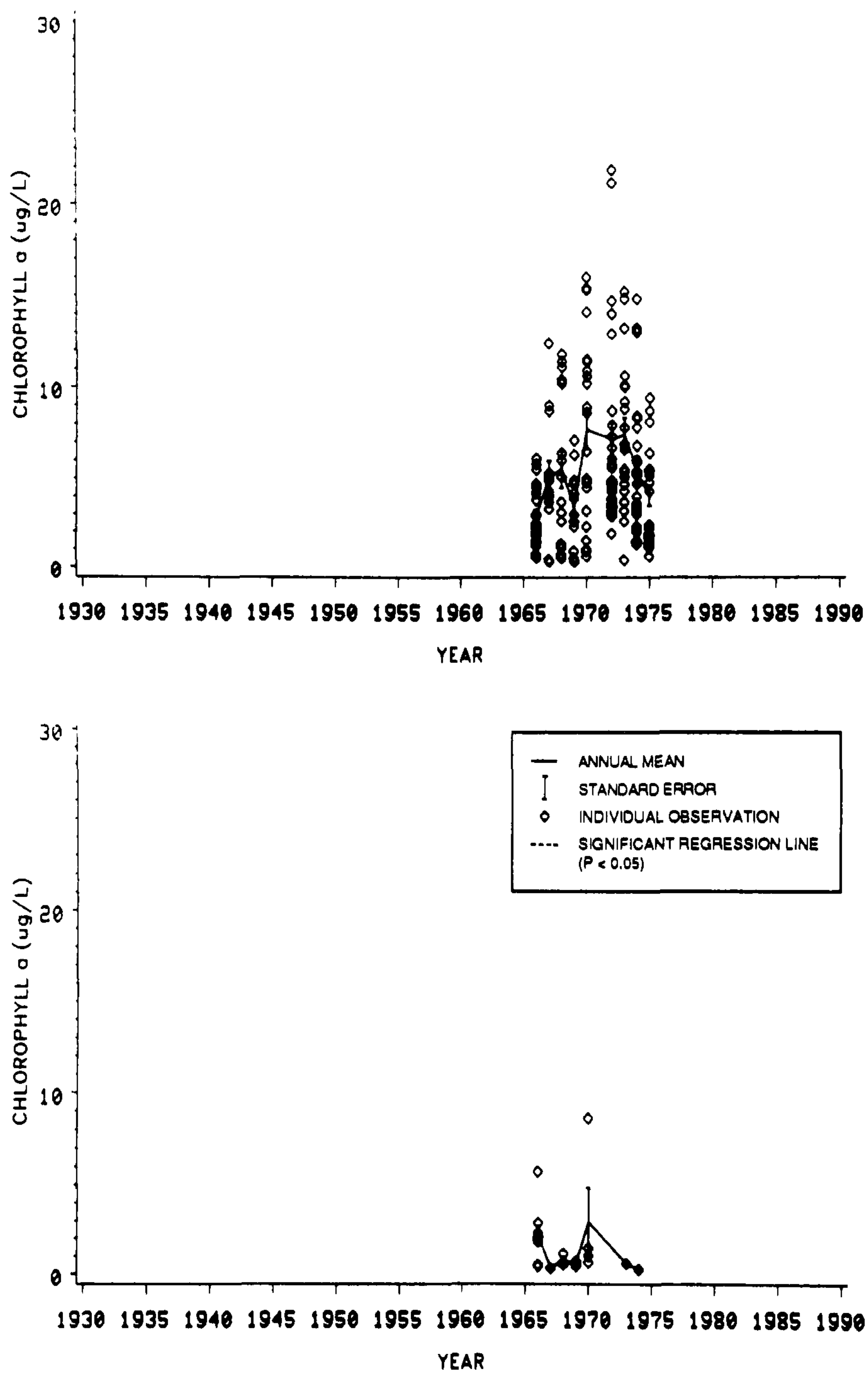


Figure 5.45. Concentrations of chlorophyll a at the surface and at 10-m depth in the Point Jefferson study area during the algal bloom season.

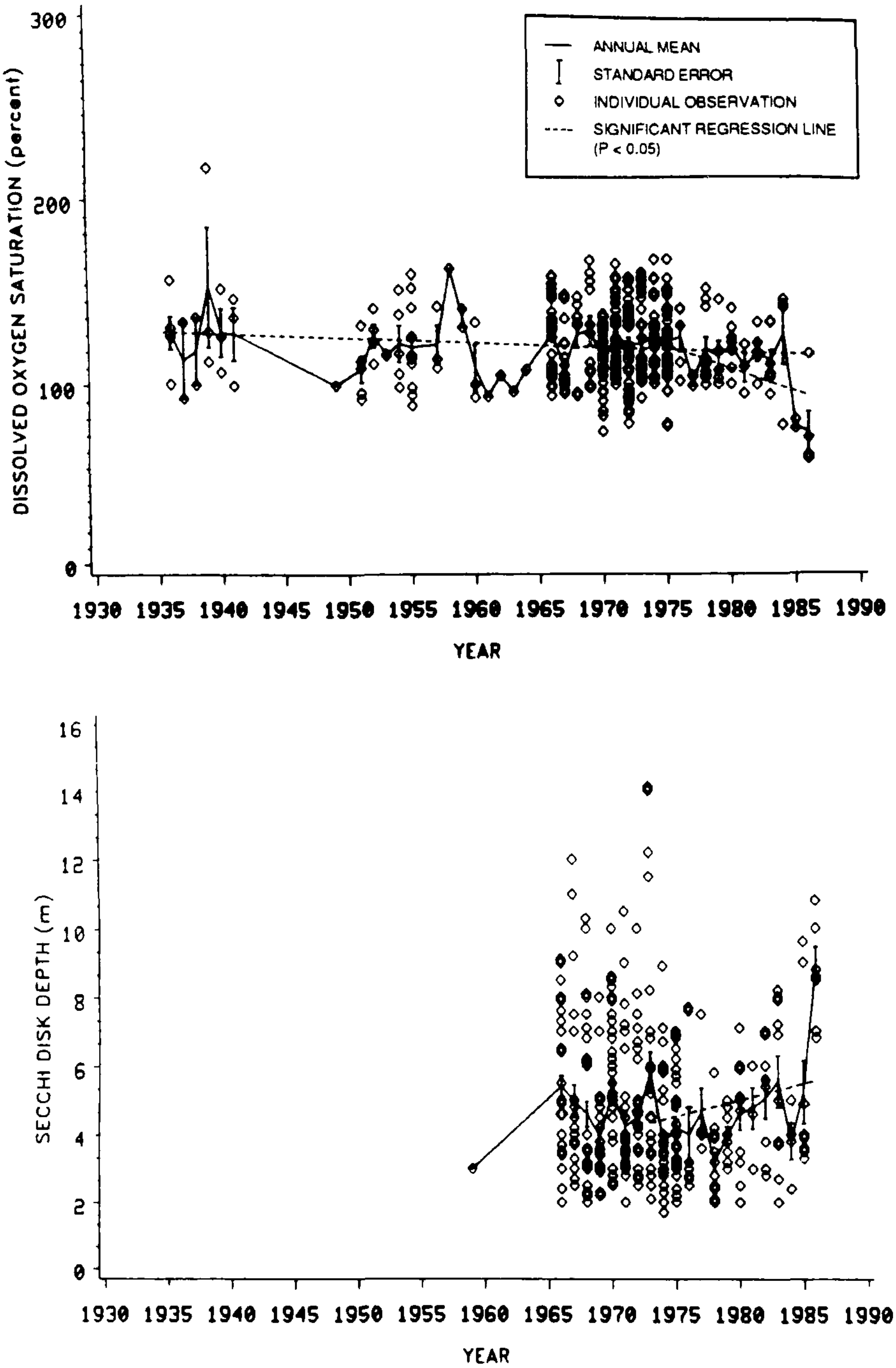


Figure 5.46. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Point Jefferson study area during the algal bloom season.

Sinclair Inlet

The Sinclair Inlet study area is on the western side of the central sound, separated from the Main Basin of Puget Sound by Bainbridge Island (see Figure 5.20). It is located in midchannel about two-thirds of the way from the mouth to the head of Sinclair Inlet, off the City of Bremerton and the Puget Sound Naval Shipyard. The maximum depth of Sinclair Inlet is approximately 65 m at the mouth; depths generally become shallower from the mouth to the head. Salt marshes and mudflats extend out approximately 0.6 km into the inlet from the head. Average depth in the study area is approximately 12 m. Class A water quality standards apply in the area (see Table 4.2). Contamination of the sediments by heavy metals has been detected near the naval shipyard (U.S. EPA 1986b).

The principal forces that produce currents in Sinclair Inlet are tidal (Lincoln and Collias 1975). Generally, weak tidal currents oscillate in direction, moving water in and out of the inlet. Two small creeks provide most of the freshwater input to Sinclair Inlet, so the flushing rate is low, especially during neap tides. In addition, wind stress substantially affects water transport. Southwesterly winds often force surface water out of the inlet, which draws replacement water into the inlet at depth.

Improvements in wastewater treatment facilities in and around the City of Bremerton were completed in 1985 (Baker, D., 29 October 1987, personal communication; Poppe, J., 9 November 1987, personal communication). Effluent previously discharged from two primary sewage treatment plants is now consolidated and given secondary treatment prior to discharge into Sinclair Inlet near the City of Bremerton. Most combined sewer overflows that discharged to Port Washington Narrows (on the eastern side of Bremerton), or to Sinclair Inlet (on the western end of the naval shipyard), were closed in 1985. However, several combined sewer overflows still exist in the City of Bremerton and the naval shipyard. It is anticipated that these remaining combined sewer overflows will be closed in the next few years (Baker, D., 13 November 1987, personal communication). One of the small creeks mentioned above, Gorst Creek, is a known source of contamination by fecal coliform bacteria (Struck, P., 9 November 1987, personal communication).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are shown in Figure 5.21. Data are available from 1967 through 1986. More data are available for the surface water than for 10-m depth. The salinity gradient over depth was small (i.e., the mean salinity value at the surface was only 0.5 ppt lower than the mean salinity value at 10-m depth). This gradient reflects the lack of large inputs of fresh water into Sinclair Inlet. The temperature gradient over depth was large, with the surface temperature averaging approximately 1.7° C higher than the temperature at 10-m depth. Thus, density stratification over the water column was caused principally by the temperature gradient. The magnitude of the surface warming suggests that vertical mixing rates are low, comparable to the vertical mixing rates in City Waterway (see below) and less than those at Point Jefferson.

Depth gradients in the concentrations of dissolved oxygen and nutrients were well developed (Figures 5.22 and 5.23). Mean dissolved oxygen concentration at the surface in Sinclair Inlet was the highest of any central sound study area (11.3 mg/L), while mean dissolved oxygen concentration at 10-m depth was the lowest of any central sound study area (8.9 mg/L). Mean nitrate concentrations were quite low at the surface (<2.7 ug-at/L) and at 10-m depth (8.1 ug-at/L). The mean phosphate concentrations at Sinclair Inlet were not markedly different from those at the other central sound study areas. The significant negative correlations ($P<0.05$) between dissolved oxygen and nitrate concentrations (Appendix F) suggest that nitrate concentrations were strongly influenced by photosynthetic rates.

Intense algal blooms appear to have occurred in the study area. The mean percent dissolved oxygen saturation at the surface (134 percent) was the highest of any area studied in this characterization study. The next highest mean value for this variable (128.5 percent) was detected in Carr Inlet (Appendix E). Also, the mean Secchi disk depth (3.5 m) was relatively low (Figure 5.24). Although Secchi disk depths may have been influenced by disturbances from the City of Bremerton and the naval shipyard, the absence of substantial freshwater inputs suggests that the major factor limiting Secchi disk depths in Sinclair Inlet was phytoplankton abundance.

Geometric mean concentrations of sulfite waste liquor (3.6 Pearl Benson Index) and fecal coliform bacteria (1.9 organisms/100 mL) were low in the study area (Figure 5.25). There was no source of sulfite waste liquor near the study area, and raw sewage was discharged only through combined sewer overflows during the study period.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected prior to and after 1973 is given in Table 5.7. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.8.

Physical Conditions--Plots of salinity and water temperature by year are shown in Figures 5.47 and 5.48. No temporal trends were detected for either variable.

Dissolved Oxygen--Plots of dissolved oxygen concentrations by year are shown in Figure 5.49. Violations of the Class A water quality standard (see Table 4.2) were recorded at 10-m depth in 1974 and 1980. No temporal trends were detected.

Nutrients--Plots of concentrations of nitrate and phosphate by year are shown in Figures 5.50 and 5.51, respectively. Nutrient data are available since 1973. No temporal trends were detected in nitrate concentrations, but an increase in phosphate concentrations at 10-m depth was detected (Table 5.8). No explanation was readily apparent for the increased phosphate concentrations, but it did not appear to be influenced by improvements in the sewage treatment system implemented in 1985. It is possible that changes in other anthropogenic factors or in oceanic inputs influenced the phosphate data.

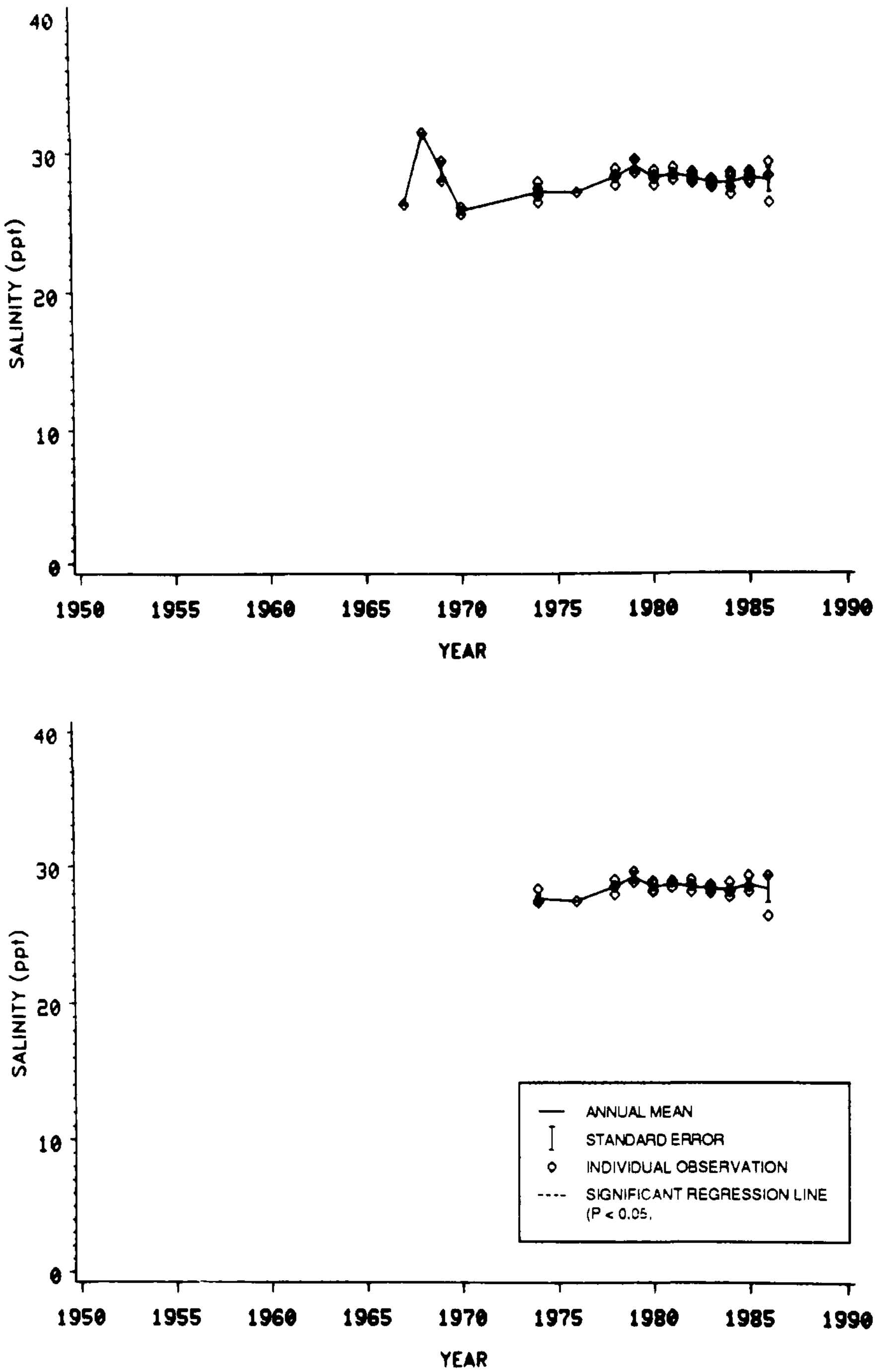


Figure 5.47. Salinity values at the surface and at 10-m depth in the Sinclair Inlet study area during the algal bloom season.

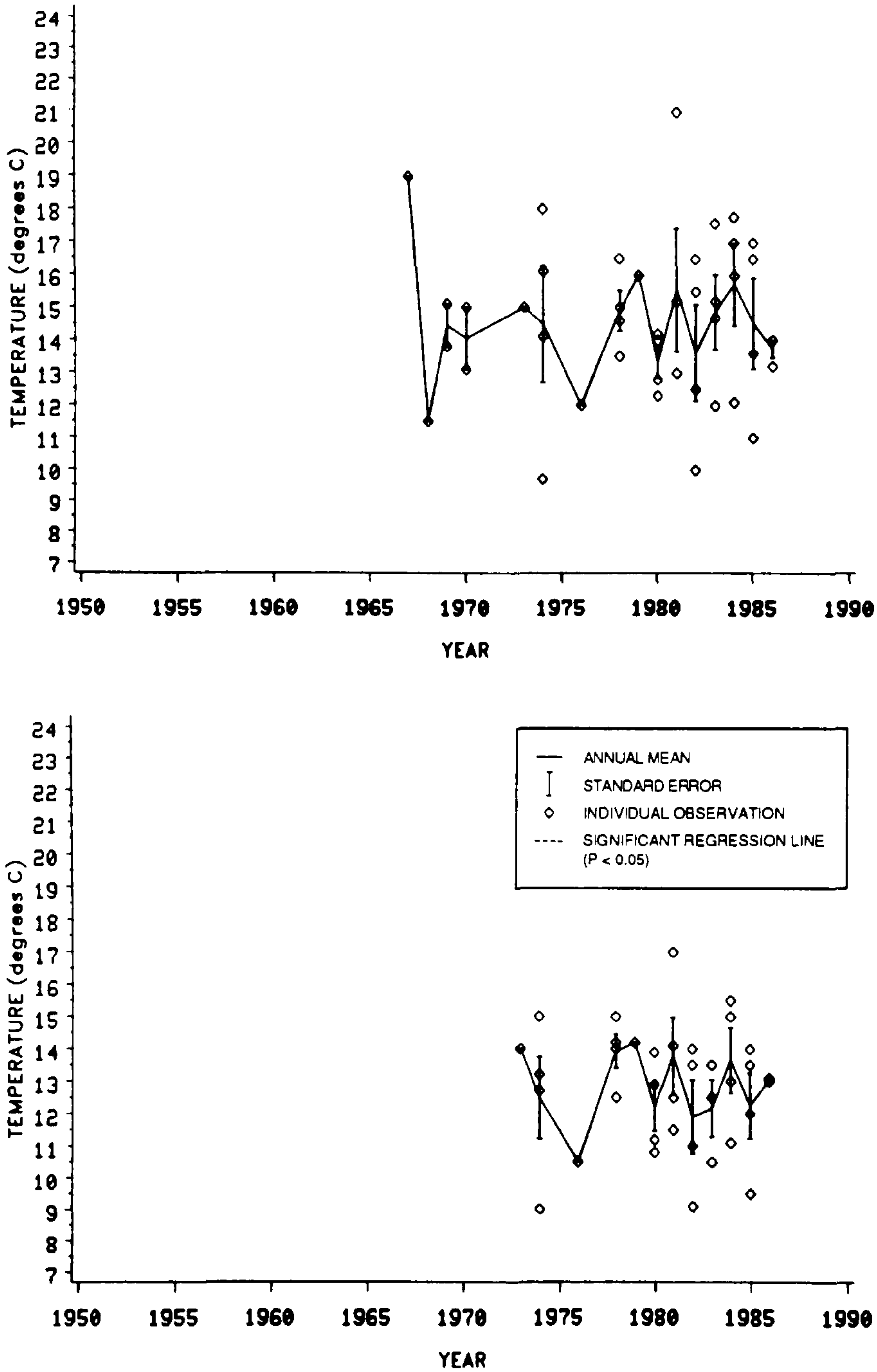


Figure 5.48. Water temperatures at the surface and at 10-m depth in the Sinclair Inlet study area during the algal bloom season.

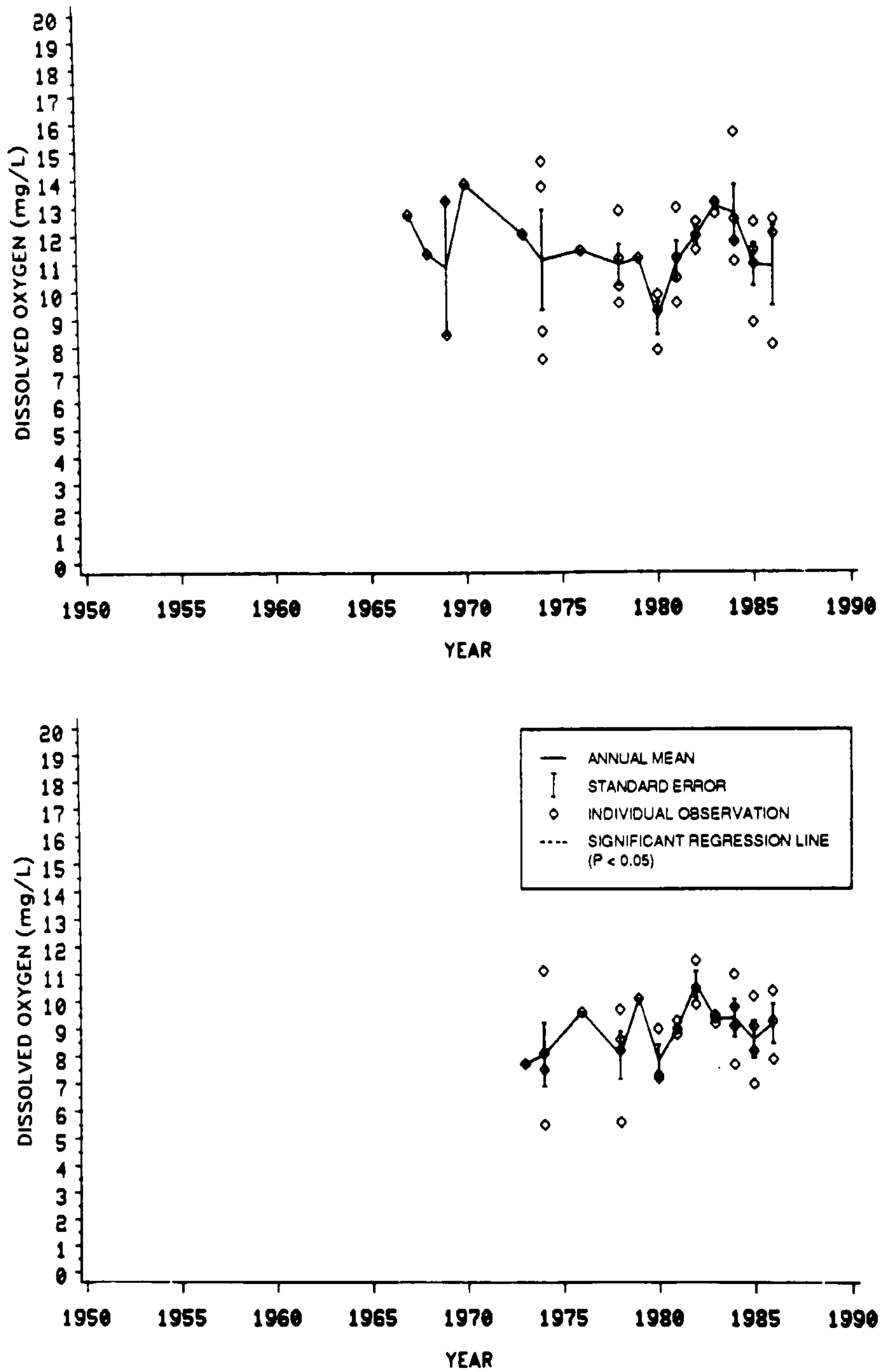


Figure 5.49. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Sinclair Inlet study area during the algal bloom season.

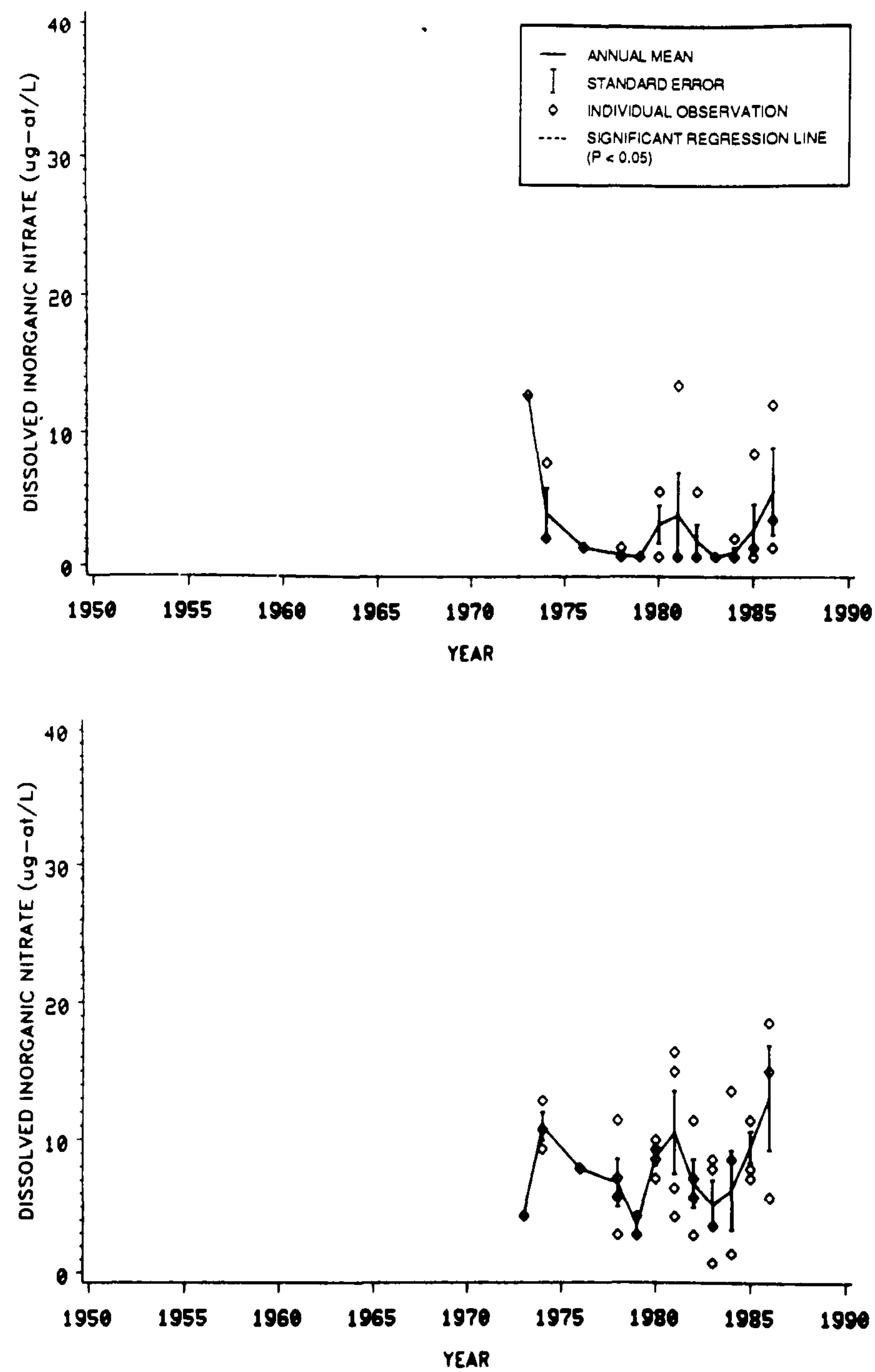


Figure 5.50. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the Sinclair Inlet study area during the algal bloom season.

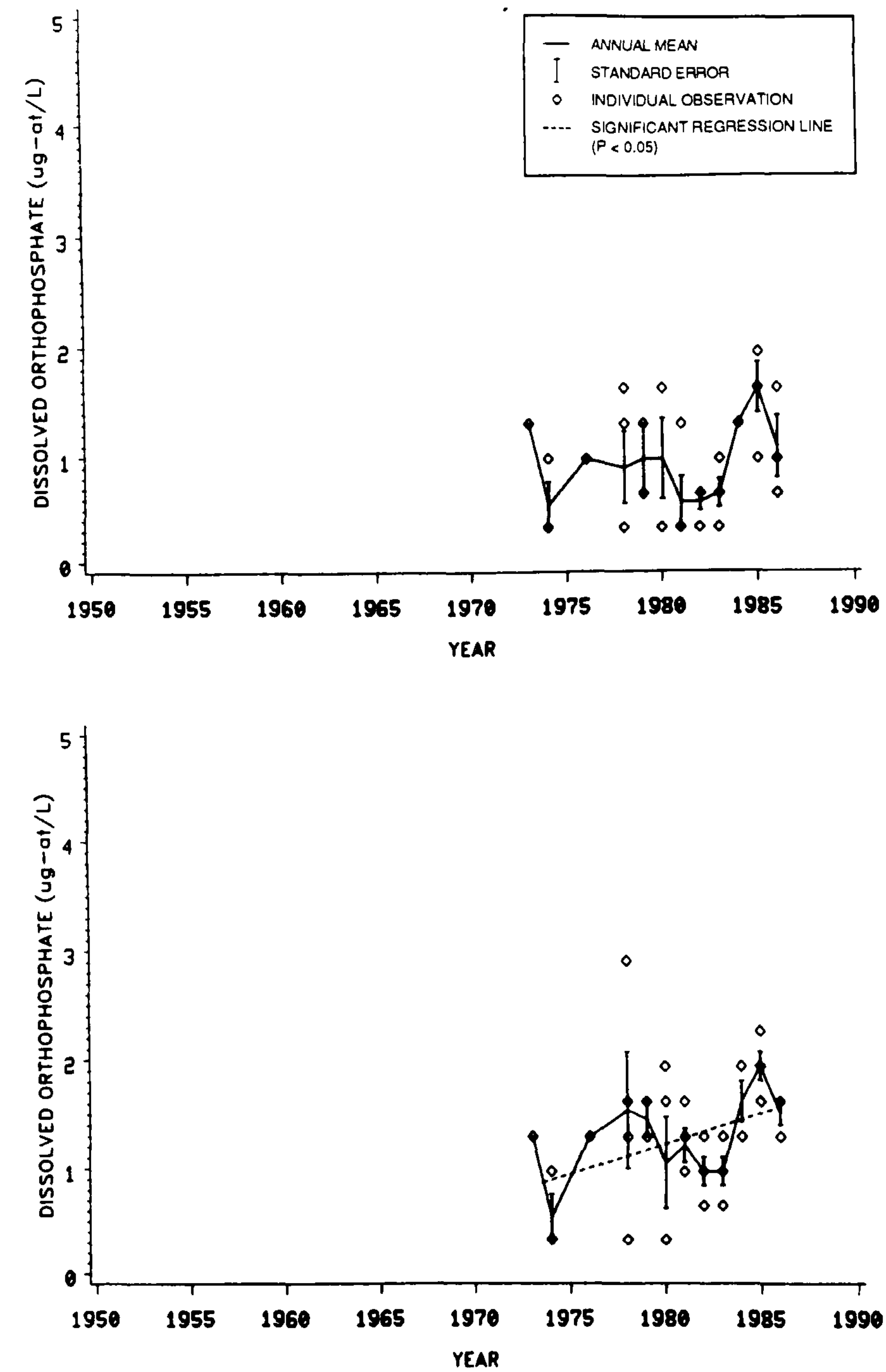


Figure 5.51. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Sinclair Inlet study area during the algal bloom season.

Indicators of Phytoplankton Growth--Chlorophyll *a* data are not available. Percent dissolved oxygen saturation at the surface and Secchi disk depth are plotted by year in Figure 5.52. No temporal trends were detected.

Pollutants--Data for sulfite waste liquor and fecal coliform bacteria are plotted by year in Figure 5.53. Sulfite waste liquor data are only available from 1968 through 1976; no changes were detected. Trends in the concentration of fecal coliform bacteria were not statistically significant, but a few high values, in violation of Class A water quality standards (Table 4.2), were detected from 1978 through 1983. No explanation was available to explain this phenomenon, although the combined sewer overflows that were closed in 1985 may have contributed to the earlier elevations in fecal coliform bacteria.

City Waterway

The study area is located in the mouth of City Waterway in the southeastern corner of Commencement Bay (see Figure 5.20). Commencement Bay is a deep (over 150 m), open embayment. City Waterway is a manmade commercial waterway bordered by the industrial City of Tacoma. The depth near the study area has been maintained by dredging at approximately 10 m. The Puyallup River empties into Commencement Bay approximately 1.2 km north of City Waterway. The Puyallup River discharges 6 percent of the total volume of fresh water entering into the sound (see Table 2.1). It carries a heavy load of sediment, creating a delta at its mouth and a highly turbid surface layer in the bay (City of Tacoma 1983a,b; NOAA 1987).

Water movements in Commencement Bay are highly variable, and are influenced by tides, the flow of the Puyallup River, and winds (Dames and Moore 1981; City of Tacoma 1983a,b; NOAA 1986b, 1987). On ebbing tides, the plume from the river exits out along the central axis of the bay as a turbid surface flow. On flooding tides, the flow of the river is deflected and backs up, causing low salinities to occur along the northern shoreline and in the southeastern corner of the bay. Winds principally affect surface

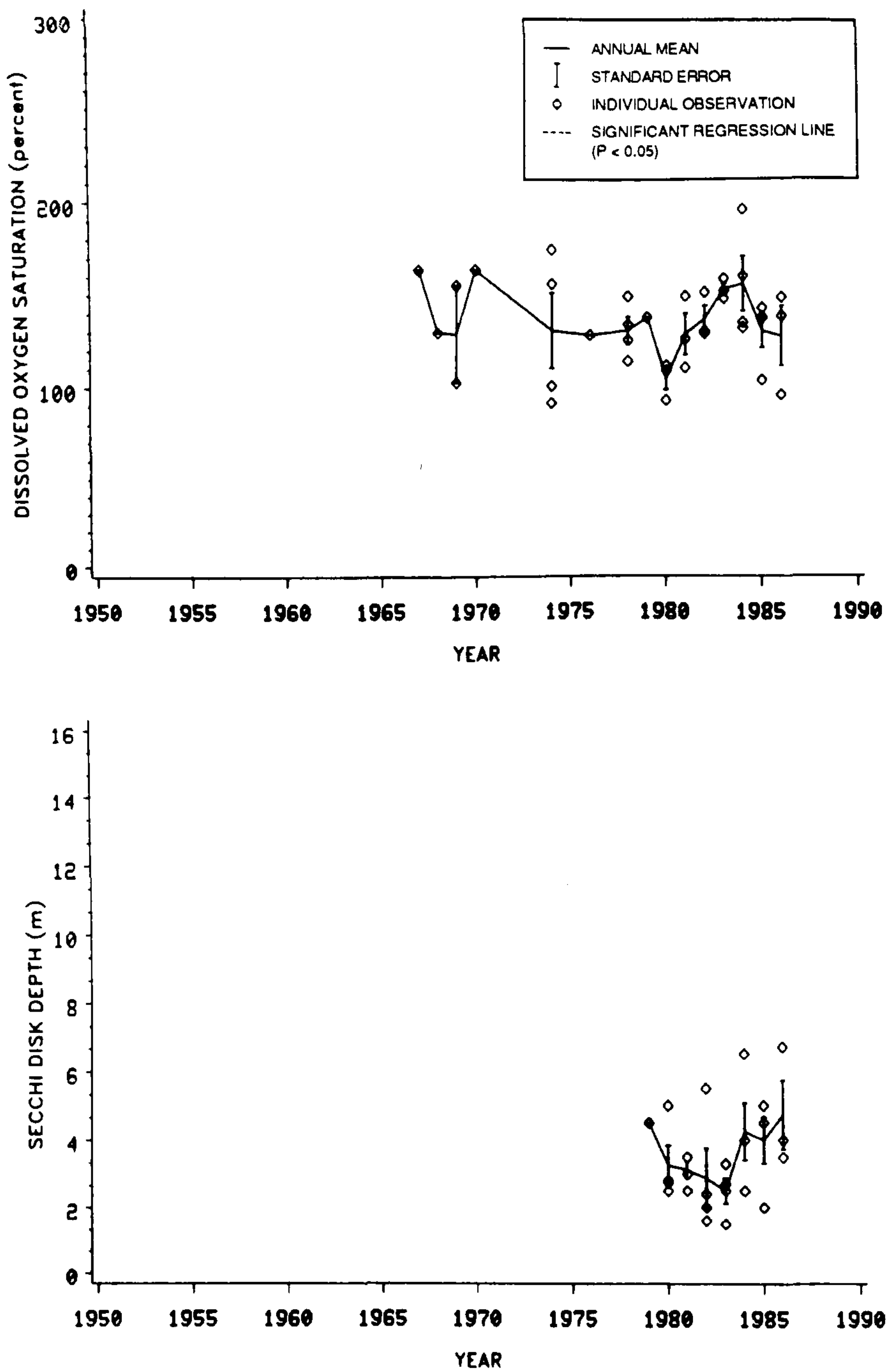


Figure 5.52. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Sinclair Inlet study area during the algal bloom season.

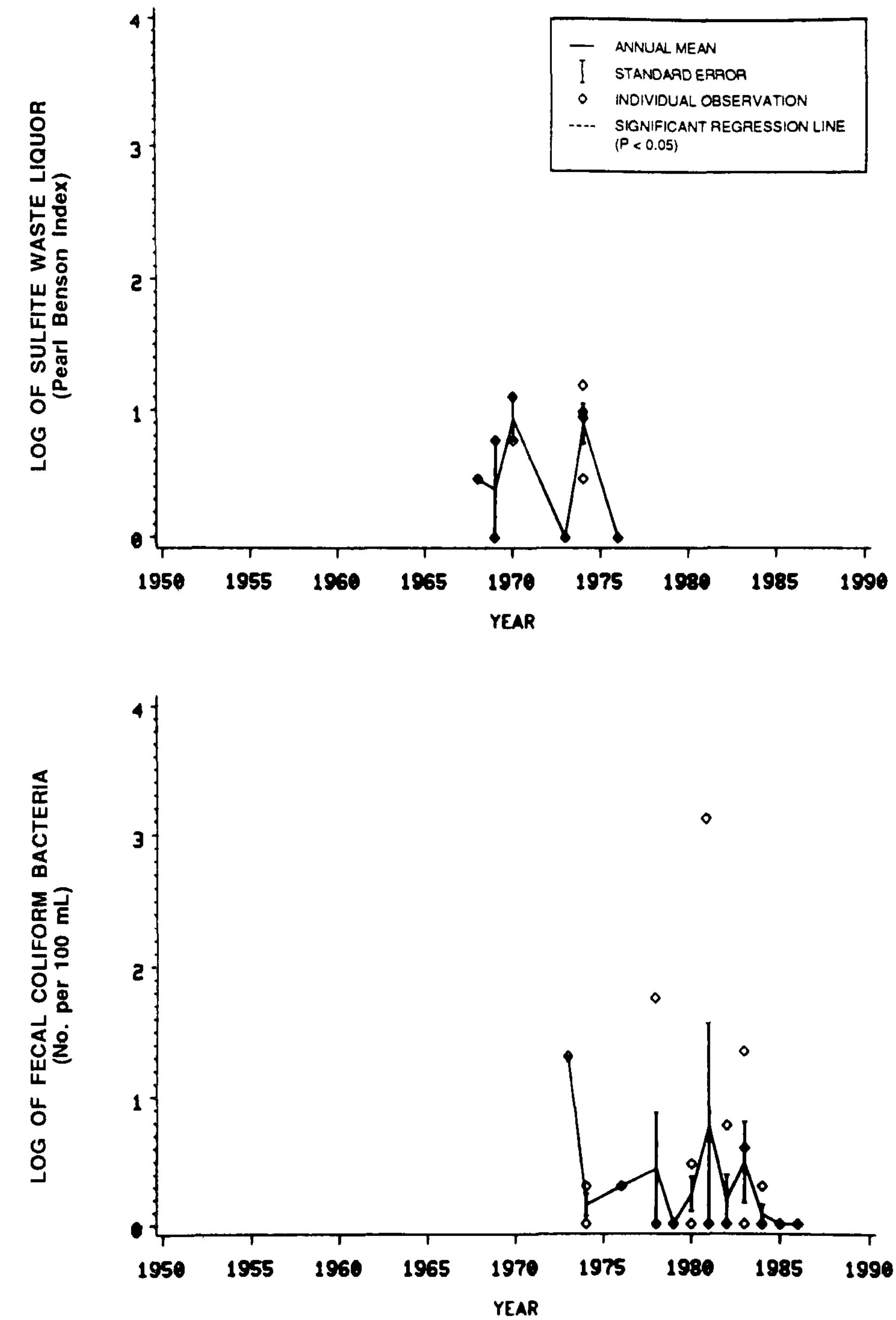


Figure 5.53. Log of concentrations of sulfite waste liquor and fecal coliform bacteria at the surface in the Sinclair Inlet study area during the algal bloom season.

waters (e.g., northerly and westerly winds may force surface waters back into the bay and into the waterways). At depth in Commencement Bay, nontidal flows are weak and erratic, but the net movement of sub-surface water typically is onshore. The depth of no net horizontal movement in the bay has been estimated to be between 10 and 20 m (Dames and Moore 1981).

Because City Waterway is sheltered, water movements are weak and erratic. The major forces influencing water movements in the waterway are tides and wind stress (Dames and Moore 1981). The influence of the plume from the Puyallup River has been debated, but recent evidence suggests that water from the Puyallup River can enter the mouths of the waterways (see below). The frequency with which the plume influences City Waterway and the distance over which the plume water may penetrate into City Waterway are unknown. Dames and Moore (1981) concluded that City Waterway is largely isolated from the influences of the Puyallup River by the effects of a back eddy in the southeastern corner of the bay. Tetra Tech (1985) noted that the water at the mouth of City Waterway contained lower levels of total suspended solids than the water in the other waterways of Commencement Bay. This observation supports the interpretation that City Waterway is not affected substantially by the Puyallup River. However, NOAA (1986b) showed that fresh water and suspended particulate matter from the Puyallup River plume can enter the mouths of the waterways, including City Waterway, along the surface. In this characterization study, surface salinity values at the mouth of City Waterway appear to be quite low (the mean surface salinity was 23.3 ppt) relative to the salinities found in the bay. Average surface salinity values near the center of Commencement Bay exceed 29 ppt (NOAA 1987). Because there is no other substantial source of fresh water for the mouth of City Waterway, water from the Puyallup River appears to influence salinity values at the study site.

Water quality in City Waterway has been affected by numerous historical and present day waste discharges. The waterway currently receives input from over 50 storm drains and at least seven industrial discharges permitted by the National Pollutant Discharge Elimination System (NPDES) (Tetra Tech 1985). Pulp and wood product industries have been present in Tacoma since the late nineteenth century. The Simpson Tacoma Kraft pulp mill, which discharges about 750 m northwest of the mouth of City Waterway, began primary effluent treatment in 1970 and secondary effluent treatment in 1977 (Tetra Tech 1985). Historically, at least six combined sewer overflows drained into City Waterway. Between 1969 and 1979, the amount of sanitary wastes discharged through these combined sewer overflows was progressively reduced and then eliminated. However, effluent from the Central Waste Water Treatment Plant is discharged to the Puyallup River, about 2 km above the river's mouth (City of Tacoma 1983a). Also, effluent from the North End Wastewater Treatment Plant is discharged at Ruston, along the southern shoreline of Commencement Bay. Sub-surface flow from this area might reach the mouth of City Waterway (City of Tacoma 1983b). Although organic enrichment has caused sediments to become anoxic near the head of City Waterway, anoxic sediments are less of a problem near the study area (Tetra Tech 1985).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are shown in Figure 5.21. Data are available from 1968 through 1986. All the data came from a single station, Ecology's Station CMB006. There was a large gradient of salinity over depth, with a difference of approximately 5.1 ppt between the surface and 10-m depth (Appendix E). The magnitude of the salinity depth gradient probably reflects freshwater inputs from the Puyallup River plume to the mouth of City Waterway (see above). The depth gradient in water temperature was also well developed. The average temperature at the surface was approximately 1.6^{o} C higher than the average temperature at 10-m depth. The relatively large depth gradients of salinity and water temperature suggest that vertical mixing rates were low in the study area. The low rate of vertical mixing presumably results because the study area is sheltered from turbulence and because the rate of circulation in the waterway is low (Dames and Moore 1981).

Depth gradients in the concentrations of dissolved oxygen and nutrients in the City Waterway study area were less well developed than those in any other study area in the northern or central sound (i.e., Bellingham Bay, Port Gardner, Point Jefferson, and Sinclair Inlet). The mean concentrations of dissolved oxygen at the surface and at 10-m depth only differed by 0.3 mg/L, while the concentrations of nitrate and phosphate at the surface and at 10-m depth only differed by 1.8 ug-at/L and 0.03 ug-at/L, respectively. The poorly developed gradients appear to have resulted from conditions at the surface in City Waterway. Surface concentrations of dissolved oxygen were relatively low at this site, while surface nutrient concentrations were relatively high. Evidently, intense algal blooms that would increase surface dissolved oxygen concentrations and decrease surface nutrient concentrations rarely developed in the City Waterway study area.

The interpretation that algal blooms were of low intensity in the City Waterway study area is supported by the relatively low average percent dissolved oxygen saturation at the surface (104.5 percent) (see Figure 5.24). Also, the mean concentration of chlorophyll a (4.8 ug/L) was significantly lower ($P<0.001$) than the mean concentration reported for the Point Jefferson study area (5.6 ug/L) (see Figure 5.23). High turbidity in City Waterway, as indicated by the low mean Secchi disk depth (2.9 m) (Figure 5.24), may have limited the depth of the photic zone such that intense algal blooms could not develop.

The apparent geometric mean concentration of sulfite waste liquor at the City Waterway site was low (4.7 Pearl Benson Index) (Figure 5.25). Sulfite waste liquor was measured by Ecology using the Pearl Benson Index, but kraft mills, such as the Simpson-Tacoma mill, do not release sulfite waste liquor. However, the effluent from such mills contains substances that are detected by the Pearl Benson Index (Felicetta and McCarthy 1963; Henry, C., 17 November 1987, personal communication). Thus, the sulfite waste liquor detected in City Waterway probably reflected the presence of effluent from the Simpson-Tacoma mill.

The geometric mean concentration of fecal coliform bacteria in City Waterway (13.8 organisms/100 mL) was the second highest of any study area in the characterization study (see Figure 5.25 and Appendix E). Port Gardner had a higher geometric mean. However, the fecal coliform values at Port Gardner were probably inflated by high concentrations of Klebsiella from the secondary treatment system of the Scott sulfite pulp mill, and were probably not indicative of sewage contamination. A similar elevation of Klebsiella would not be expected from a kraft mill, such as the Simpson Tacoma mill. It is possible that the fecal coliform bacteria in City Waterway came from combined sewer overflows (see below).

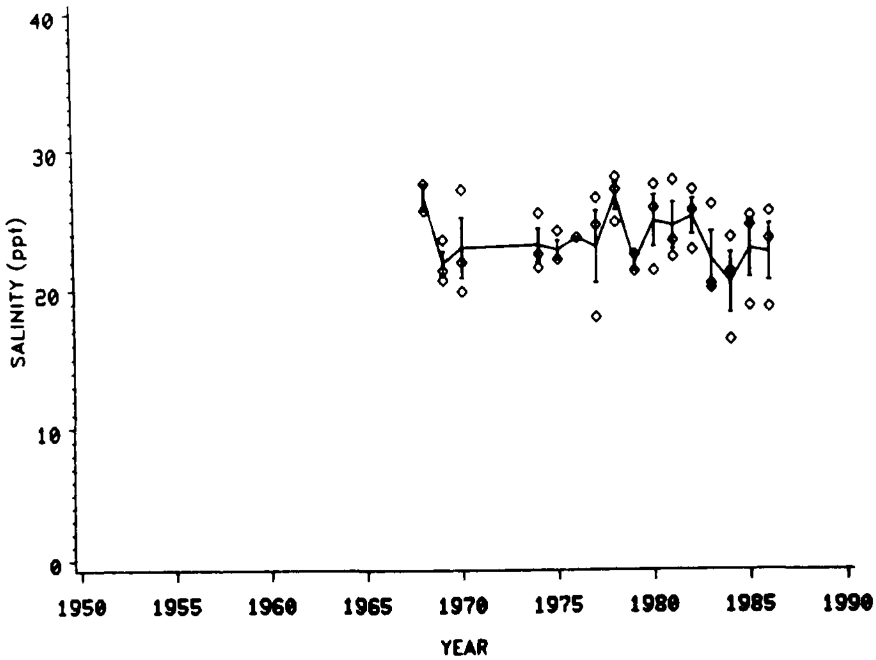
Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.7. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.8.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.54 and 5.55. No temporal trends were detected for either variable (Tables 5.7 and 5.8).

Dissolved Oxygen--Plots of dissolved oxygen concentration by year are shown in Figure 5.56. There is no evidence that the Class B water quality standard (see Table 4.2) was violated in the study area, although a few values below the Class AA standard (7 mg/L) were detected prior to 1981. No statistically significant temporal trends were detected in the concentrations of dissolved oxygen.

Nutrients--Plots of nitrate concentrations by year are shown in Figure 5.57. Increasing concentrations of nitrate were detected statistically at 10-m depth (Table 5.8). However, it cannot be determined whether this apparent increase was caused by an actual change in environmental conditions. It is possible that the statistical increase in nitrate concentrations at 10-m depth was driven by erratic variation in the data, which included some low values near the beginning of the data set and some high values near the end of the data set. Plots of phosphate concentration by year are shown in Figure 5.58. A significant positive slope ($P<0.05$) was detected both at the surface and at 10 m depth (Table 5.8). Despite considerable scatter in the data, generally increasing trends seem to be evident in the data.



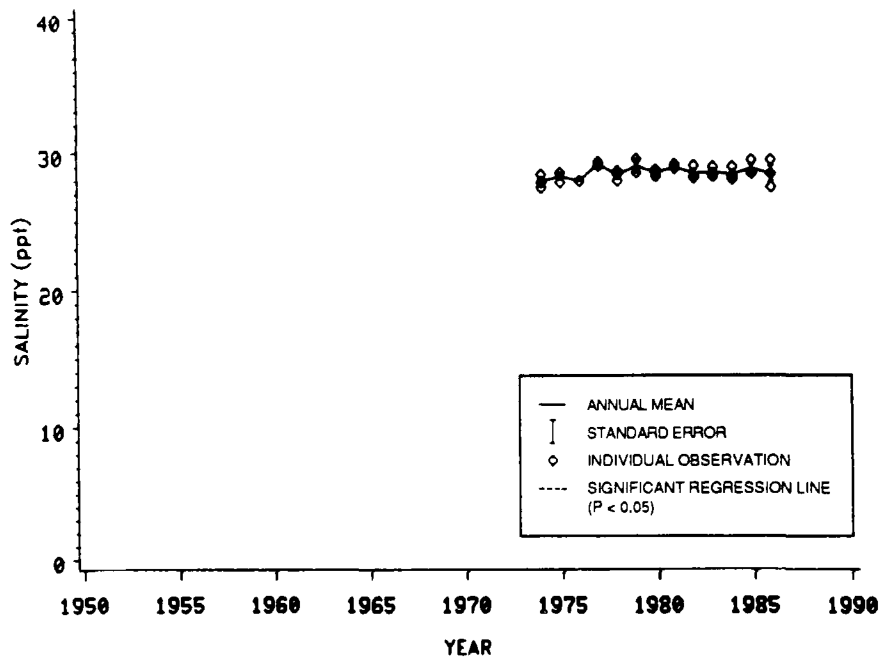


Figure 5.54. Salinity values at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

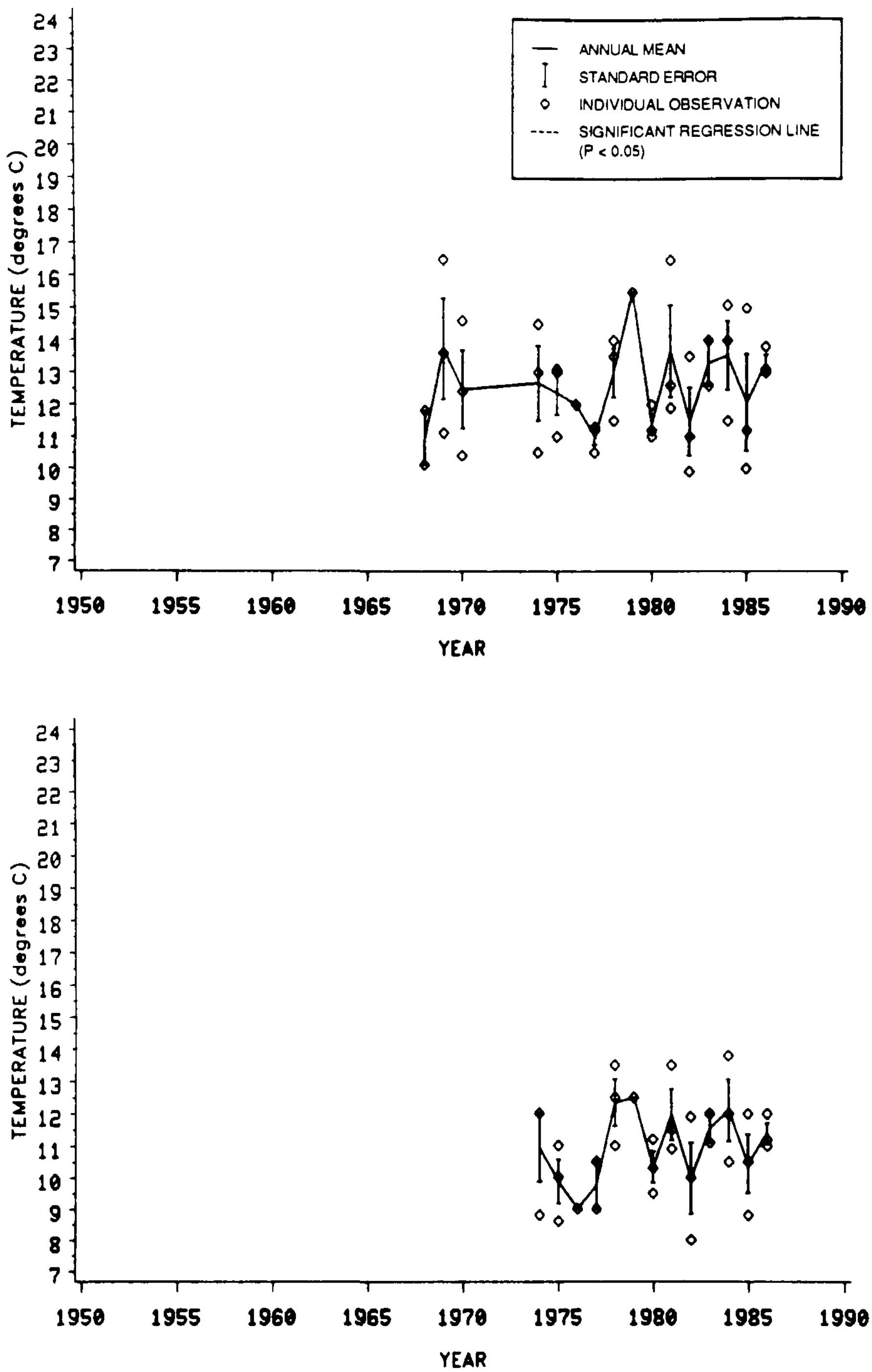


Figure 5.55. Water temperatures at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

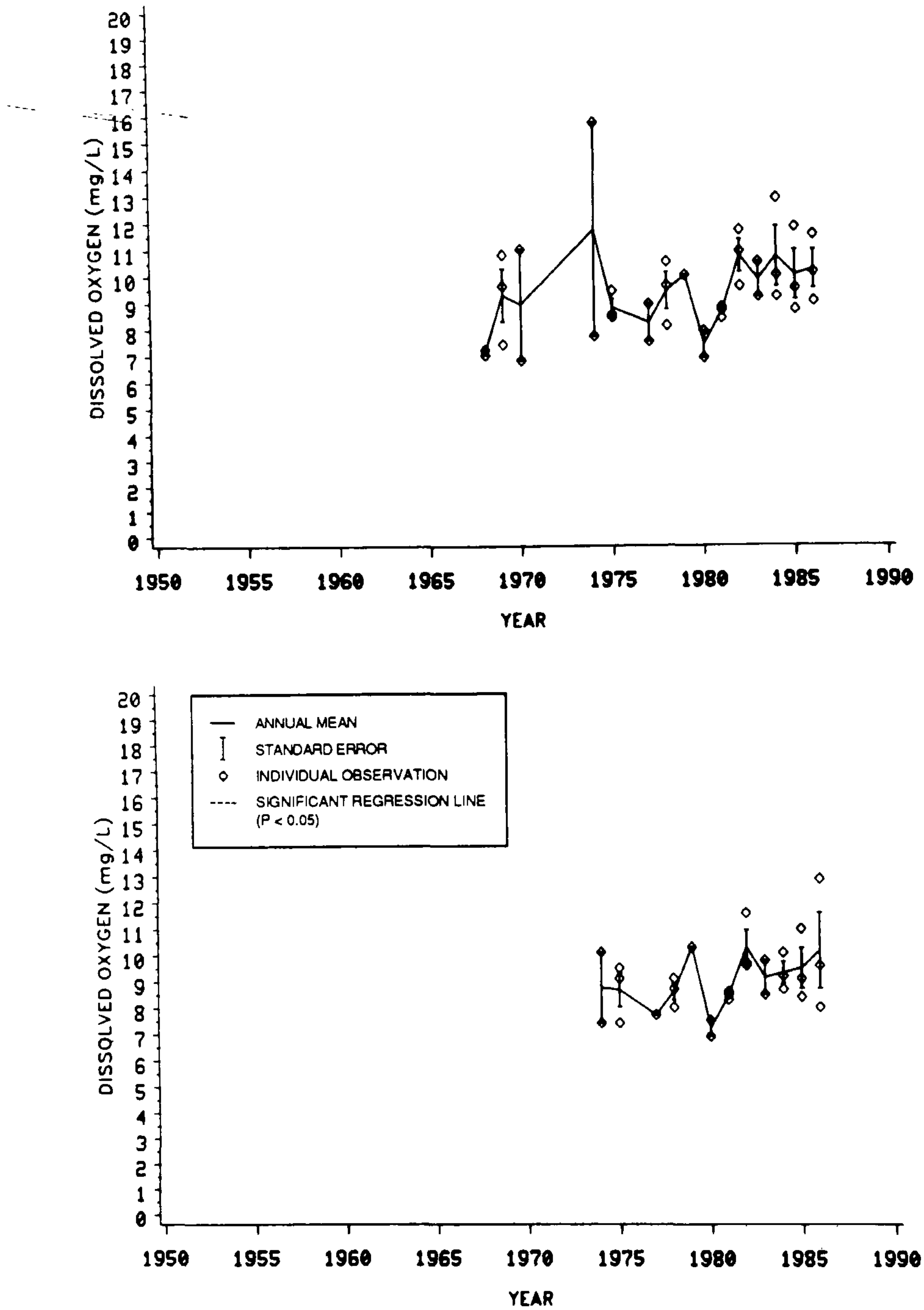


Figure 5.56. Concentrations of dissolved oxygen at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

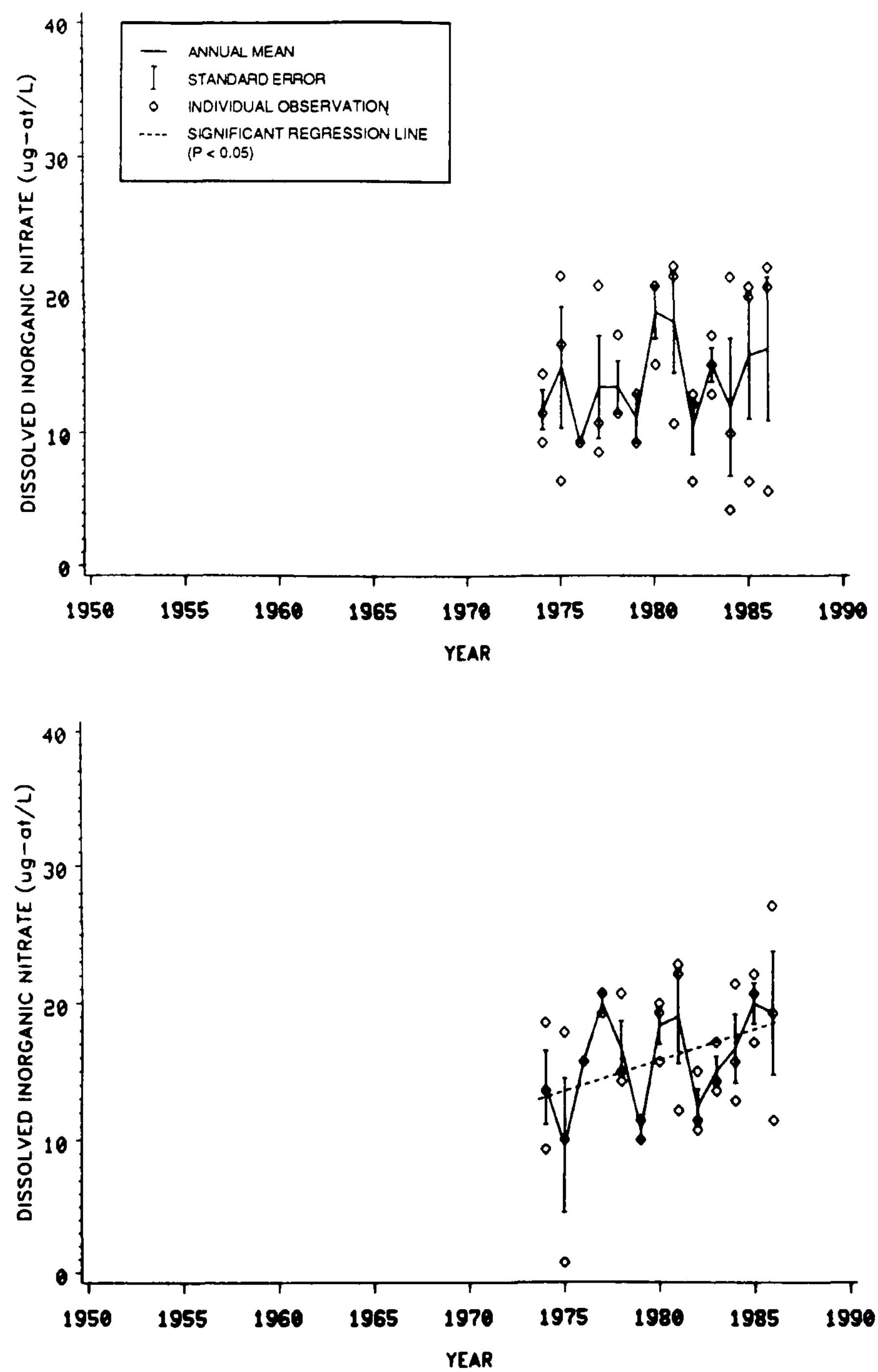


Figure 5.57. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

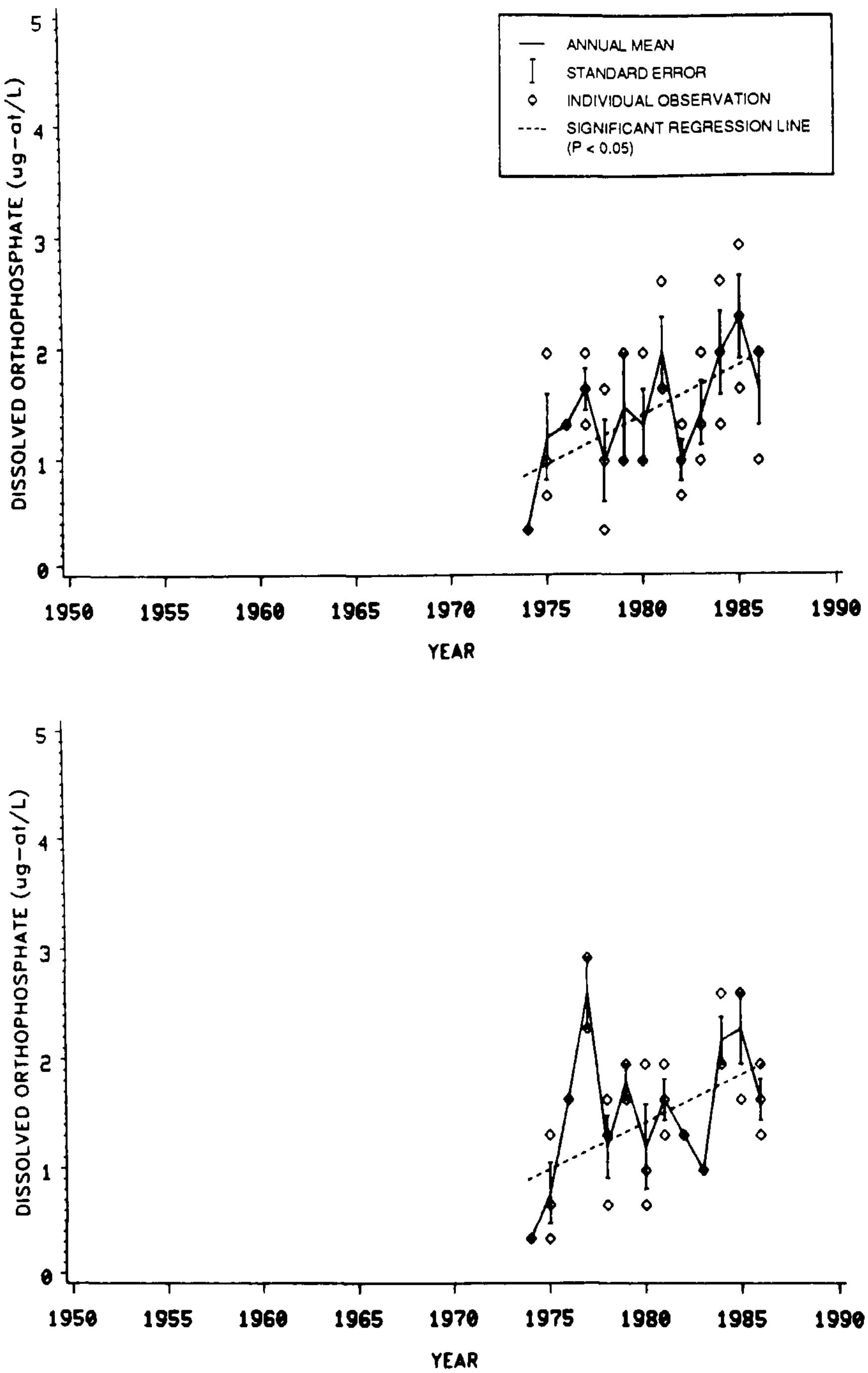


Figure 5.58. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

The cause(s) of the apparent increases in nutrient concentrations in the City Waterway study area are unknown. Possible contributing factors include increased nutrient loadings in runoff and in effluent from the Tacoma Central and North End Wastewater Treatment Plants. Also, the Simpson-Tacoma pulp mill has added phosphoric acid to their effluent since secondary effluent treatment was instituted in 1977 (Henry, C., 17 November 1987, personal communication). The increases in phosphate concentrations detected in City Waterway might have been influenced by this practice. Information to test these hypotheses is not available for this characterization study.

Indicators of Phytoplankton Growth--Chlorophyll *a* concentrations at the surface and 10-m depth are plotted by year in Figure 5.59. Plots of percent dissolved oxygen saturation at the surface and Secchi disk depth are plotted by year in Figure 5.60. No significant temporal trends were detected for any of these variables. Data on the concentration of chlorophyll *a* are only available since 1982. Although the changes in chlorophyll *a* concentrations were not statistically significant ($P>0.05$), high concentrations (up to 19 ug/L) were recorded at the surface in 1986. However, percent dissolved oxygen saturation at the surface and Secchi disk depth did not appear to be affected by the high concentrations of chlorophyll *a* in 1986. It appears that the elevation of chlorophyll *a* did not affect transparency or photosynthetic production of oxygen, at least at the time of sampling.

Pollutants--Plots of sulfite waste liquor concentration by year are shown in Figure 5.61. Statistically significant declines ($P<0.05$) were detected at both the surface and at 10-m depth (see Tables 5.7 and 5.8). As discussed above, kraft pulp mills do not discharge sulfite waste liquor. However, the Pearl Benson Index, which is used to detect sulfite waste liquor, also detects kraft wastes. Therefore, the declines in the Pearl Benson Index probably reflect the declines in waste discharges that occurred when the Simpson Tacoma Kraft plant adopted secondary waste treatment in 1977.

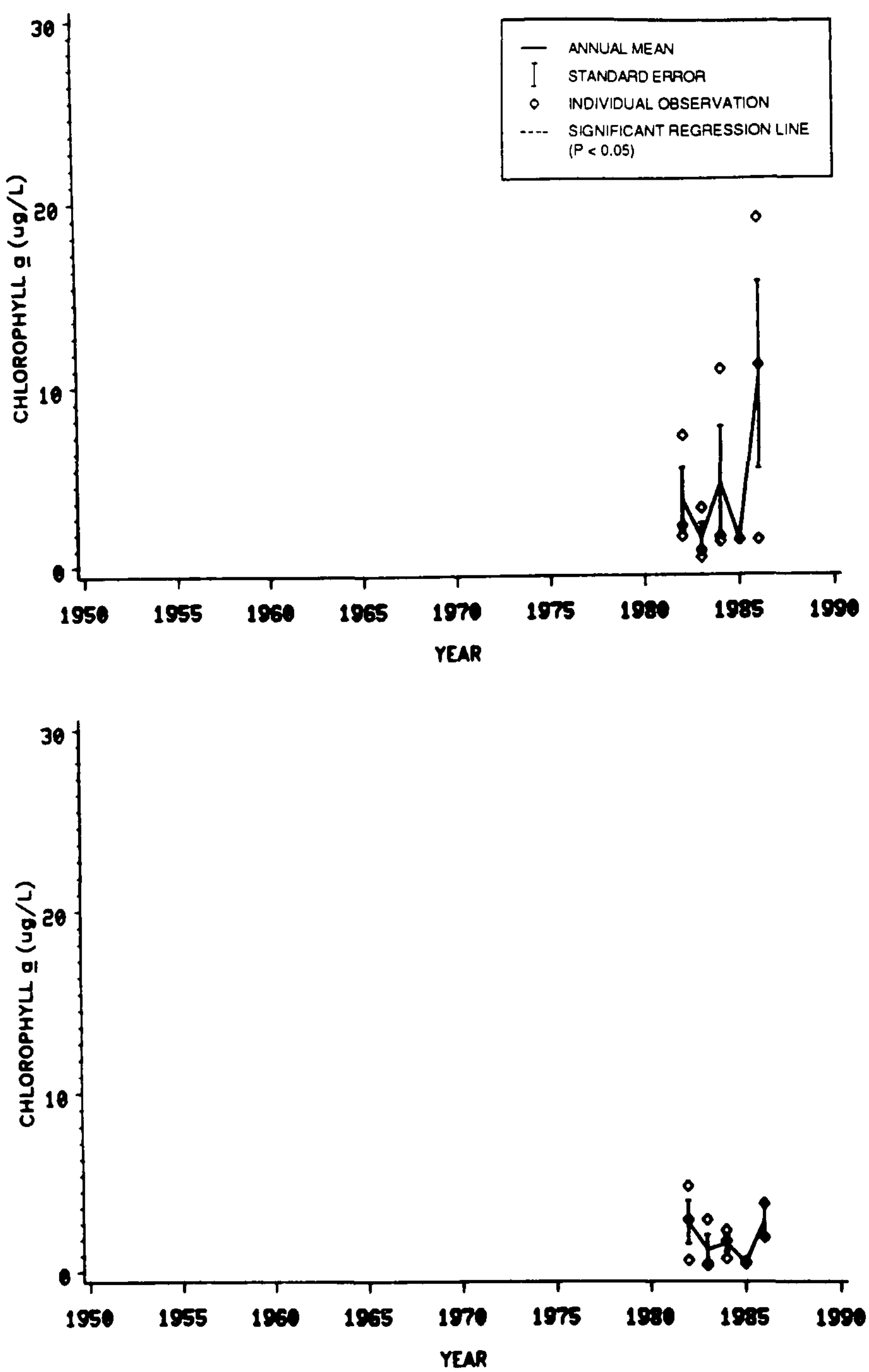


Figure 5.59. Concentrations of chlorophyll a at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

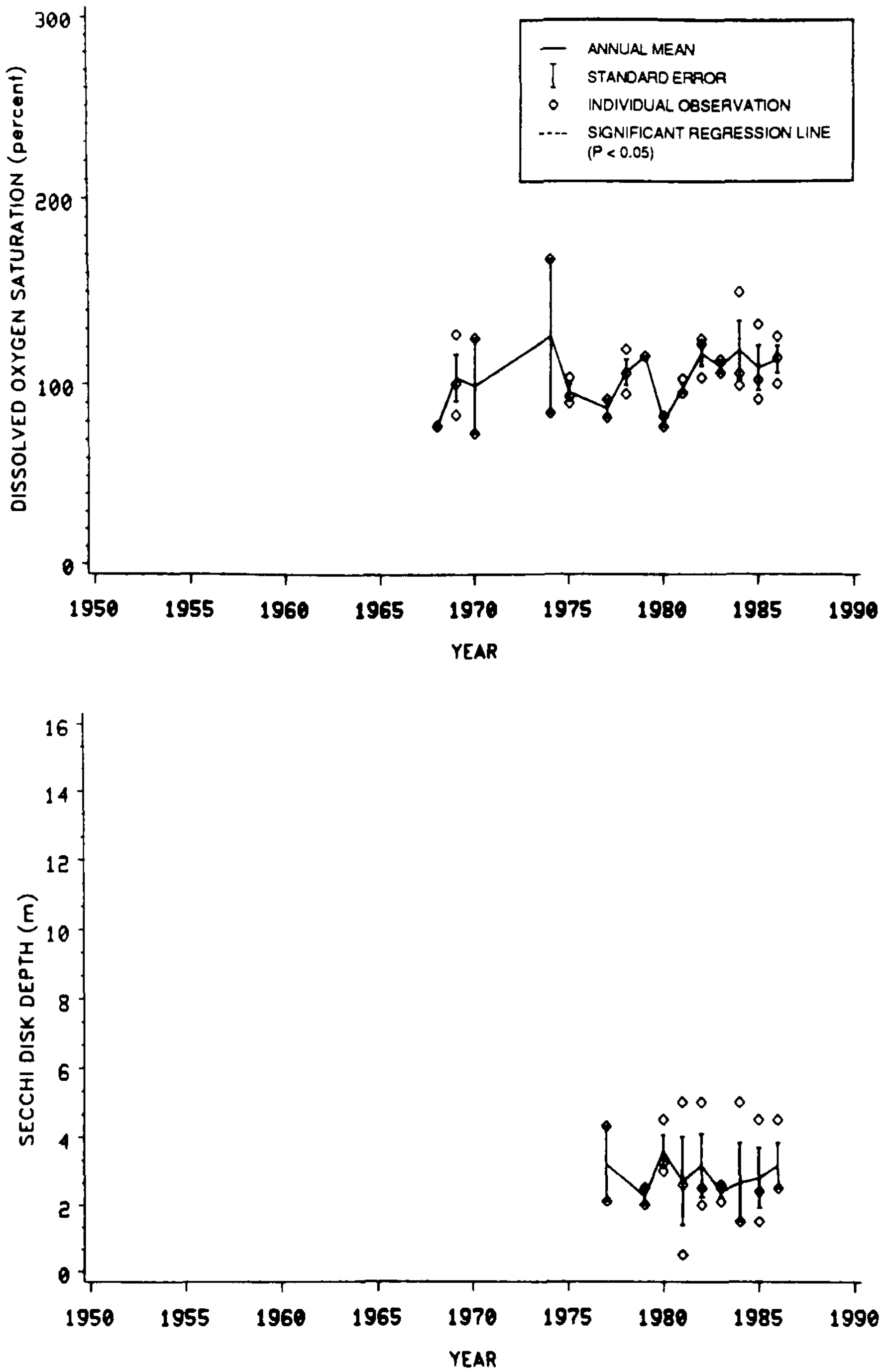


Figure 5.60. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the City Waterway study area during the algal bloom season.

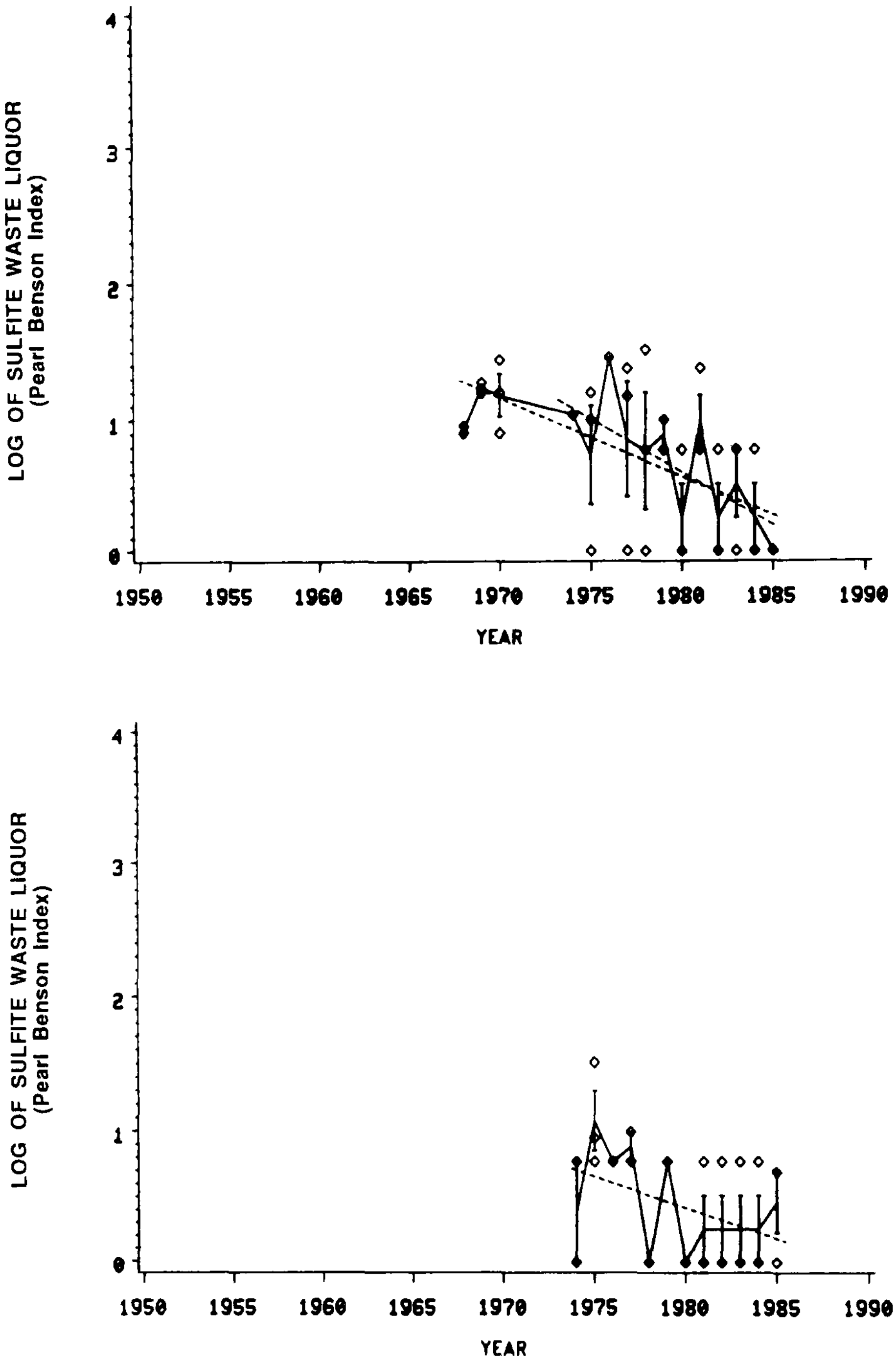


Figure 5.61. Log of concentrations of sulfite waste liquor at the surface and at 10-m depth in the City Waterway study area during the algal bloom season.

Concentrations of fecal coliform bacteria are plotted by year in Figure 5.62. No statistically significant ($P>0.05$) changes were detected. However, a few high concentrations (up to 1,000 organisms/100 mL) were recorded before 1981, some of which violated Class B water quality standards (Table 4.2). The absence of high concentrations of fecal coliform bacteria since 1981 may reflect the cessation of discharges of raw sewage through combined sewer overflows into City Waterway in 1979. In addition, improvements in the chlorination facilities at Tacoma's North End and Central Wastewater Treatment Plants were completed in 1982. The North End plant discharges along the southern shoreline of Commencement Bay at Ruston, while the Central plant discharges 2-km upstream in the Puyallup River (City of Tacoma 1983a,b).

Summary of Results for the Central Sound

This section summarizes the major findings of this report for the central sound. Environmental conditions in the study areas are summarized and compared. A brief assessment of the sensitivity of the central sound study areas to pollution is provided. Temporal trends in water quality are also summarized.

Environmental Conditions--

Salinity depth gradients were well developed in the study areas that have substantial sources of fresh water: Port Gardner and City Waterway. Salinity values at 10-m depth were similar in all four study areas (approximately 28.3 ppt). Substantial depth gradients of water temperature were present in all the central sound study sites. The thermal gradient was least developed at Point Jefferson, where vertical mixing rates were probably highest. Mean temperatures at both the surface (14.5^{o} C) and at 10-m depth (12.8^{o} C) were highest in the Sinclair Inlet site. The large thermal depth gradients at Sinclair Inlet and City Waterway suggest that mixing rates were lowest in those two areas.

Depth gradients of dissolved oxygen concentrations reflected differences in photosynthetic enhancement of dissolved oxygen in near-surface waters.

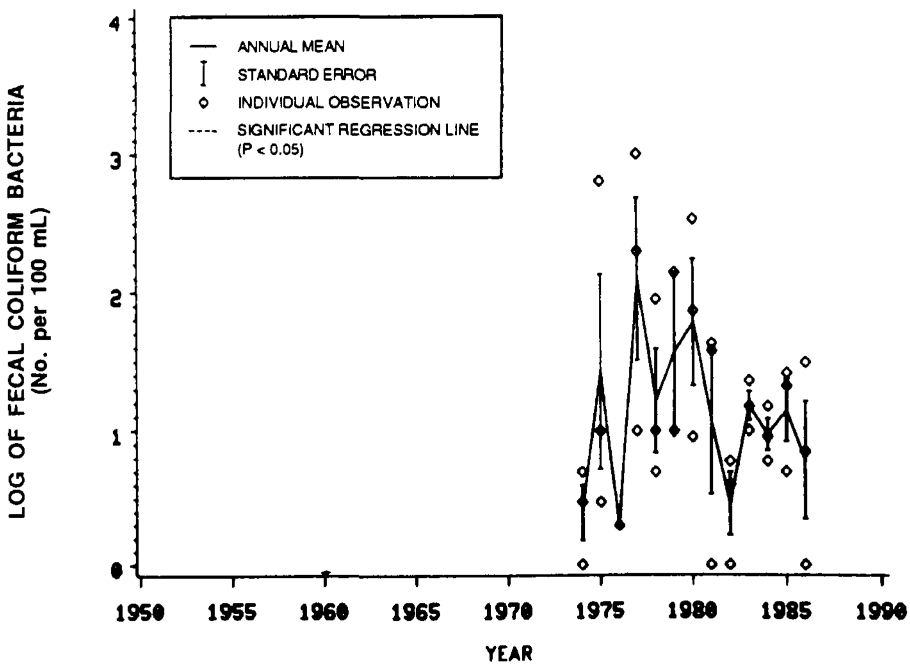


Figure 5.62. Log of concentrations of fecal coliform bacteria at the surface in the City Waterway study area during the algal bloom season.

The largest and smallest depth gradients of dissolved oxygen concentrations were detected at the Sinclair Inlet and City Waterway study areas, respectively. The differences between mean dissolved oxygen concentrations at the surface and at 10-m depth were 2.5 mg/L at the Sinclair Inlet site and 0.4 mg/L at the City Waterway site. The mean concentration of dissolved oxygen at 10-m depth was elevated at Point Jefferson (9.7 mg/L), possibly because the clarity of the water column was sufficient to allow substantial photosynthesis to occur at this depth.

Extremely low dissolved oxygen concentrations at depth were rarely observed. Dissolved oxygen concentrations averaged over 7 mg/L down to 200-m depth in the Point Jefferson area. Unfortunately, data from water deeper than 30 m were not available from the other central sound study areas. Problems with low dissolved oxygen concentrations at depth could have occurred in any of those areas. Sinclair Inlet had intense blooms, with low flushing and circulation rates. Die-off and decay of algal blooms could cause problems with low dissolved oxygen concentrations at depth in this area. City Waterway has low flushing rates and anoxic sediments near its head. Oxygen-demanding wastes could accumulate on the bottom of City Waterway, causing problems with low dissolved oxygen concentrations at depth. Port Gardner has somewhat better flushing than do Sinclair Inlet and City Waterway, but circulation along the bottom is slow, and large accumulations of organic matter from log yards and discharges from pulp mills have been found in the area in the past. Therefore, problems with low dissolved oxygen concentrations at depth also could occur in this area.

Nutrient data are available from the Port Gardner, Sinclair Inlet, and City Waterway study areas. Mean concentrations of nitrate were much lower in Sinclair Inlet than at the other sites, especially at the surface (e.g., less than one-fifth of the concentration of the City Waterway site). Geographic variation in phosphate concentrations was less conspicuous than the geographic variation in nitrate concentrations. The lower concentrations of nitrate in the Sinclair Inlet study area may have been due to the higher intensity of the algal blooms in this area (see below). The paucity of freshwater sources that drain into Sinclair Inlet may also have influenced the nitrate concentrations because rivers are a major source of nitrogen for Puget Sound (Robinson and Brown 1983). The largest depth gradients in phosphate concentrations were found at the Sinclair Inlet and Port Gardner sites. Phytoplankton blooms probably lowered phosphate concentrations near the surface, especially in Sinclair Inlet. The surface nutrient concentrations at the Port Gardner site were probably influenced by flows from the Snohomish River.

Based on the percent dissolved oxygen saturation in surface water, the intensity of algal blooms was greatest at the Sinclair Inlet site. Phytoplankton blooms at Point Jefferson were also well developed, while the blooms at Port Gardner and City Waterway were less intense. The limited chlorophyll a data indicated that these concentrations were higher in the Point Jefferson study area than in the City Waterway study area.

Because the transparency of surface water can be affected by phytoplankton density and by the concentration of suspended particulate material, geographic variation in Secchi disk depths was not consistent with the above interpretation of geographic variation in the intensity of algal blooms. Mean Secchi disk depths were lowest at the Port Gardner and City Waterway sites (<3 m), where blooms appeared to be least developed. Presumably, the Secchi disk depths in these two areas were influenced by suspended particulate material from the Snohomish and Puyallup Rivers. The high mean Secchi disk depth at Point Jefferson (4.7 m) probably reflected the absence of nearby large sources of fresh water and suspended particulates, rather than the absence of algal blooms, because Secchi disk depths and chlorophyll a concentrations were negatively correlated ($P<0.05$) in this area. Compared with the other central sound study areas, Secchi disk depths were intermediate in the Sinclair Inlet study area. This result also probably reflects the lack of sources of suspended particulate material from rivers and streams, rather than the intensity of algal blooms in the area.

Sensitivity to Nutrient Enrichment--

Based on inherent limitations in its capacity to export or assimilate pollutants without deleterious ecological effects, Sinclair Inlet is probably the most sensitive of the central sound study areas to impacts from excess nutrients. The intense blooms and low nitrate concentrations that occur at the Sinclair Inlet site suggest that further nutrient enrichment could increase the intensity of the algal blooms in the area. Because the flushing rate of Sinclair Inlet is quite low, the rate of export of pollutants from Sinclair Inlet also would be low.

City Waterway also may appear to be sensitive to the enhancement of algal blooms by nutrient enrichment, given its small volume and low flushing rate. However, intense blooms did not appear to develop in City Waterway. Bloom intensity in the study area may be limited by some factor other than nutrient concentrations, such as turbidity.

Point Jefferson probably has the best capacity of any central sound study area to export or assimilate nutrient inputs. The volume of water in this area and the lack of restrictions on water movements both facilitate assimilation (by dilution) and export of nutrients. However, because phytoplankton blooms were moderately well developed in the Point Jefferson study area, nutrient enrichment in this area might enhance bloom intensity. Unfortunately, sufficient nutrient data are not available from Point Jefferson site to determine whether low nutrient concentrations occurred during phytoplankton blooms in this area.

Based on both the volume and the exchange of water, the Port Gardner area appears to be less sensitive to the effects of nutrient enrichment than are the Sinclair Inlet and City Waterway areas. However, the Port Gardner area appears to be more sensitive to nutrient enrichment than the Point Jefferson area. Intense phytoplankton blooms did not appear to be prevalent in the Port Gardner area.

Trends in Water Quality--

The interpretation of the statistical data is summarized in Tables 5.7 and 5.8. A few interpretable patterns of environmental change were evident in the individual study areas within the central sound. Problems in interpretation caused by changes in station location and data sources only occurred in the Port Gardner study area. The most readily detected trends were changes in the concentrations of sulfite waste liquor in study areas near sulfite pulp mills.

Physical Conditions--The temporal trends in salinity values that were detected in the Port Gardner study area may have been artifacts of changed station locations. Average surface salinity values in the Point Jefferson study area appear to have been slightly higher since 1973 than from 1932 through 1972. However, subsurface salinity values appear to have been decreasing in the Point Jefferson area. The salinity data collected at the Point Jefferson area could have been affected by actual environmental changes and by artifacts in the data caused by differences in the analytical procedures used by the University of Washington and Metro. Salinity changes were not detected at the Sinclair Inlet or City Waterway sites, where data are available only since the late 1960s.

Temporal changes in water temperature at Port Gardner also appear to have been caused by changes in station locations. At Point Jefferson, surface temperature appears to have decreased slightly since 1973. However, increased temperatures have been detected at depths from 10 to 100 m since 1932. These temperature increases at depth at Point Jefferson may have been influenced by the cool period that occurred in the late 1940s and early 1950s.

Dissolved Oxygen--There was no substantial evidence that dissolved oxygen concentrations have changed in the central sound study areas. The only statistically significant ($P<0.05$) trend was a decline in the dissolved oxygen concentration at the surface in the Point Jefferson study area since 1973. However, this decline appears to have been caused by erratic variations in dissolved oxygen concentrations that by chance included some high values in the mid-1970s and some low values in 1986.

Nutrients--Substantial changes in nitrate concentrations were apparent in the Port Gardner and City Waterway study areas. (Unfortunately, nutrient data are not available from the Point Jefferson study area.) The apparent increase in nitrate concentrations at 10-m depth in City Waterway may be attributable to increased nutrient inputs. Alternatively, this increase may be attributable to erratic fluctuations in the data that introduced an apparent change into the data that did not reflect an underlying change in the environment. No explanation for the decline in nitrate concentrations at 10-m depth in the Port Gardner study area is known. This decline probably was not an artifact of changes in station location.

Decreases in phosphate concentrations since the 1950s were detected in the Port Gardner study area, the only central sound study area for which long-term data on phosphate concentrations are available. Increases in phosphate concentrations since the mid-1970s were detected in the Port Gardner, Sinclair Inlet, and City Waterway study areas. These three sites are in urban areas, suggesting that anthropogenic factors may have influenced the data. However, oceanic influences cannot be ruled out. The above study sites may have been affected by changes in nutrient inputs from point sources or runoff. Increased phosphate concentrations at Port Gardner may have been influenced by reductions in emissions of sulfite waste liquor in the area. At the City Waterway site, the apparent increase in phosphate concentrations might have reflected additions of phosphoric acid to the secondary effluent discharged by the Simpson-Tacoma Kraft mill. This mill adopted secondary effluent treatment in 1977. However, testing the above hypotheses was beyond the scope of this study. No explanation involving a point source is apparent for increased phosphate concentrations in the Sinclair Inlet study area.

Indicators of Phytoplankton Growth--Data on chlorophyll *a* concentrations are available for Point Jefferson from 1966 through 1975 and for City Waterway from 1982 through 1986. No temporal trends in chlorophyll *a* concentrations were detected at either site. At Point Jefferson, percent dissolved oxygen saturation at the surface has declined recently, while Secchi disk depths have increased recently. These results suggest that algal production has declined in the Point Jefferson area. However, these temporal changes in oxygen saturation and Secchi disk depth were not well developed in the data. Thus, the determination of whether the apparent decline in primary production at Point Jefferson reflected short-term variation within the normal range, or the beginning of a long-term trend must await future studies.

Pollutants--Declines in the concentrations of sulfite waste liquor were detected at Port Gardner and at the mouth of City Waterway. Data on this variable are not available from Point Jefferson. The decline in the Port Gardner study area appeared to coincide with improvements in effluent treatment by the local pulp mills. The sulfite waste liquor declines detected in City Waterway could have been related to improvements in the effluent treatment by the Simpson-Tacoma Kraft mill. This mill has never discharged sulfite waste liquor. However, kraft effluent from this mill may contain material that is detected by the Pearl Benson Index test.

The only statistically significant ($P<0.05$) change that was detected in concentrations of fecal coliform bacteria was an apparent increase that occurred in the Port Gardner study area since 1981. This increase coincided with the initiation of secondary effluent treatment by the Scott sulfite pulp mill at Port Gardner. The organism detected in the fecal coliform tests in this area probably was the bacterium, Klebsiella. This organism grows rapidly in the secondary effluent treatment facilities of sulfite pulp mills. Thus, the apparent increases in the concentrations of fecal coliform bacteria in the Port Gardner area probably reflected secondary treatment by the Scott mill, rather than increased contamination from sewage effluent.

SOUTHERN SOUND

The South Sound is defined herein as all of Puget Sound upstream of Tacoma Narrows (see Figure 2.1). This region of Puget Sound (exclusive of Hood Canal) is the most removed from direct oceanic influences. Most of the region is relatively shallow and poorly flushed. Numerous shallow embayments and large islands are present. The southern sound contains 16 percent of the surface area, 29 percent of the shoreline, and 21 percent of the tidelands of Puget Sound, but only 9 percent of the volume of Puget Sound south of Admiralty Inlet (Burns 1985). Population centers are the Cities of Olympia and Shelton, located on Budd Inlet and Oakland Bay, respectively. Most of the remaining southern sound region is sparsely populated.

Five study areas were located in the South Sound: Carr Inlet, Nisqually Reach, Budd Inlet, Totten Inlet, and Oakland Bay. Station locations are shown in Figure 5.63; data sources are given in Table 5.9. Algal bloom seasons for the study sites are given in Table 5.10. Histograms summarizing the water quality variables are given in Figures 5.64-5.68. Back-up tables of the summary data are given in Appendix E. The ANOVAs comparing the water quality variables before and after 1973 are summarized in Table 5.11. Long-term and recent regressions are summarized in Table 5.12.

With the exception of Nisqually Reach, the study areas in the southern sound are located in sheltered embayments. Because of a limited capacity to assimilate or export contaminants, these areas may be vulnerable to deleterious effects of pollution. Carr Inlet is relatively deep, averaging about 92 m deep. Budd Inlet, Totten Inlet, and Oakland Bay are shallower than Carr Inlet. The depth of Oakland Bay is less than 5 m over much of its area. Although Nisqually Reach is in the main channel of the South Basin, it is near a sill that is about 36 m deep. Circulation is sluggish in the four embayments, but it is more rapid and turbulent at Nisqually Reach.

Based on the percent dissolved oxygen saturation at the surface, algal blooms were most prevalent in the southern sound study areas from May through August. However, in Oakland Bay the algal blooms were best developed from April through June (see Table 5.10). Algal blooms appear to have been more intense in Carr, Budd, and Totten Inlets, and less intense in Oakland Bay and Nisqually Reach.

Carr Inlet

The study area is located approximately half way up the axis of Carr Inlet, off Green Point (Figure 5.63). The region is rural, and sometimes serves as a reference area for studies of contaminated urban bays (e.g., Tetra Tech 1985). Class AA water quality standards apply in the area (Table 4.2). Because Carr Inlet is a deep (approximately 92 m) embayment, tidal flushing is slower than in the shallower southern embayments, such as Budd Inlet (URS 1986b). The study area has no nearby source of fresh water. Net current velocities are low in the study area (e.g., 0.6 cm/sec at 5-m

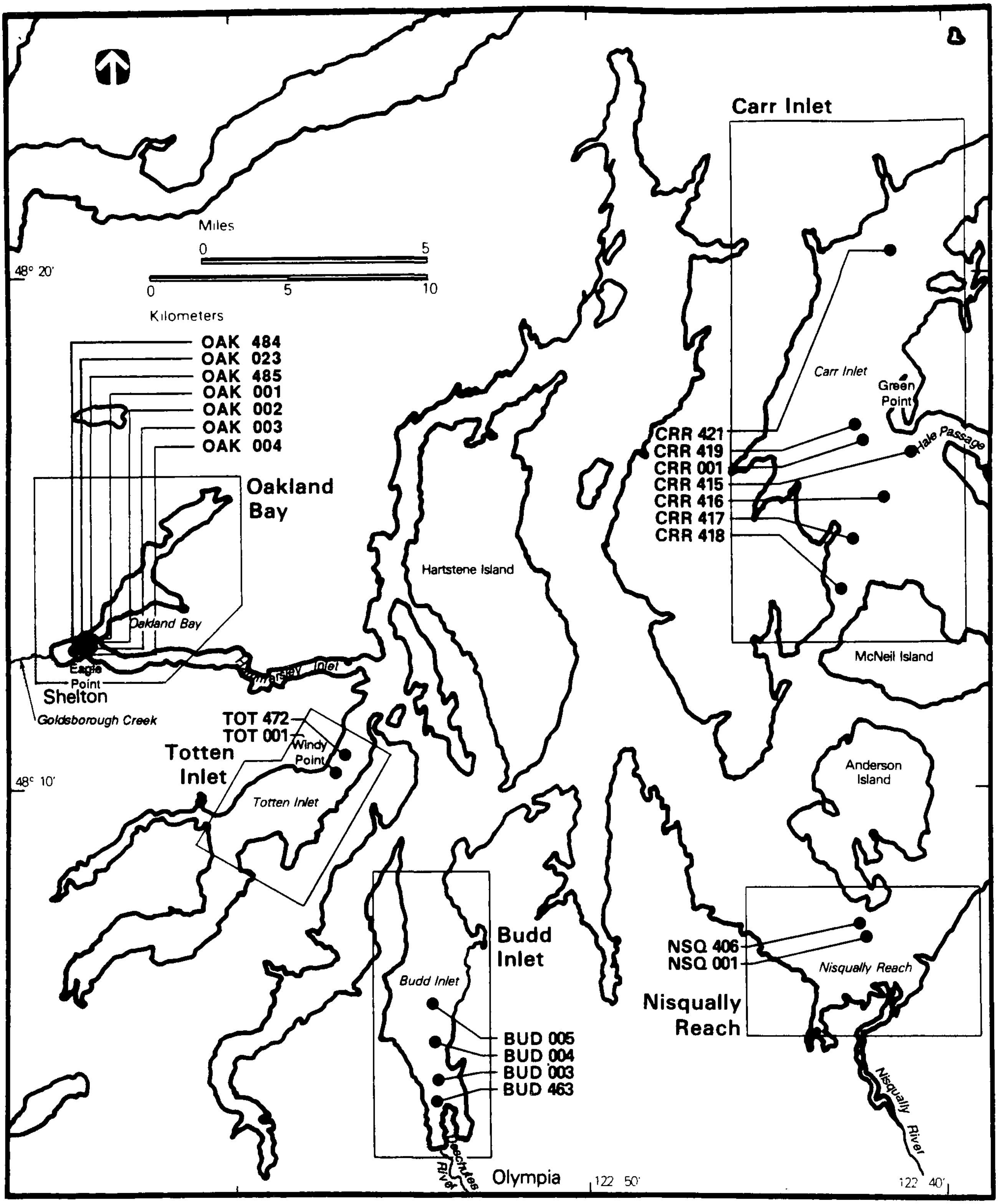


Figure 5.63. Locations of study areas and sampling stations in the southern sound.

TABLE 5.9. SAMPLING STATION NUMBERS, DATA SOURCES, AND TIME PERIODS FOR THE STUDY AREAS IN THE SOUTHERN SOUND

Study Area	Station Number	Data Source	Sampling Period
Carr Inlet	CRR415	UW[a]	1954-55
	CRR416	UW	1954-62
	CRR417	UW	1954-55
	CRR418	UW	1954-55
	CRR419	UW	1935-41, 1950-67
	CRR421	UW	1953-62
	CRR001	Ecology	1967-70, 1977-86
Nisqually Reach	NSQ406	UW	1932-41, 1949-62
	NSQ001	Ecology	1967-70, 1977-86
Budd Inlet	BUD463	UW	1957-58
	BUD003	Ecology	1967-70, 1973-77
	BUD004	Ecology	1967-70, 1976-77
	BUD005	Ecology	1967-70, 1973-86
Totten Inlet	TOT472	UW	1956-60 (includes data from WDF[b])
	TOT001	Ecology	1967-70, 1977-86
Oakland Bay	OAK484	UW	1956-57 (includes data from WDF)
	OAK485	UW	1956-58 (includes data from WDF)
	OAK001	Ecology	1967-70
	OAK002	Ecology	1967-70
	OAK003	Ecology	1967-70
	OAK004	Ecology	1967-70, 1975, 1978-86
	23	WDF	1964-71

[a] UW = University of Washington.

[b] WDF = Washington Department of Fisheries.

TABLE 5.10. ALGAL BLOOM SEASONS FOR THE SOUTHERN SOUND STUDY AREAS, AS DEFINED BY MONTHLY MEAN AND STANDARD ERROR OF PERCENT DISSOLVED OXYGEN SATURATION IN SURFACE WATER

	Percent Dissolved Oxygen Saturation				
Month	Carr Inlet	Nisqually Reach	Budd Inlet	Totten Inlet	Oakland Bay
April	105 +/- 3	96 +/- 3	107 +/- 2	102 +/- 2	102 +/- 1[a]
May	141 +/- 5[a]	107 +/- 4[a]	131 +/- 8[a]	121 +/- 4[a]	105 +/- 3[a]
June	121 +/- 4[a]	103 +/- 2[a]	115 +/- 5[a]	114 +/- 4[a]	104 +/- 6[a]
July	126 +/- 4[a]	103 +/- 3[a]	117 +/- 6[a]	113 +/- 3[a]	96 +/- 4
August	123 +/- 7[a]	117 +/- 8[a]	121 +/- 6[a]	117 +/- 4[a]	92 +/- 3
September	116 +/- 5	91 +/- 4	111 +/- 10	106 +/- 3	83 +/- 3

[a] Months included in the algal bloom season.

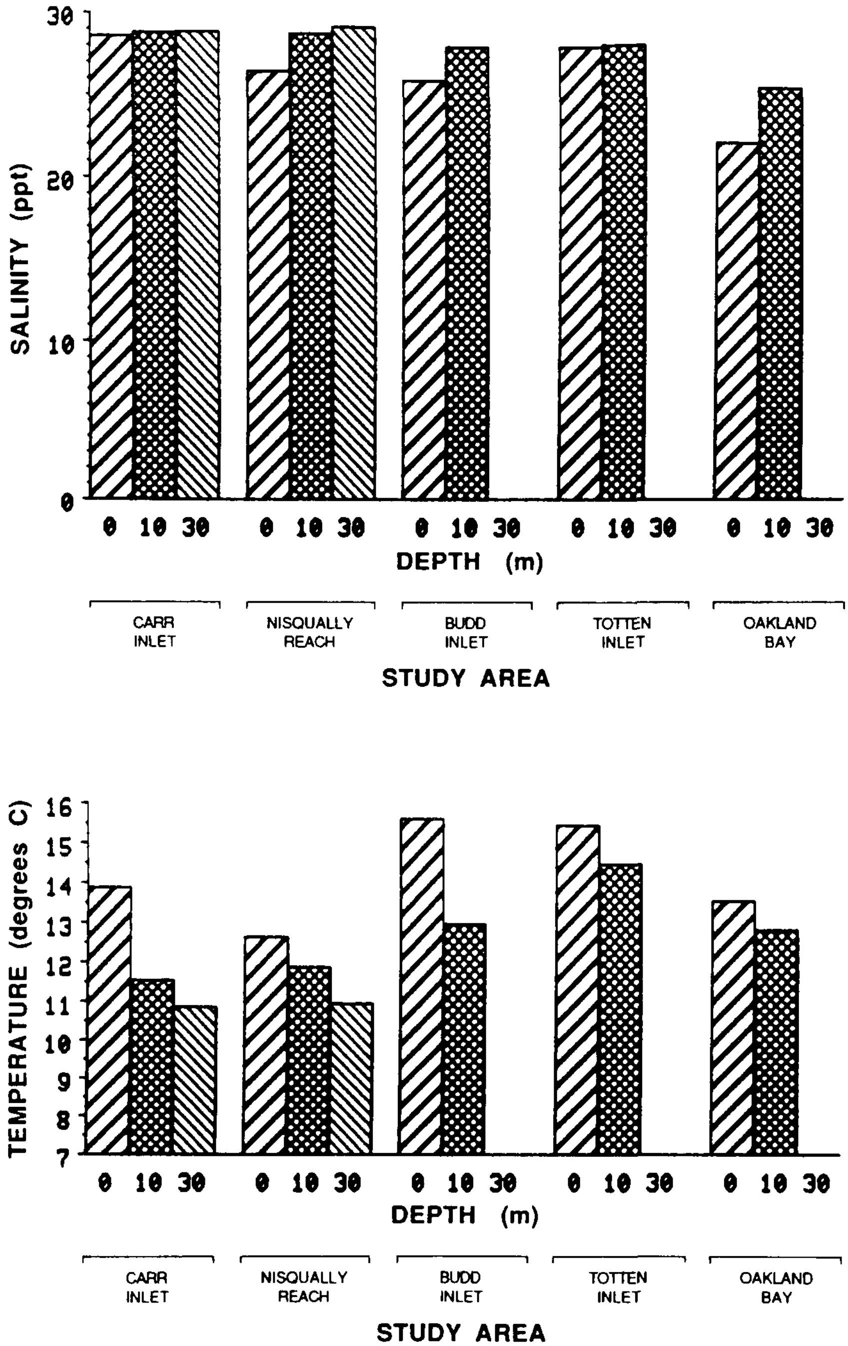


Figure 5.64. Mean salinity and water temperature values in the southern sound study areas during the algal bloom season.

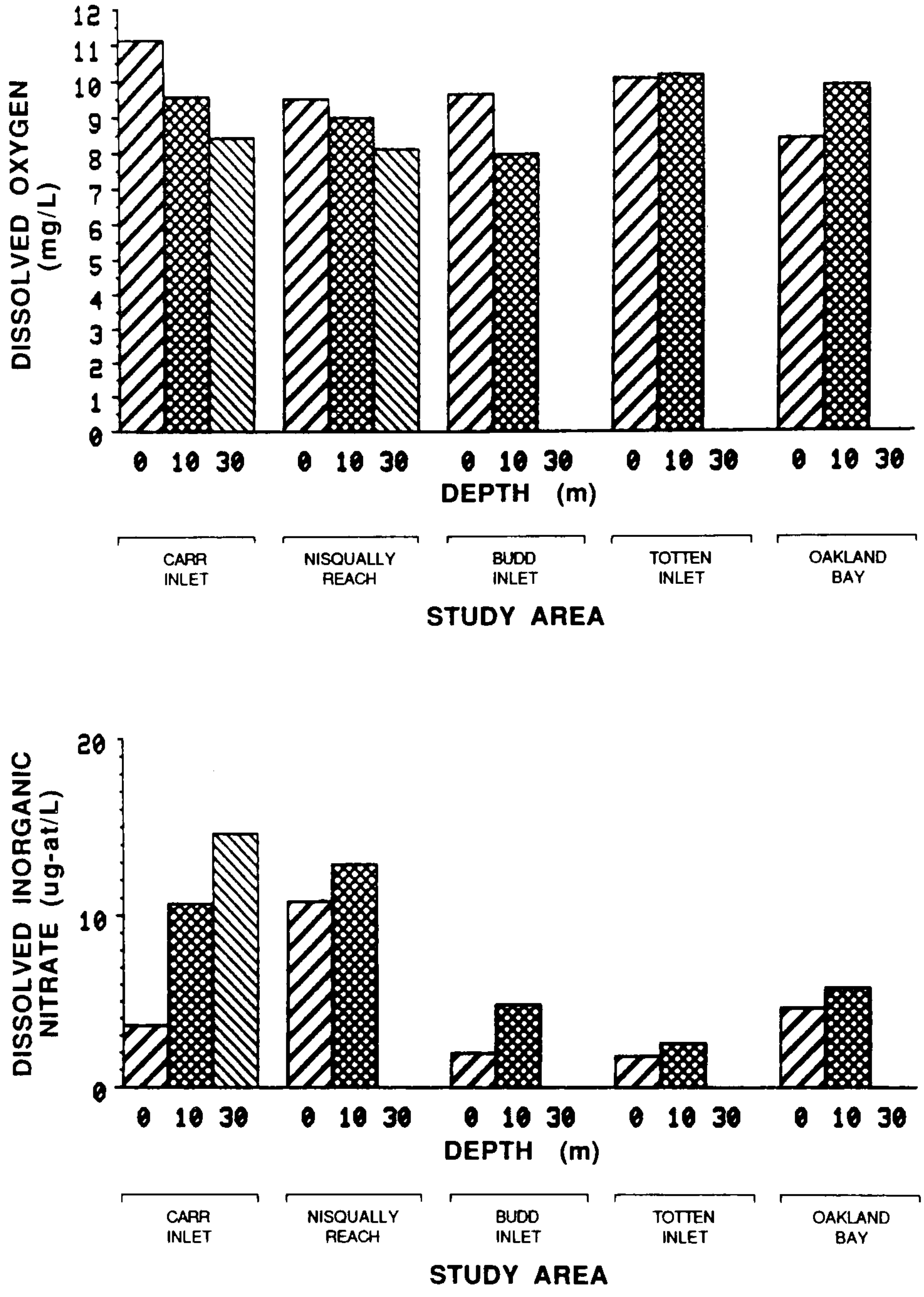


Figure 5.65. Mean concentrations of dissolved oxygen and dissolved inorganic nitrate in the southern sound study areas during the algal bloom season.

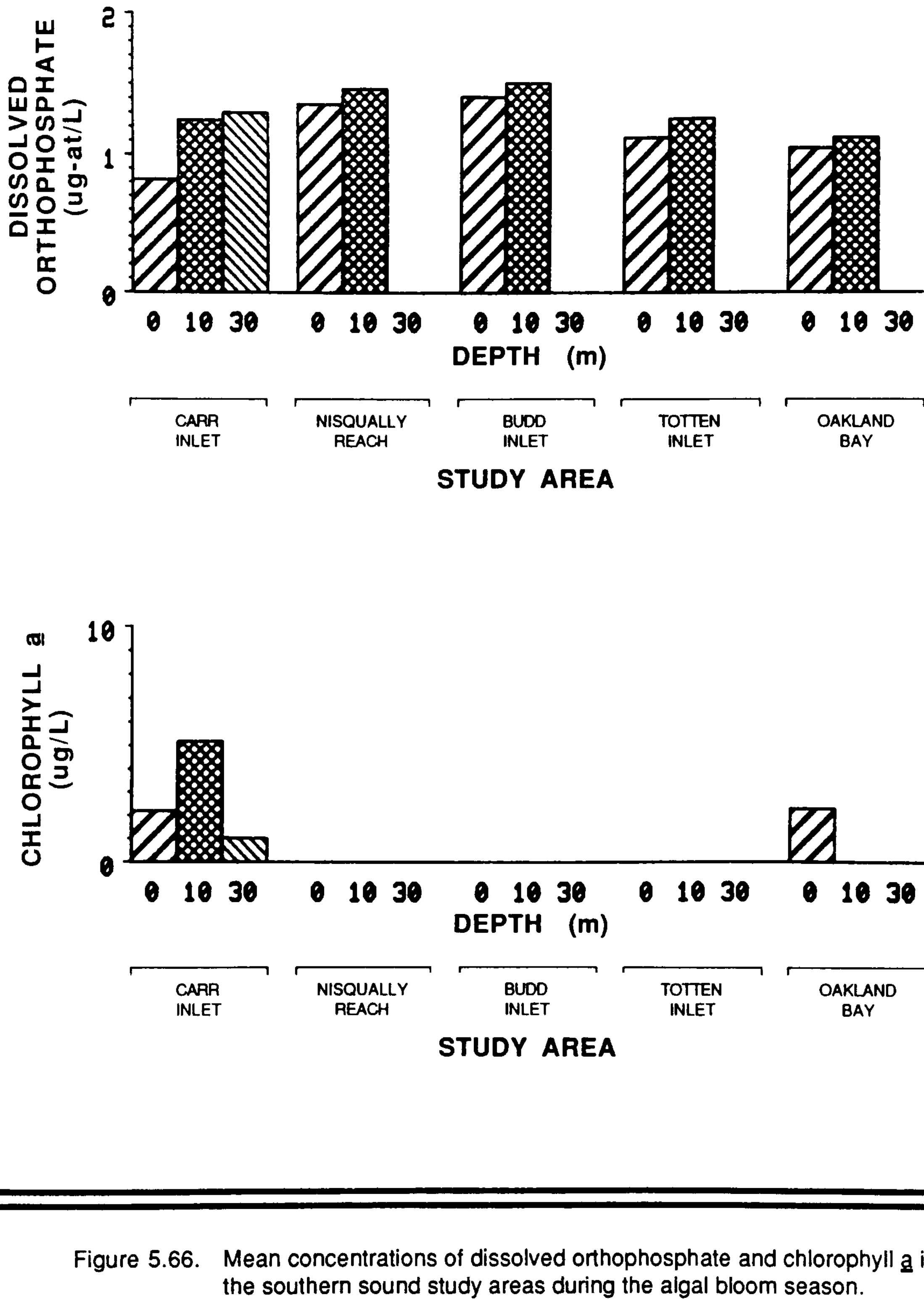
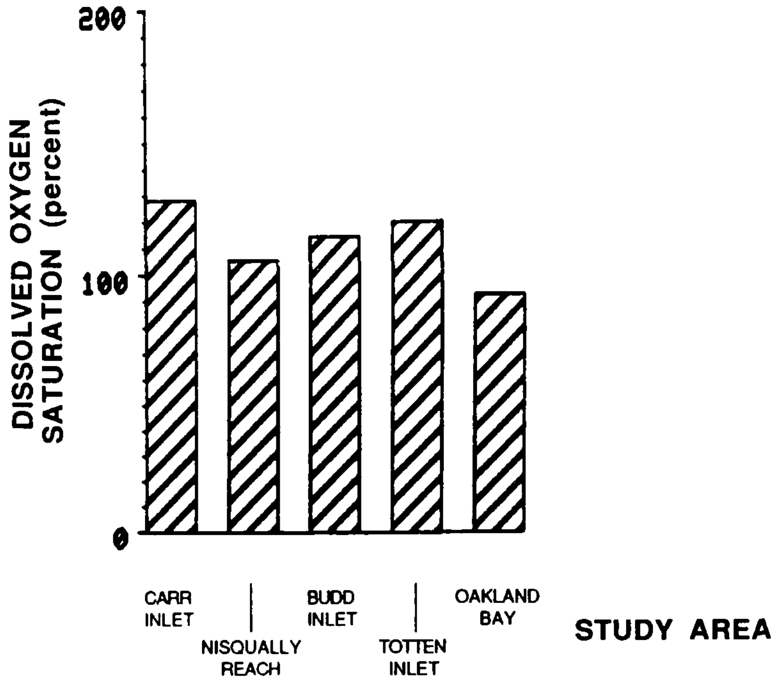


Figure 5.66. Mean concentrations of dissolved orthophosphate and chlorophyll a in the southern sound study areas during the algal bloom season.



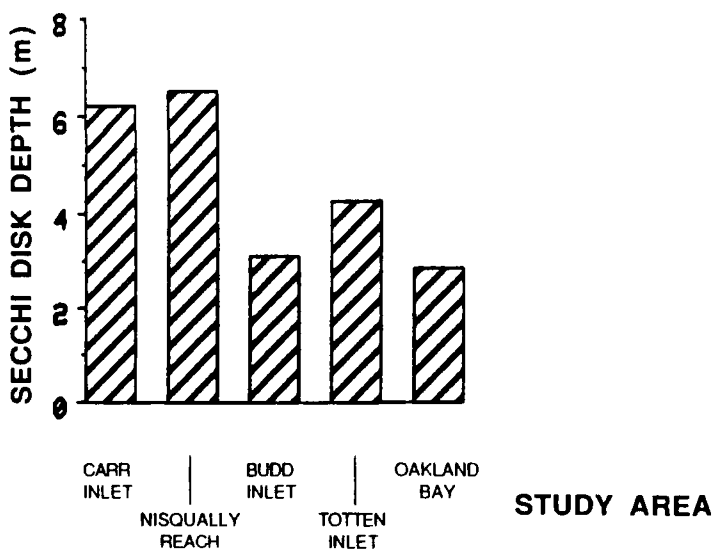


Figure 5.67. Mean percent dissolved oxygen saturation at the surface and Secchi disk depth in the southern sound study areas during the algal bloom season.

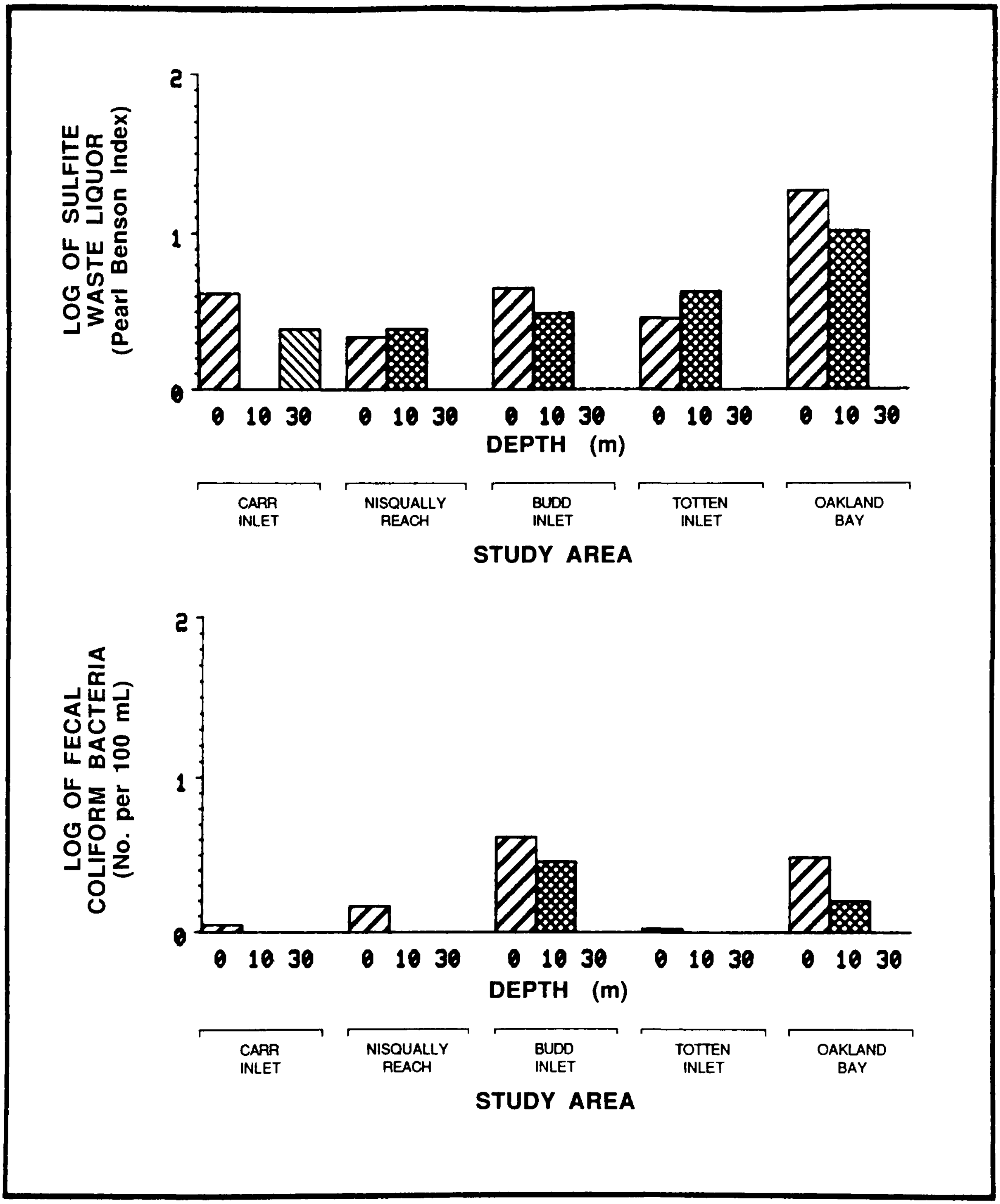


Figure 5.68. Log of geometric mean concentrations of sulfite waste liquor and fecal coliform bacteria in the southern sound study areas during the algal bloom season.

TABLE 5.11. NET CHANGE AND PERCENT CHANGE IN THE MEAN VALUES OF WATER QUALITY VARIABLES IN THE SOUTHERN SOUND, BASED ON ANOVA COMPARISONS OF DATA TAKEN BEFORE 1973 WITH DATA TAKEN FROM 1973 TO 1986

Depth (m)	Carr Inlet Change Net	Carr Inlet Change Percent	Nisqually Reach Change Net	Nisqually Reach Change Percent	Budd Inlet Change Net	Budd Inlet Change Percent	Totten Inlet Change Net	Totten Inlet Change Percent	Oakland Bay Change Net	Oakland Bay Change Percent
Salinity (ppt)										
0	-0.39	1.4	-1.49	5.5	NS[a]	-	NS		NS	
10	-0.38	1.3	-0.50	1.7	na[b]		NS		na	
30	-0.42	1.4	na		na	-	na		na	
Water Temperature (^{o} C)										
0	+1.51	11.4	+1.14	9.4	-1.97	11.6	NS		NS	
10	+1.12	10.1	+0.90	8.0	na	-	NS		na	
30	+1.16	11.3	na		na		na	-	na	
Dissolved Oxygen (mg/L)										
0	NS		NS		+1.39	16.2	NS		+1.80	23.1
10	NS		+0.67	7.8	na		NS		na	
30	NS		na		na		na		na	
Nitrate (ug-at/L)										
0	na		na		na		na		NS	
10	na		na		na		na		na	
30	na		na		na	-	na		na	
Phosphate (ug-at/L)										
0	NS		NS		-0.68	32.5	-0.54	32.5	-0.60	36.2
10	-0.23	15.5	NS		na		-0.48	27.6	na	
30	-0.61	31.9	na		na		na		na	
Chlorophyll <u>a</u> (ug/L)										
0	na		na		na		na		na	
10	na		na		na	-	na		na	
30	na		na		na		na		na	
Surface Dissolved Oxygen Saturation (Percent)										
0	NS		+6.87	6.7	NS		NS	-	+23.24	27.3
Secchi Disk Depth (m)										
	NS		na		NS		NS		NS	
Sulfite Waste Liquor (Pearl Benson Index)										
0	na		na		NS		na	-	NS	
10	na		na		na		na		na	
30	na		na		na	-	na	-	na	
Fecal Coliform Bacteria (No./100 mL)										
0	na		na		na	-	na		na	
10	na		na		na		na		na	
30	na		na		na	-	na		na	

[a] NS = The pre-1973 and 1973-1986 values were not significantly different at P<0.05, based on a nonparametric one-way ANOVA.

[b] na Results of the statistical test were not available because of a lack of data.

TABLE 5.12. SLOPES OF STATISTICALLY SIGNIFICANT LONG-TERM AND RECENT REGRESSIONS OF WATER QUALITY VARIABLES AS A FUNCTION OF YEAR FOR THE SOUTHERN SOUND

Depth (m)	Slopes: Carr Inlet Long-term	Carr Inlet Recent	Nisqually Reach Long-term	Nisqually Reach Recent	Budd Inlet Long-term	Budd Inlet Recent	Totten Inlet Long-term	Totten Inlet Recent	Oakland Bay Long-term	Oakland Bay Recent
					Salinity (ppt)					
0	-0.017	-0.067	-0.046	NS[a]	NS	0.242	-0.013	NS	0.131	NS
10	-0.014	NS	-0.015	NS	NS	NS	NS	NS	na	NS
30	-0.016	NS	na[b]	na	na	na	na	na	na	na
					Water Temperature (° C)					
0	0.050	NS	NS	NS	NS	NS	NS	NS	NS	NS
10	0.031	NS	NS	NS	NS	NS	NS	NS	na	NS
30	0.032	NS	na	na	na	na	na	na	na	na
					Dissolved Oxygen (mg/L)					
0	NS	0.291	NS	0.267	0.105	0.245	NS	NS	0.135	NS
10	NS	0.306	0.022	NS	NS	NS	NS	0.285	na	NS
30	0.024	0.303	na	na	na	na	na	na	na	na
					Nitrate (ug-at/L)					
0	na	-0.687	na	NS	na	NS	na	NS	NS	NS
10	na	NS	na	NS	na	NS	na	NS	na	NS
30	na	NS	na	na	na	na	na	na	na	na
					Phosphate (ug-at/L)					
0	NS	NS	NS	NS	NS	NS	-0.021	NS	-0.023	0.051
10	NS	NS	NS	NS	na	NS	-0.018	NS	na	0.065
30	-0.020	NS	na	na	na	na	na	na	na	na
					Chlorophyll a (ug/L)					
0	na	na	na	na	na	na	na	na	NS	na
10	na	na	na	na	na	na	na	na	na	na
30	na	na	na	na	na	na	na	na	na	na
					Surface Dissolved Oxygen Saturation (Percent)					
0	NS	3.457	NS	2.921	1.190	3.154	NS	NS	1.565	NS
					Secchi Disk Depth (m)					
-	NS	-0.481	na	NS	NS	0.177	NS	NS	NS	0.117
					Sulfite Waste Liquor[c] (Pearl Benson Index)					
0	na	na	na	na	NS	NS	NS	na	-0.041	na
10	na	na	na	na	NS	NS	na	na	na	na
30	na	na	na	na	na	na	na	na	na	na
					Fecal Coliform Bacteria[d] (No./100 mL)					
0	na	-0.019	na	-0.038	na	-0.095	na	NS	na	NS
10	na	na	na	na	na	na	na	na	na	na
30	na	na	na	na	na	na	na	na	na	na

[a] NS = Not significant at $P<0.05$.

[b] na = Results of the statistical test were not available because of a lack of data.

[c] Data were subjected to a log(X+1) transformation for the regressions.

[d] Data were subjected to a log transformation for the regressions.

depth) (NOAA 1984b). Current velocities in other regions of Carr Inlet, where tidal flows are restricted (e.g., Hale Passage), are 1 order of magnitude higher than those in the study area. The Nisqually River contributes approximately 5 percent of the annual river flow into Puget Sound and is the largest river entering the southern sound. The Nisqually River discharges about 14 km southwest of the mouth of Carr Inlet. When large volumes are discharged due to snowmelt during the late spring (USGS 1985), southerly winds may occasionally force Nisqually River water northward into Carr Inlet (Duxbury, A.C., 15 October 1987, personal communication).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.64. Data are available from 1950 through 1986, with the best coverage during the mid-1950s and from 1977 through 1986. Substantial vertical stratification of water temperature was evident, as indicated by the temperature gradient (mean water temperature value was approximately 2.3^{o} C higher at the surface than at 10-m depth). The vertical salinity gradient was small (mean salinity value was approximately 0.2 ppt lower at the surface than at 10-m depth), presumably because no substantial source of fresh water is near the study area. The steepness of the vertical gradient of water temperature suggests that rates of vertical mixing are low in the study area. The stability of the water column during the bloom season suggests that algal blooms could become well developed in Carr Inlet.

The vertical distribution of concentrations of dissolved oxygen and nutrients in Carr Inlet appears to have been strongly influenced by stability of the water column during the algal bloom season. Mean values of dissolved oxygen concentrations were 11.1 mg/L at the surface and 9.6 mg/L at 10-m depth (Figure 5.65). Dissolved oxygen concentrations were above 100 percent saturation at both the surface and 10-m depth (Figure 5.67 and Appendix E). Nutrient concentrations were much lower at the surface than at 10- or 30-m depths (e.g., mean values of nitrate concentrations were 3.6 ug-at/L at the surface and 10.7 ug-at/L at 10-m depth) (Figures 5.65 and 5.66). The negative correlations between nutrient concentrations and percent dissolved oxygen saturation presumably were due to the enhanced uptake of nutrients in the surface waters during algal blooms, and the reduced uptake of nutrients at depth where algal blooms were not well developed. Positive correlations between phosphate concentrations and salinity values at the surface and at 30-m depth may have been caused by the following two factors: 1) high phosphate concentrations can occur during occasional periods of high salinity when the water column is unstable and deeper, high-phosphate water is advected toward the surface, and 2) low phosphate concentrations can occur during algal blooms, when density stratification causes vertical exchange rates to be low, allowing near-surface nutrient concentrations to fall. Occasional upwelling may also explain the negative correlations between dissolved oxygen concentrations and both salinity and water temperature values at 10- and 30-m depths (i.e., upwelled water would be high in salinity and phosphate, but low in temperature and dissolved oxygen).

High values for percent saturation of dissolved oxygen in the surface waters support the interpretation that intense algal blooms occurred in the Carr Inlet study area (Figure 5.67). Based on a very limited data set, chlorophyll _a_ concentrations appear to have been highest at 10-m depth (Figure 5.66). Mean Secchi disk depth was over 6 m (Figure 5.67), which also suggests that high phytoplankton concentrations occurred below the surface. The data for mean Secchi disk depth also suggest that the photic zone averaged over 12 m deep (Preisendorfer 1986). Although the negative correlation ($r=-0.52$) between Secchi disk depth and percent dissolved oxygen saturation at the surface was not significant ($P=0.07$) when scaled with the Bonferroni inequality, the magnitude of this correlation coefficient suggests that Secchi disk depths were influenced by the intensities of algal blooms.

As would be expected for a rural site, the concentrations of the pollutants analyzed in this study were low in the study area (Figure 5.68). The geometric mean value for the concentration of sulfite waste liquor at the surface was only 3.6 (Pearl Benson Index). The geometric mean value for the concentration of fecal coliform bacteria at the surface was 1.1 organism/100 mL. This mean value is only 10 percent above the analytical detection limit.

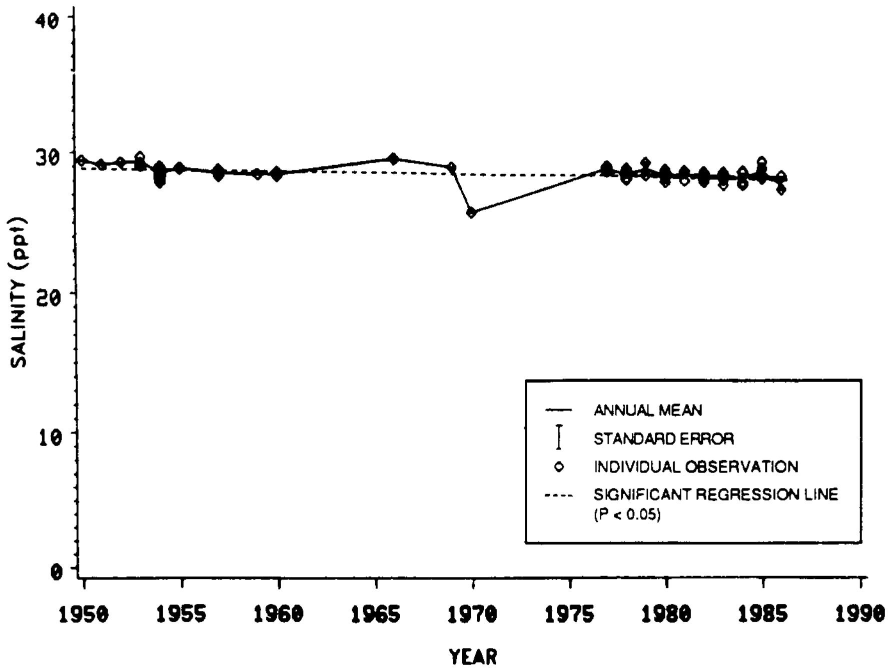
Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.11. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.12.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.69-5.71. Significant declines ($p<0.05$) in salinity values were detected at the surface, and at 10- and 30-m depths (Tables 5.11 and 5.12). The long-term trend in surface salinity values, a decline of about 0.61 ppt over the period of 1950-1986, appears to have been driven by the decline of about 0.60 ppt that occurred over the period of 1977 to 1986. This recent decline was detected using data from only one sampling station, and could not have been an artifact of changing station locations.

Significant increases ($P<0.05$) in water temperature values were detected at all depths (Tables 5.11 and 5.12). These increases appear to have coincided with the pattern of climatic change evident in the climate data collected at the Seattle-Tacoma Airport. The data set for Carr Inlet begins in 1950, during a cool period (see Figure 5.1).

Dissolved Oxygen--Plots of dissolved oxygen concentration by year are shown in Figures 5.72 and 5.73. The Class AA water quality standard (see Table 4.2) was always met in the surface waters. However, violations at 10-m depth occurred during two years in the 1950s, one year in the 1960s, and one year in the 1980s. Violations at 30-m depth occurred during four years in the 1950s, one year each in the 1960s and 1970s, and two years in the 1980s. Dissolved oxygen concentrations do not appear to have changed substantially in Carr Inlet from 1950 through 1986 because no significant differences were detected between dissolved oxygen concentrations recorded before and after 1973 (see Table 5.11). The positive slopes of the long-term regression at 30-m depth and the recent regressions at 0-, 10-, and 30-m depths may have been influenced by variations in dissolved oxygen



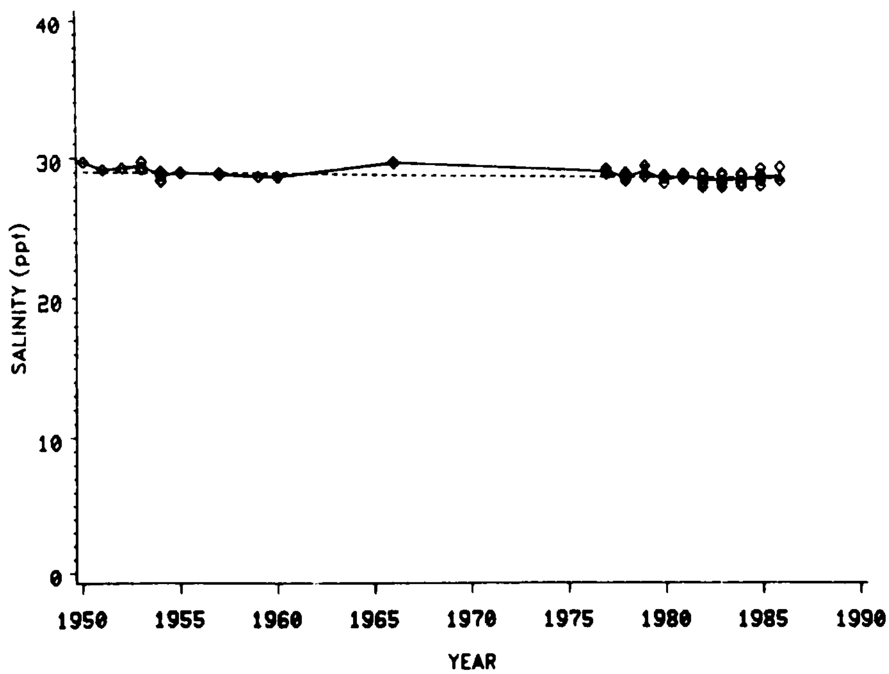


Figure 5.69. Salinity values at the surface and at 10-m depth in the Carr Inlet study area during the algal bloom season.

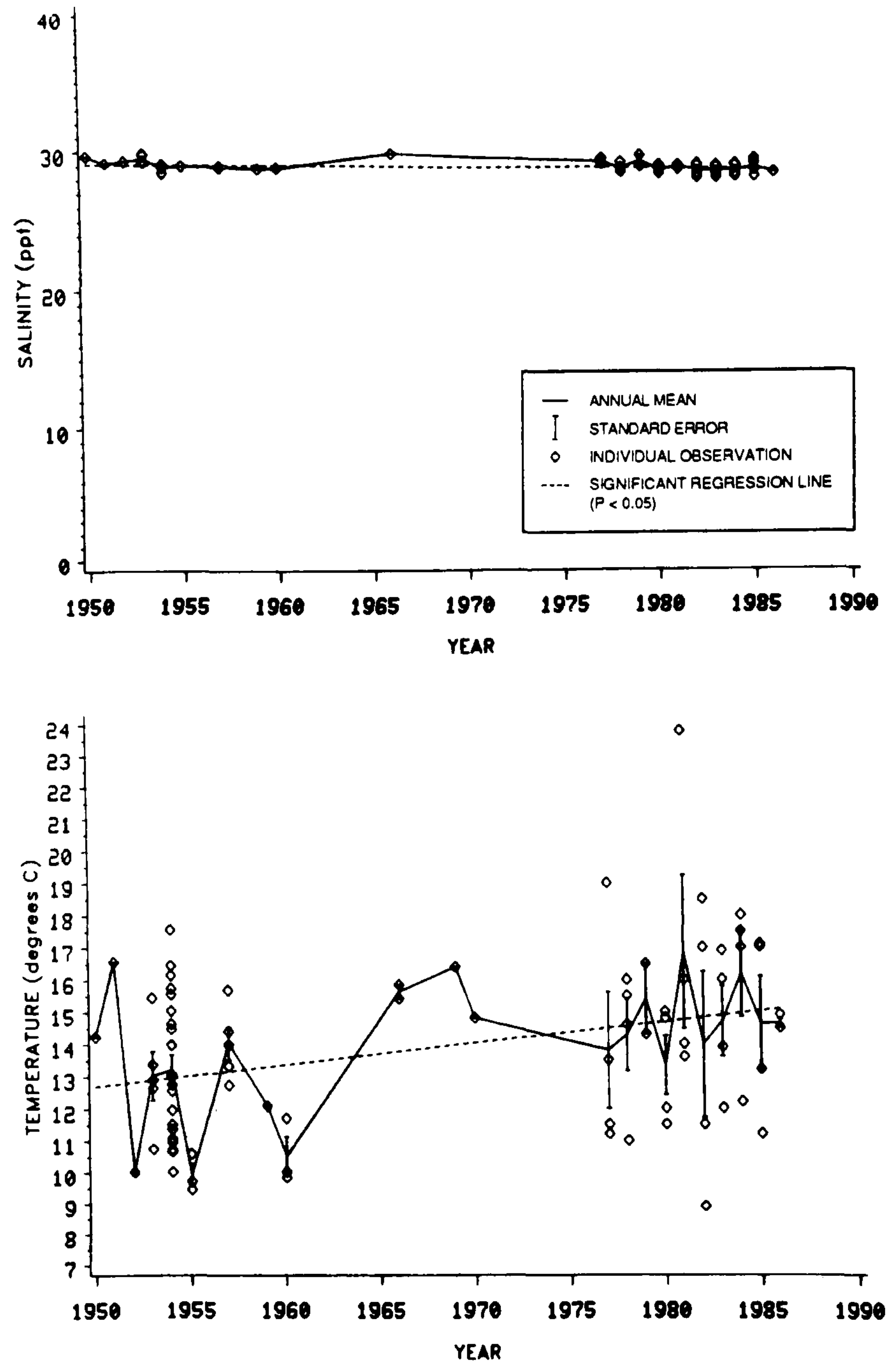
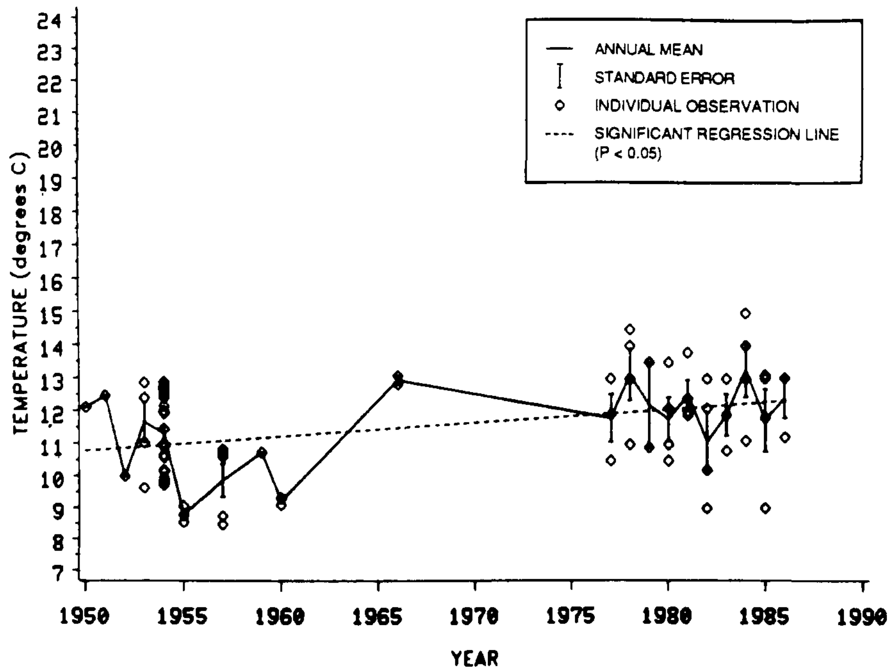


Figure 5.70. Salinity values at 30-m depth and water temperatures at the surface in the Carr Inlet study area during the algal bloom season.



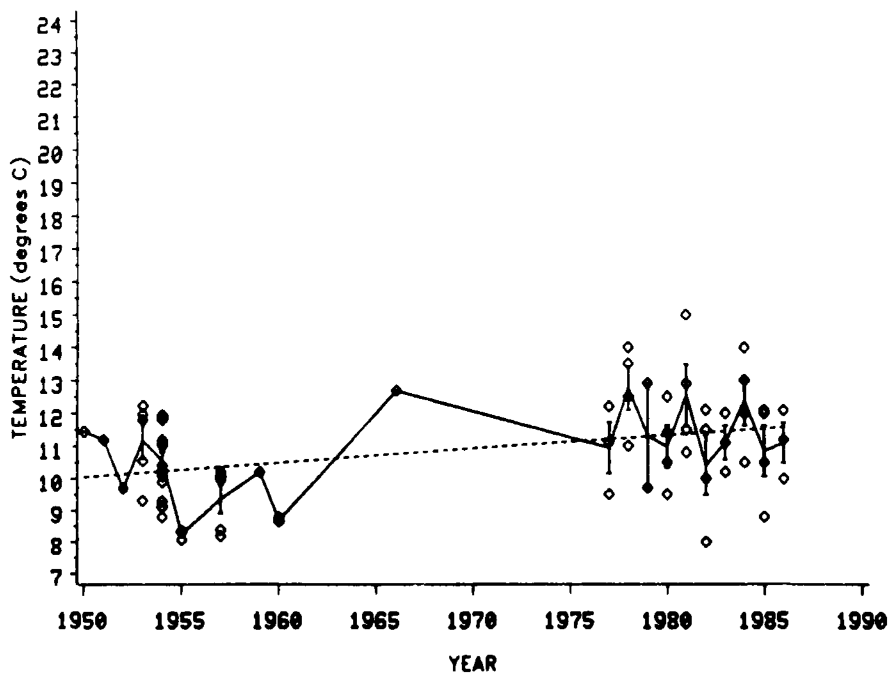


Figure 5.71. Water temperatures at 10- and 30-m depths in the Carr Inlet study area during the algal bloom season.

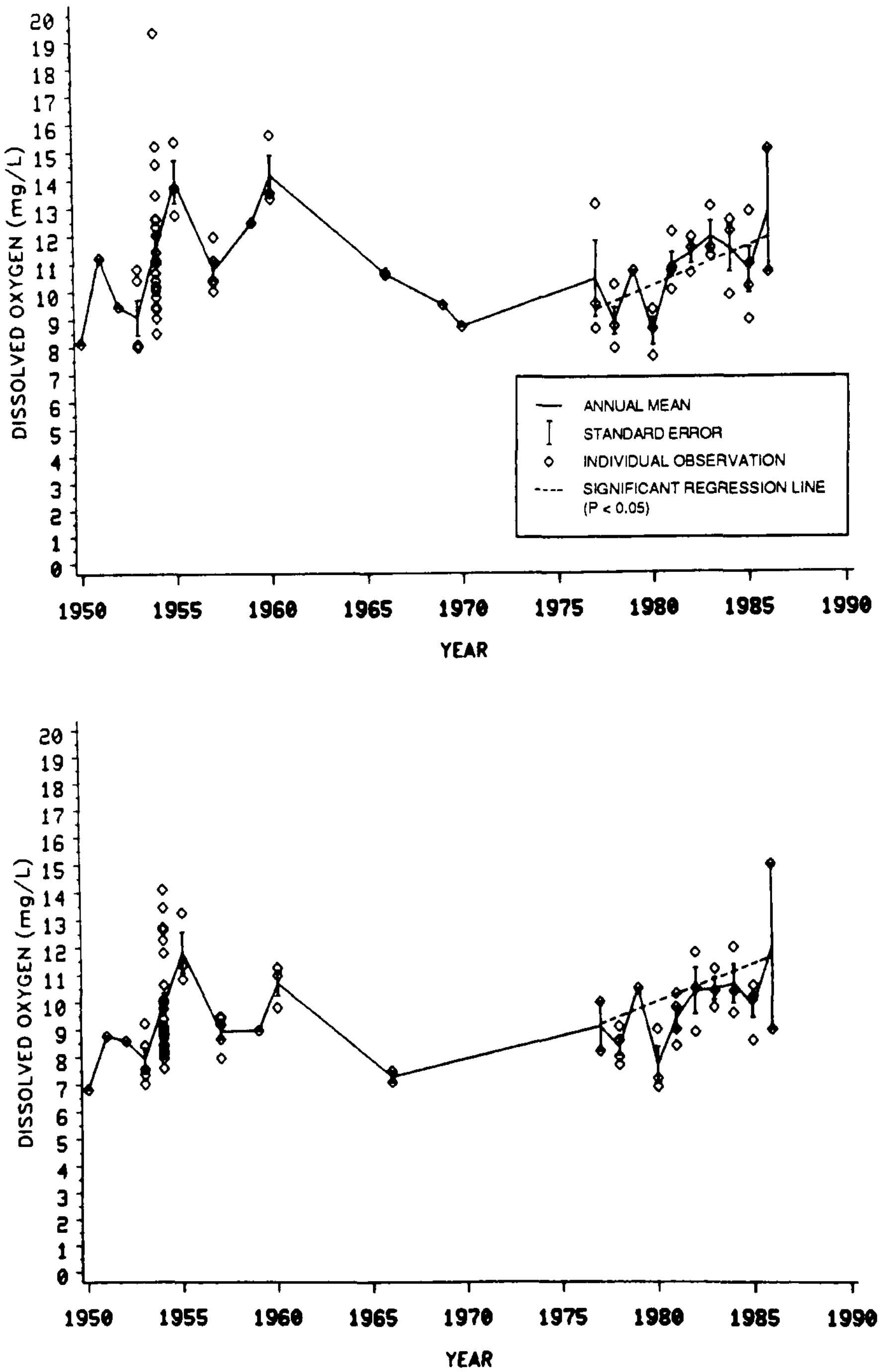


Figure 5.72. Concentrations of dissolved oxgyen at the surface and at 10-m depth in the Carr Inlet study area during the algal bloom season.

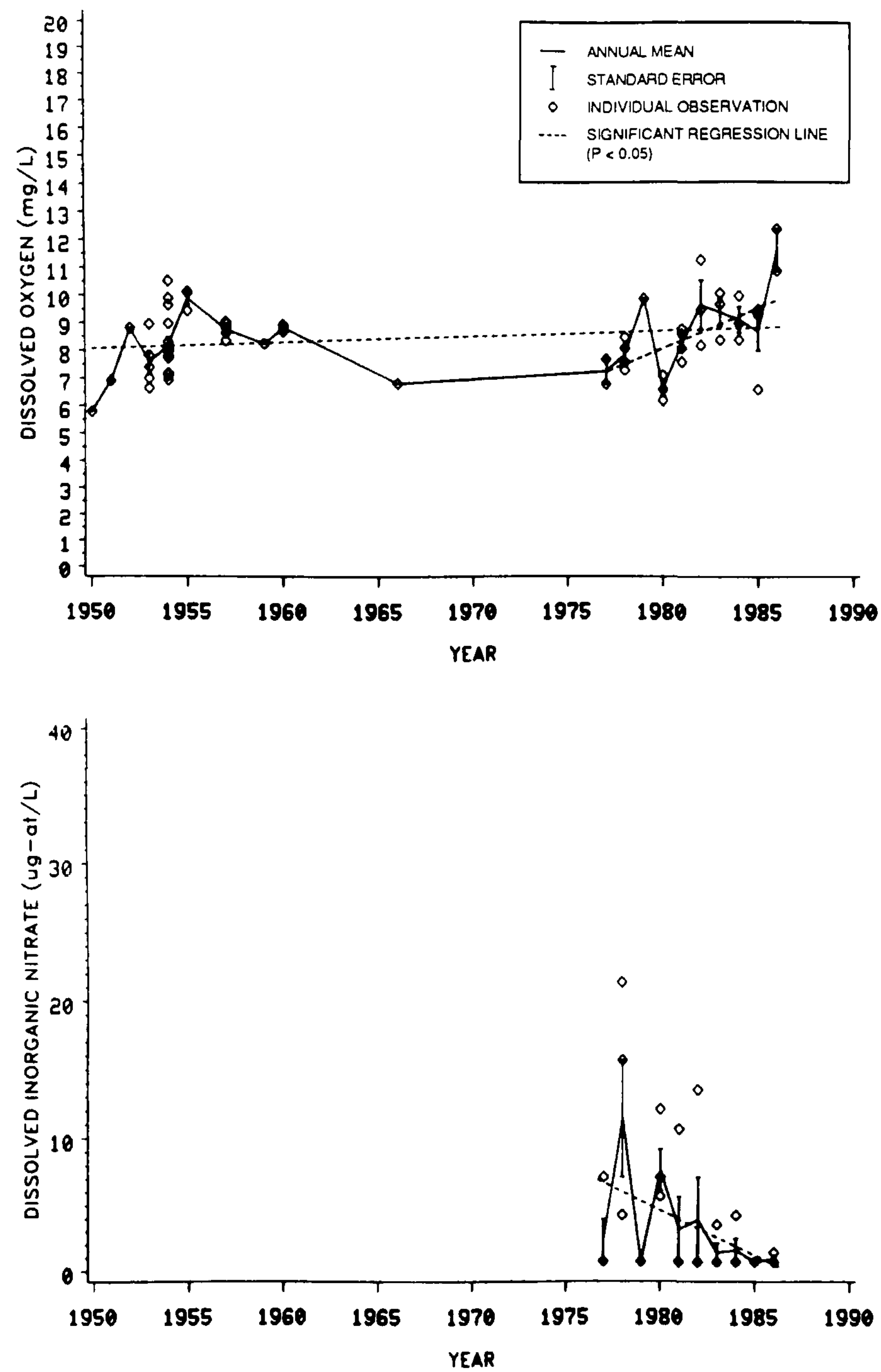


Figure 5.73. Concentrations of dissolved oxgyen at 30-m depth and dissolved inorganic nitrate at the surface in the Carr Inlet study area during the algal bloom season. season.

concentrations that occurred near the beginning and the end of the data set. High values (up to 15.0 mg/L at the surface) were detected in 1986, while low values were detected near the beginning of both the long-term data set at 30-m depth (e.g., less than 6 mg/L) and the recent data sets at all three depths (e.g., as low as 8 mg/L at the surface). The high dissolved oxygen concentrations of 1986 (observed on 19 May) may have been due to some unusual condition (e.g., an intense algal bloom) that occurred that year. Alternatively, their earlier absence could have been a consequence of the infrequency of sampling, which might have missed previous similar high concentrations.

Nutrients--Plots of nitrate values by year are shown in Figures 5.73 and 5.74. Data are available only since 1977, so comparisons between data collected before and after 1973, and long-term regressions by year could not be performed. The recent regression of surface nitrate concentration by year (Table 5.12) detected a significant negative slope, with concentrations at or near detection limits during 1985 and 1986 (Figure 5.73). This recent decline in surface nitrate concentrations may have been caused by a recent increase in algal concentrations (see below). This result suggests that surface nitrate concentrations did not limit algal growth in this study area, at least during the late 1970s. Similar declines in nitrate were not detected at 10 and 30 m.

No significant changes in surface phosphate concentrations were detected (Tables 5.11 and 5.12, Figures 5.75 and 5.76). A moderate decline in phosphate concentrations was detected by ANOVA at 10-m depth, and a more substantial decline was detected by both ANOVA and regression at 30-m depth. These declines may be attributable to changes in natural or anthropogenic inputs of phosphate. These declines in phosphate concentrations also may have been influenced by changing sampling station locations and data sources (see Figure 5.63 and Table 5.9). Because the early University of Washington data were probably generated with a spectrophotometer (Appendix A), the actual values probably were reasonably accurate. The actual changes in location of the sampling stations over time would not seem to be likely to have caused an overall decline in phosphate concentrations (Figure 5.63, Table 5.9). In summary, the decreases in phosphate concentration may have

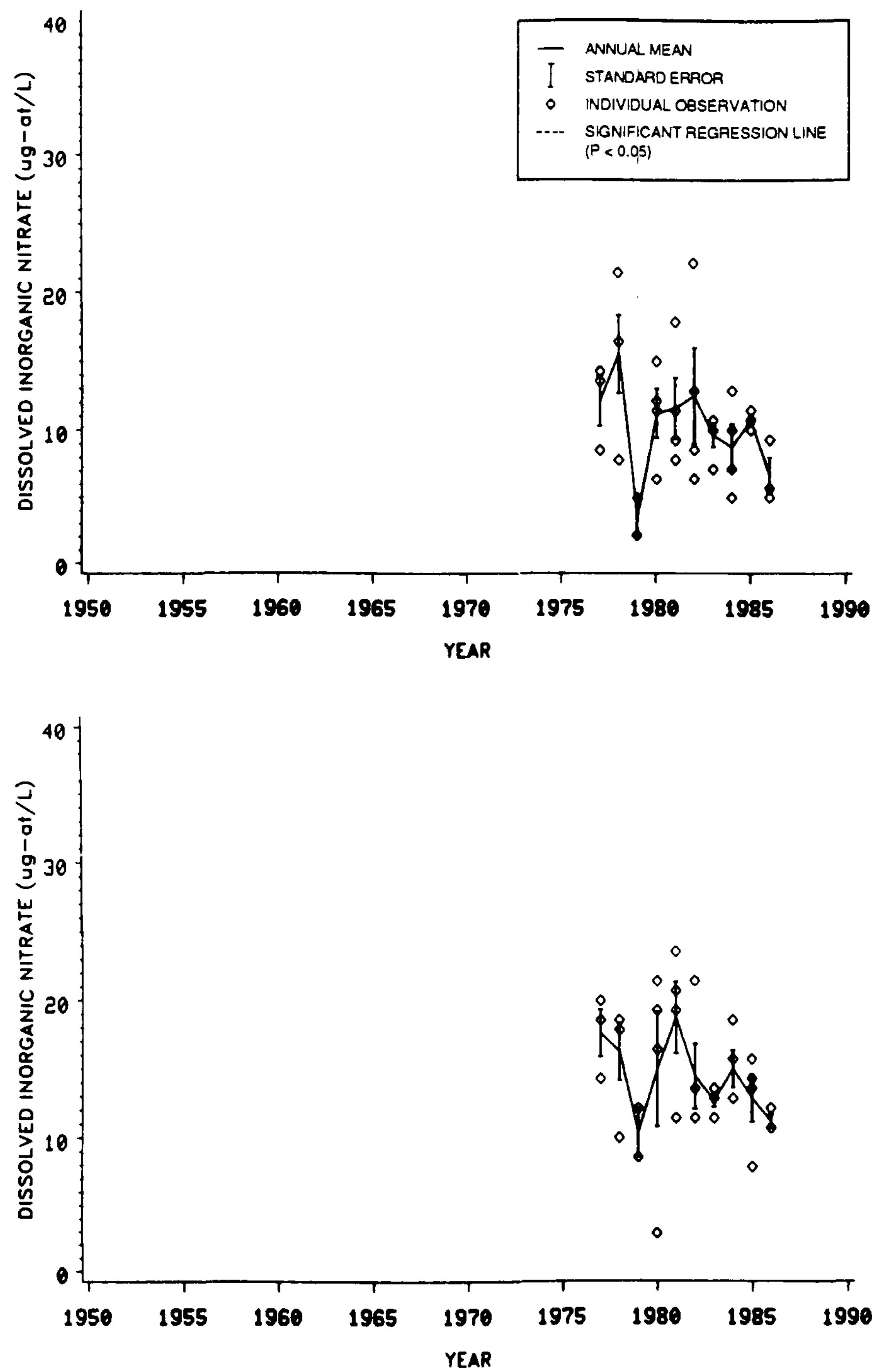


Figure 5.74. Concentrations of dissolved inorganic nitrate at 10- and 30-m depths in the Carr Inlet study area during the algal bloom season.

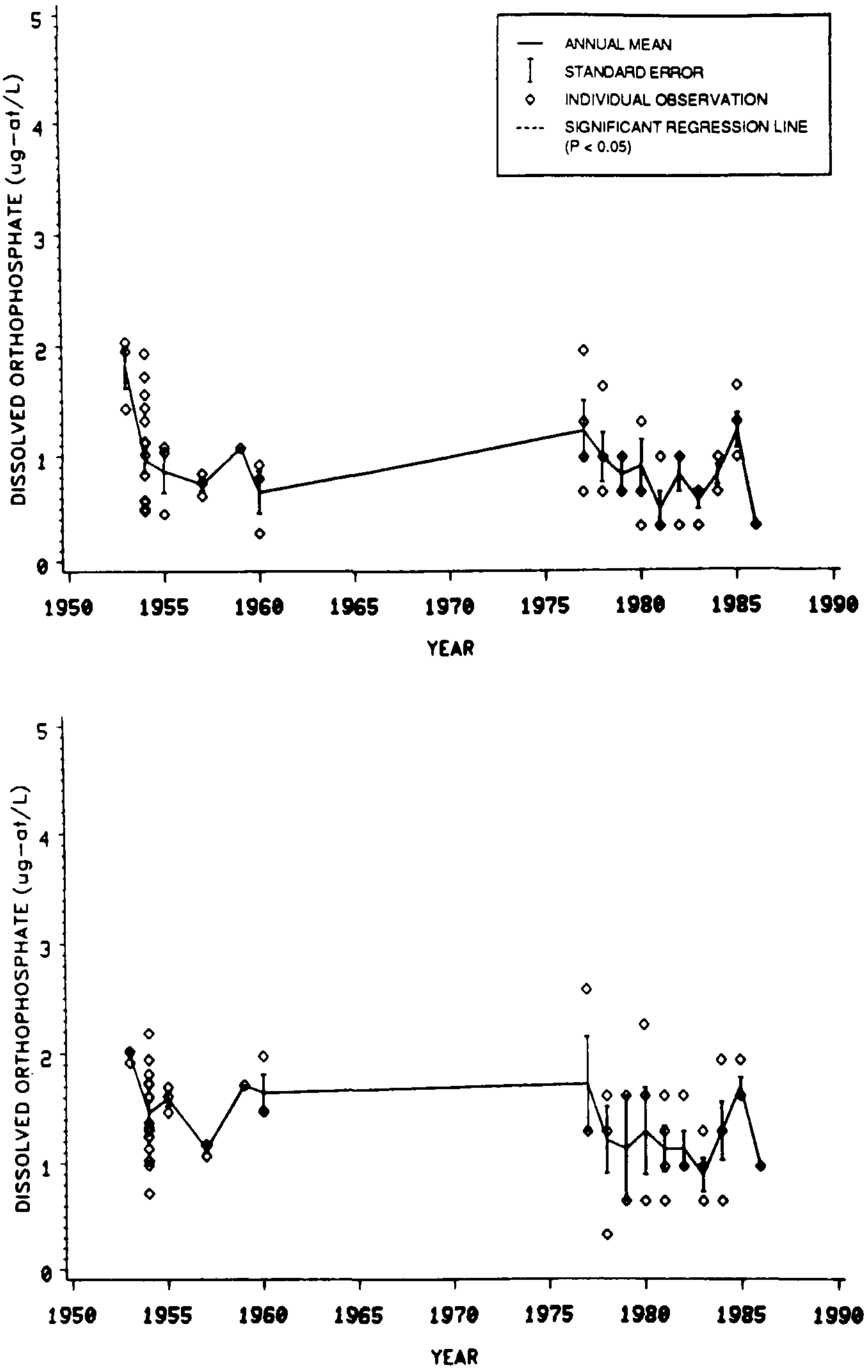


Figure 5.75. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Carr Inlet study area during the algal bloom season.

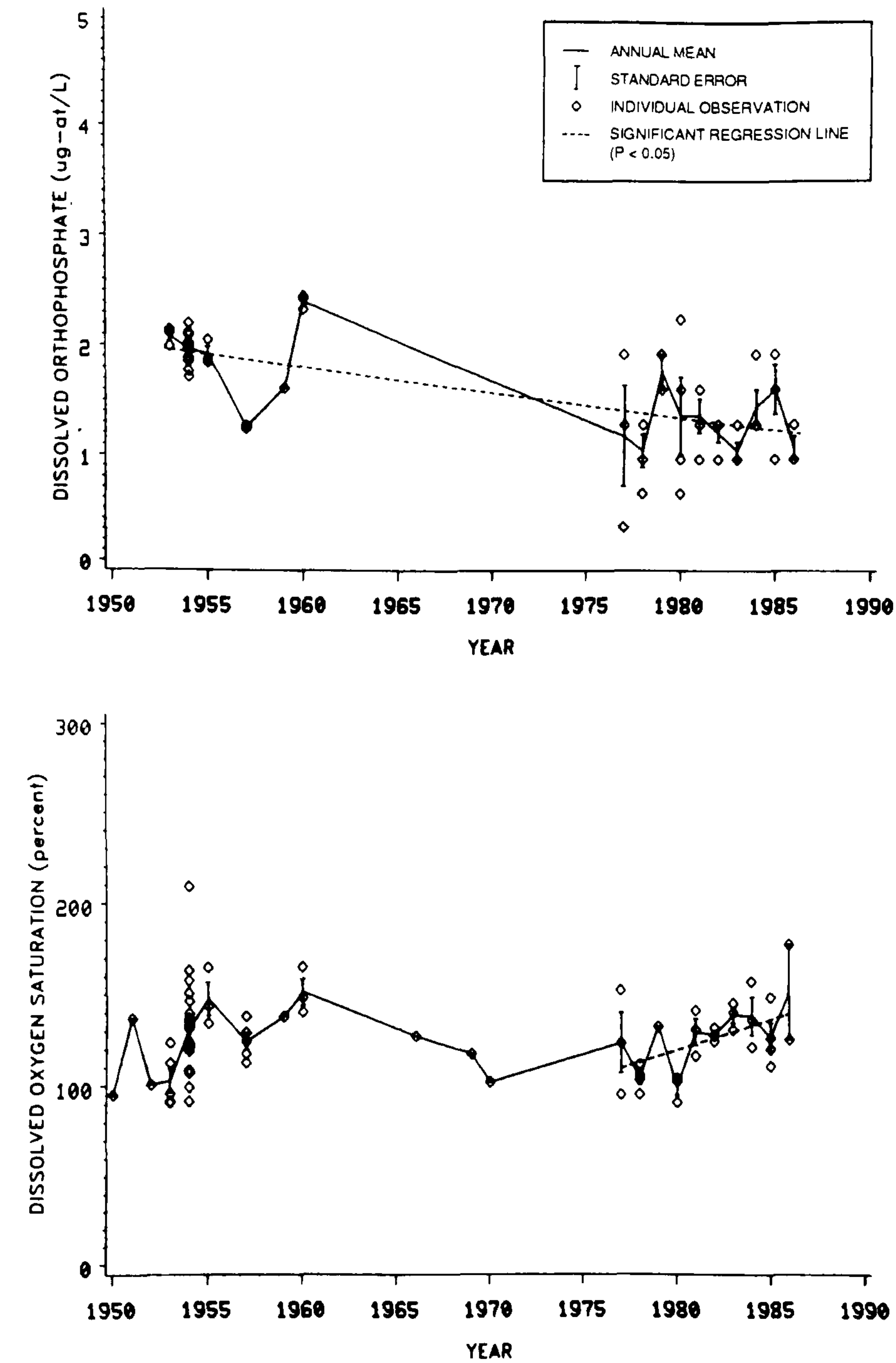


Figure 5.76. Concentrations of dissolved orthophosphate at 30-m depth and percent dissolved oxygen saturation at the surface in the Carr Inlet study area during the algal bloom season.

been real phenomena, but it is also possible that changes in station location or data sources could have affected the data.

Indicators of Phytoplankton Growth--Because chlorophyll *a* data are available only for 1979-1981, they are not plotted by year. Long-term changes in percent dissolved oxygen saturation at the surface were not detected. However, a significant ($P<0.05$) increasing trend in percent dissolved oxygen saturation at the surface was detected since 1977 (Table 5.12, Figure 5.76). This increase was influenced by high values recorded in 1986. A concomitant decrease in Secchi disk depth since 1977 was also detected. Thus, an increase in algal density since 1977 may have returned this variable to levels that occurred in the 1950s.

A problem in interpreting these results is that the Secchi disk only measures transparency from the surface down to the depth at which the disk disappears from view. In a habitat such as Carr Inlet, where water clarity is high and vertical mixing rates are low, changes in algal density could occur principally at depths below the Secchi disk depth.

Pollutants--Very little data on sulfite waste liquor are available, although a Boise-Cascade pulp mill is located across Puget Sound from the mouth of Carr Inlet. Data on fecal coliform bacteria are available for surface water since 1977 (Figure 5.77). Values were generally at the detection limit (1 organism/100 mL). However, a significant decrease ($P<0.05$) was detected (Table 5.12) and may be attributed to a single high value recorded in 1977. There is no known large source of bacterial contamination in the Carr Inlet area.

Nisqually Reach

The Nisqually Reach study area is in a rural region of the southern sound (see Figure 5.63). Class AA water quality standards apply in the area. Nisqually Reach is located near a sill, and is shallow (36 m) for a main channel site. Turbulent mixing of the water column in the study area is caused by the rapid currents south of Tacoma Narrows, and by the proximity of the sills at Nisqually Reach and Tacoma Narrows. The Nisqually

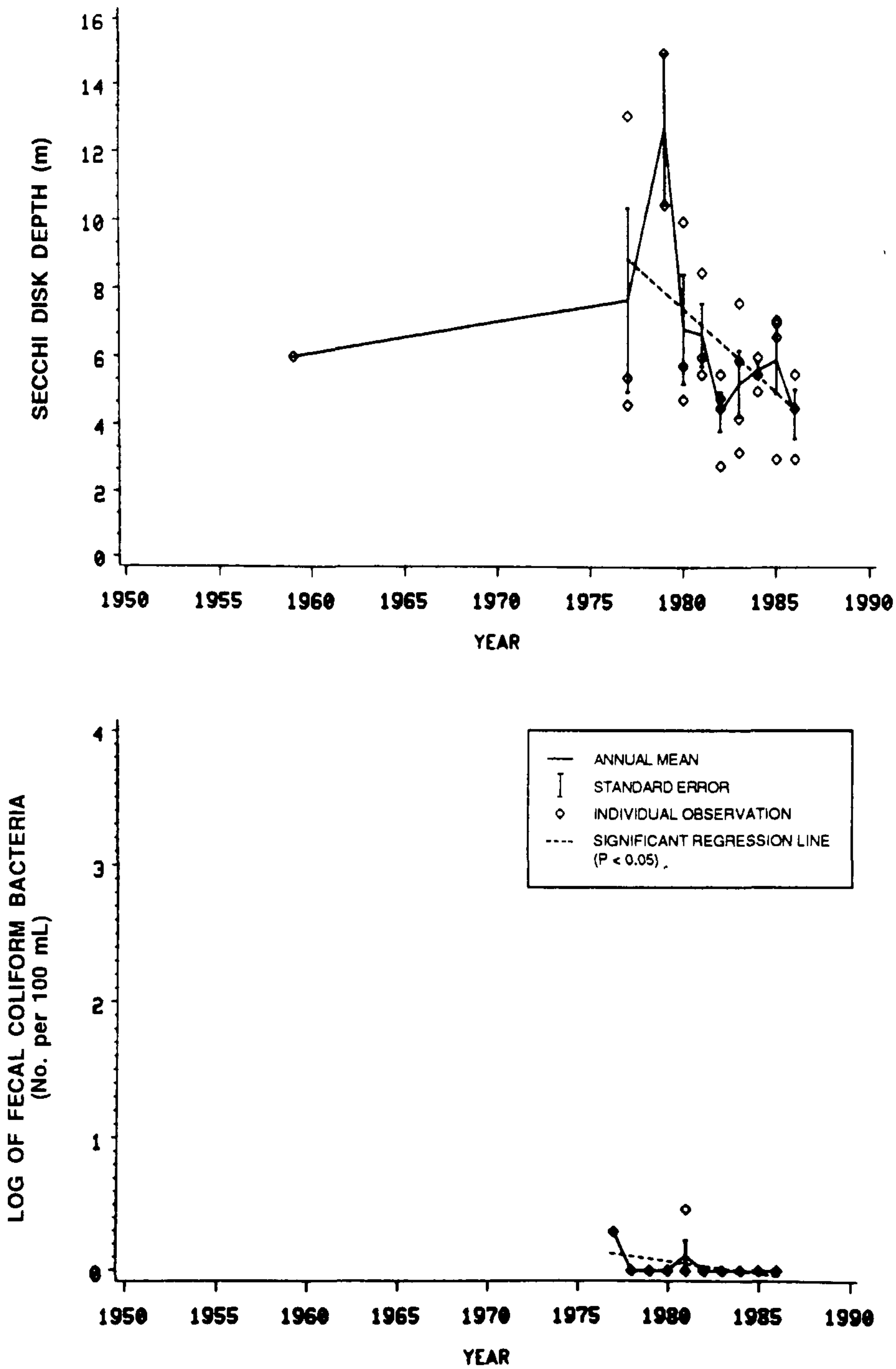


Figure 5.77. Secchi disk depth and log of concentrations of fecal coliform bacteria at the surface in the Carr Inlet study area during the algal bloom season.

River enters the sound approximately 1.5 km south of the study area. It contributes only 5 percent of the total freshwater input to Puget Sound, but is the largest river in the southern sound (Table 2.1). Flow rates are high in the winter through the late spring, when snowmelt occurs (USGS 1985). Nisqually Reach was included in the study because changes at various locations in the southern sound might be expected to be integrated in this region.

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.64. Data are available from 1932 to 1986, with the best coverage during the mid-1950s and since 1977. Only surface and 10-m depth data were suitable for analysis. Moderate density stratification was evident. The mean surface salinity value was 26.4 ppt, while the mean value at 10-m depth was 2.2 ppt higher. The mean surface water temperature value was 12.6° C, while the mean value at 10-m depth was 0.8° C lower. The salinity gradient was greater than that observed at Carr Inlet (0.2 ppt difference between the mean salinity values at the surface and at 10-m depth), presumably because of the proximity of the Nisqually Reach study area to the outlet of the Nisqually River. The thermal depth gradient at Nisqually Reach was smaller than the thermal gradients observed at either Carr or Budd Inlets (over 2.3° C difference between the mean water temperature values at the surface and at 10-m depth), probably because of the higher turbulence and rates of vertical mixing of the water column at Nisqually Reach.

The concentrations of dissolved oxygen and nutrients, and the potential for the development of intense algal blooms, were affected by the moderate density stratification and the propensity for vertical mixing (Figures 5.65 and 5.66). Although no chlorophyll a data are available, algal blooms did not seem to become highly developed in the Nisqually Reach study area. The percent saturation of dissolved oxygen at the surface was only about 105 percent (Figure 5.67 and Appendix E). The percent saturation of dissolved oxygen was still near 100 percent at 10-m depth, which supports the hypothesis of well-developed vertical mixing in the study area.

Although the water column was well mixed, mean Secchi disk depth was high, over 6.5 m (Figure 5.67). This deep Secchi disk depth supports the assessment that algal densities were not high at Nisqually Reach. Moreover, nutrient concentrations generally were higher than in the other southern sound sites (e.g., mean nitrate concentration at the surface was 10.3 ug/L). These high nutrient concentrations suggest that rates of nutrient uptake by the phytoplankton in the area, and, thus, rates of algal growth in the area, generally were lower than in the other southern sound sites.

Results of the correlations between pairs of water quality variables at the surface (Appendix F) suggest that the moderate blooms of the Nisqually Reach study area occurred when salinity was low and the water column was stratified. The positive correlation between surface salinity values and Secchi disk depths indicates that water clarity was lower when surface salinity was low. Moreover, the negative correlation between nitrate concentrations and water temperature values at the surface suggests that algal blooms occurred when thermal gradients were present.

Pollution in the Nisqually Reach area does not appear to have been a severe problem (Figure 5.68). Limited data on sulfite waste liquor are available, but concentrations were lower than in any other southern sound study area. The geometric mean concentration of sulfite waste liquor for surface waters was only 2.0 (Pearl Benson Index). The geometric mean concentration of fecal coliform bacteria also was low (1.5 organisms/100 mL for surface waters).

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.11. Slopes of statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.12.

<u>Physical Conditions</u>--Plots of salinity values by year are shown in Figure 5.78. There was a long-term decrease in salinity values at both the surface and at 10-m depth. These changes appear to have been a steady

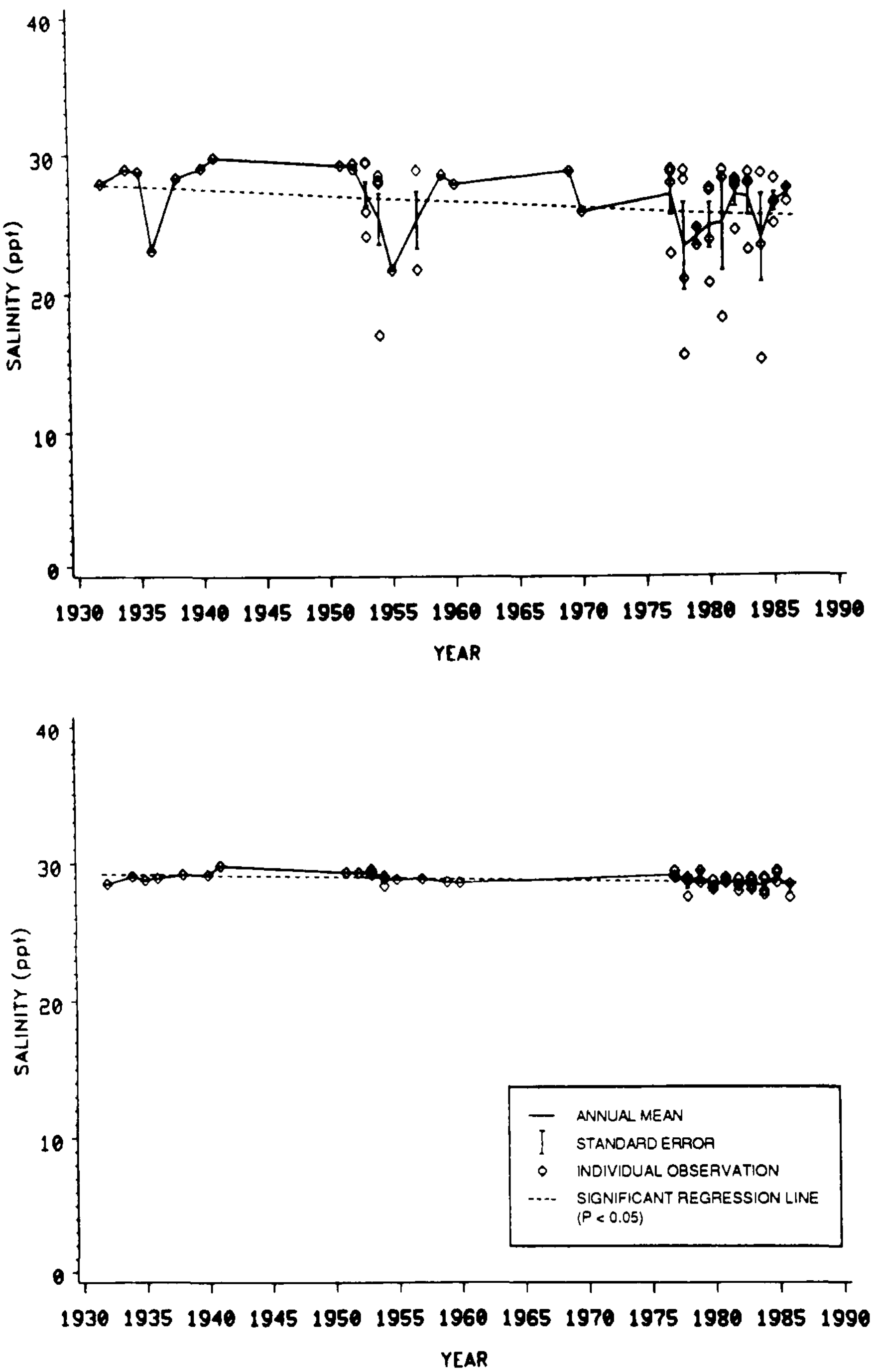


Figure 5.78. Salinity values at the surface and at 10-m depth in the Nisqually Reach study area during the algal bloom season.

decline over the entire period of available data. The locations of the sampling stations at Nisqually Reach used by the University of Washington and Ecology are nearly identical, so changing station locations probably did not contribute to the pattern of changing salinity values. At the surface, the mean salinity value for the period 1973-1986 was approximately 1.5 ppt lower than the mean salinity value for the period 1932-1972. The decreases in salinity values at Nisqually Reach do not appear to have been caused by increases in the flow of the Nisqually River (USGS 1985).

Plots of water temperature values by year are shown in Figure 5.79. Mean temperatures at both the surface and at 10-m depth were higher for the period 1973-1986 than for the period 1932-1972 (Table 5.11). The mean values were 9.4 percent (surface) and 8.0 percent (10-m depth) higher during the recent period. However, neither the long-term nor the recent regressions of water temperature by year had statistically significant ($P>0.05$) slopes (Table 5.12). Apparently temperatures during the cool period of the 1950s lowered the overall mean temperature for the period 1932-1972.

Dissolved Oxygen--Plots of dissolved oxygen concentrations by year are shown in Figure 5.80. Concentrations did not fall below the Class AA standard (see Table 4.2) at either the surface or 10-m depth. There was a general pattern of increasing dissolved oxygen concentrations at both the surface and 10-m depth. Both of these trends were influenced by high dissolved oxygen concentrations reported in 1986 (e.g., 15.0 mg/L at the surface on 19 May 1986). These high dissolved oxygen concentrations may have been caused by an intense algal bloom. No changes in the discharges of anthropogenic oxygen-demanding pollutants to the Nisqually River or to the Nisqually Reach area were identified.

Nutrients--Plots of nitrate and phosphate concentrations by year are shown in Figures 5.81 and 5.82. No significant temporal trends were detected. Although the amount of data collected before 1977 was limited, phosphate concentrations do not appear to have changed substantially since the 1930s. Analytical techniques used in the 1950s were reliable, but the

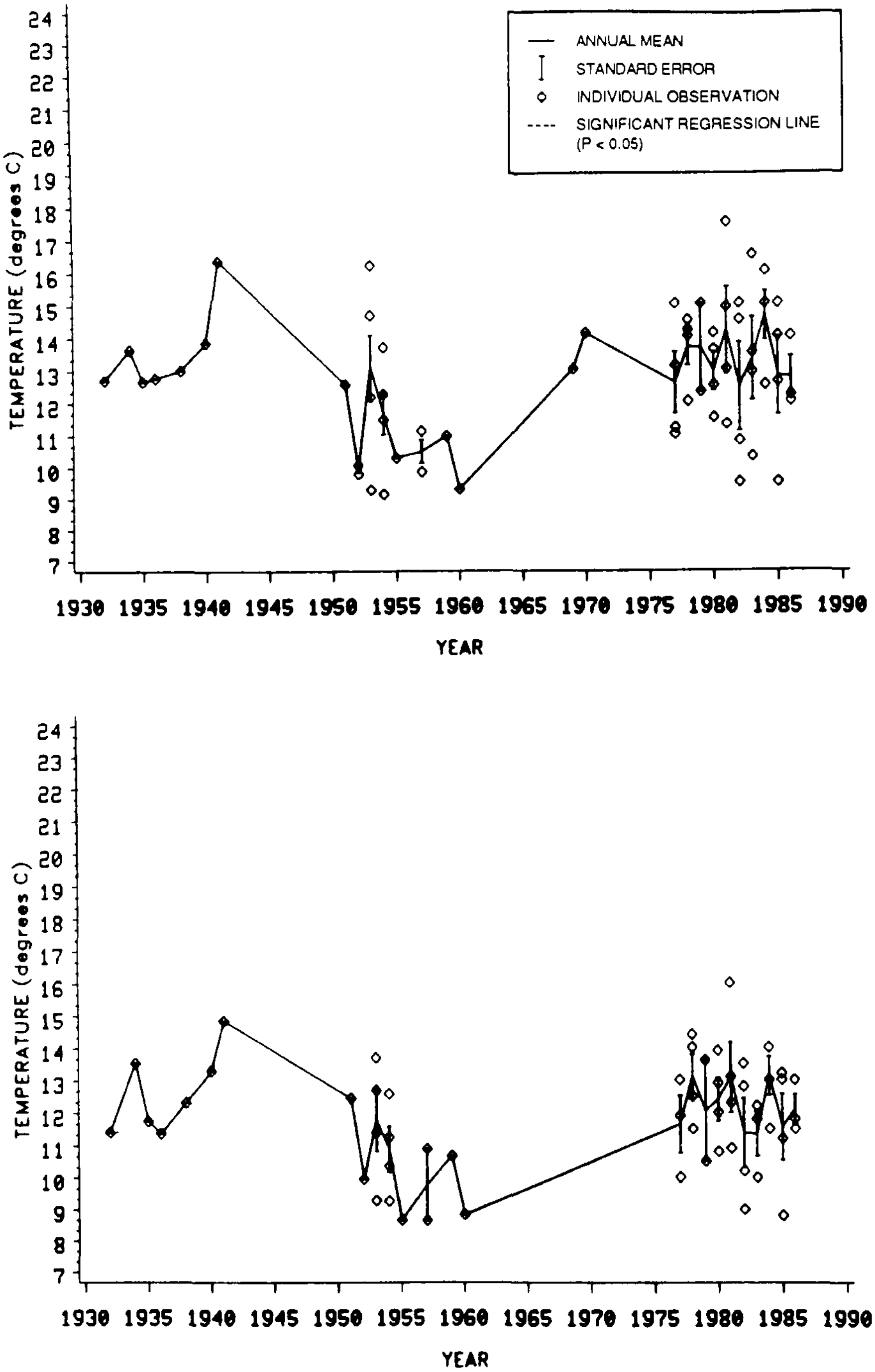


Figure 5.79. Water temperatures at the surface and at 10-m depth in the Nisqually Reach study area during the algal bloom season.

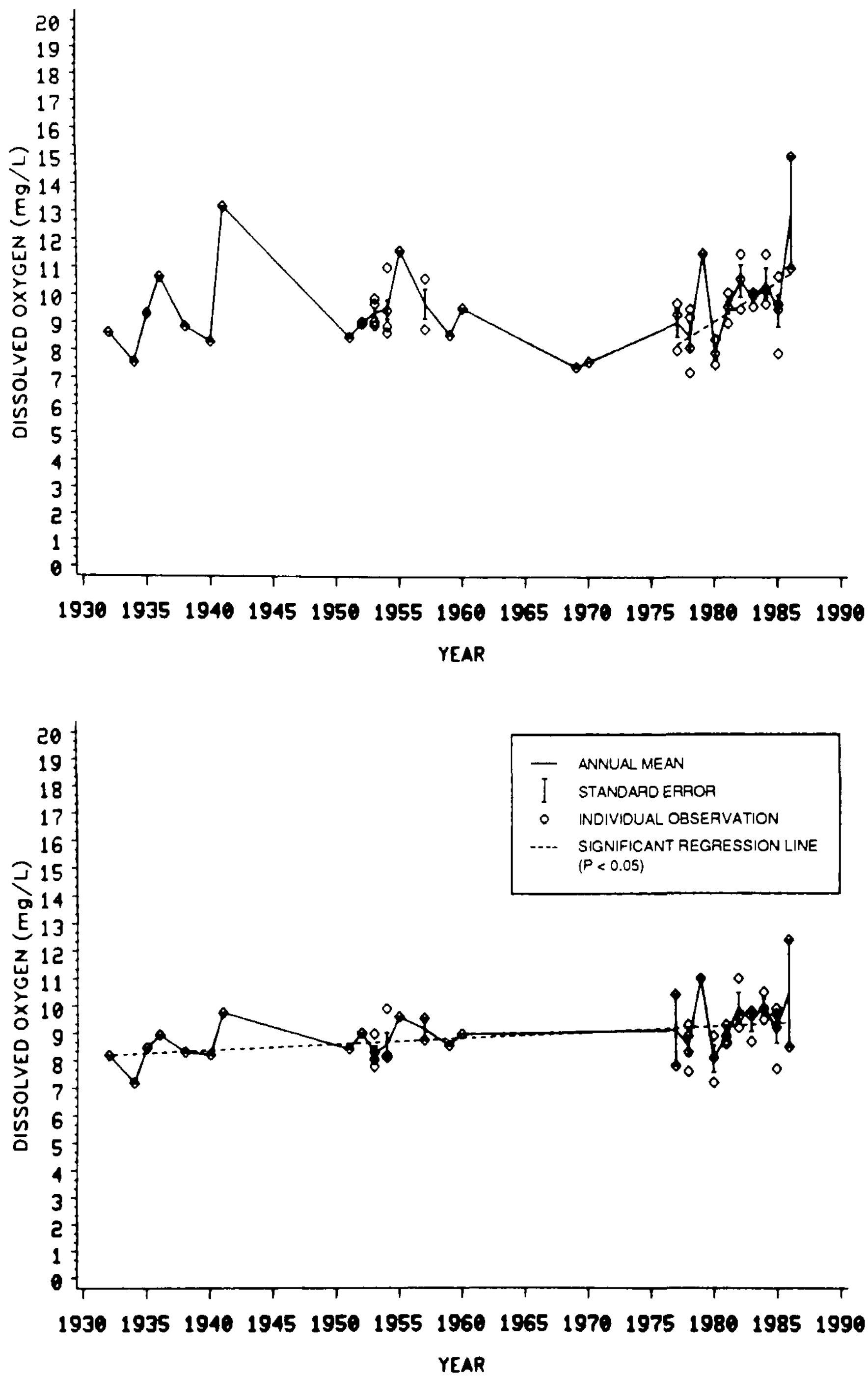


Figure 5.80. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Nisqually Reach study area during the algal bloom season.

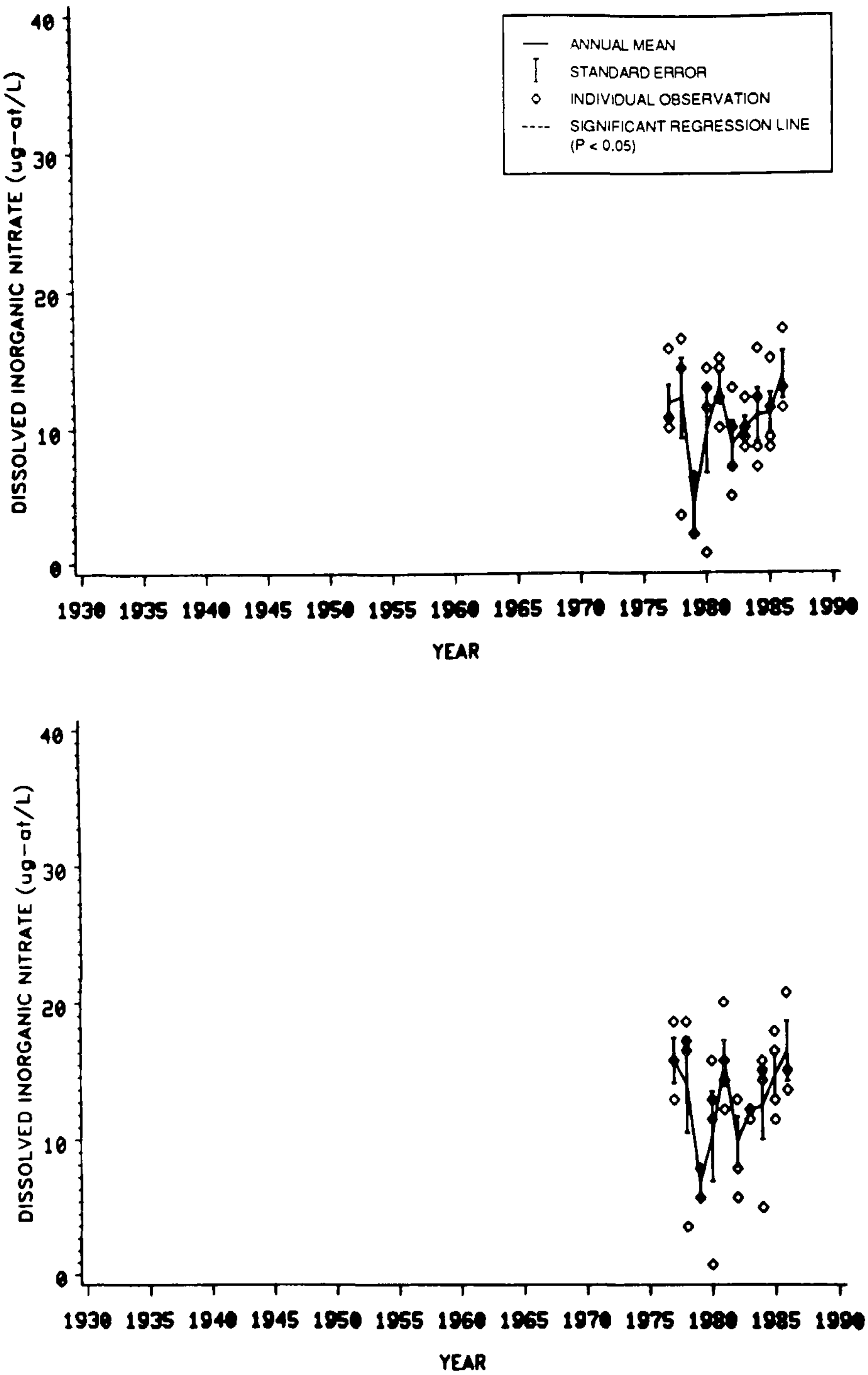


Figure 5.81. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the Nisqually Reach study area during the algal bloom season.

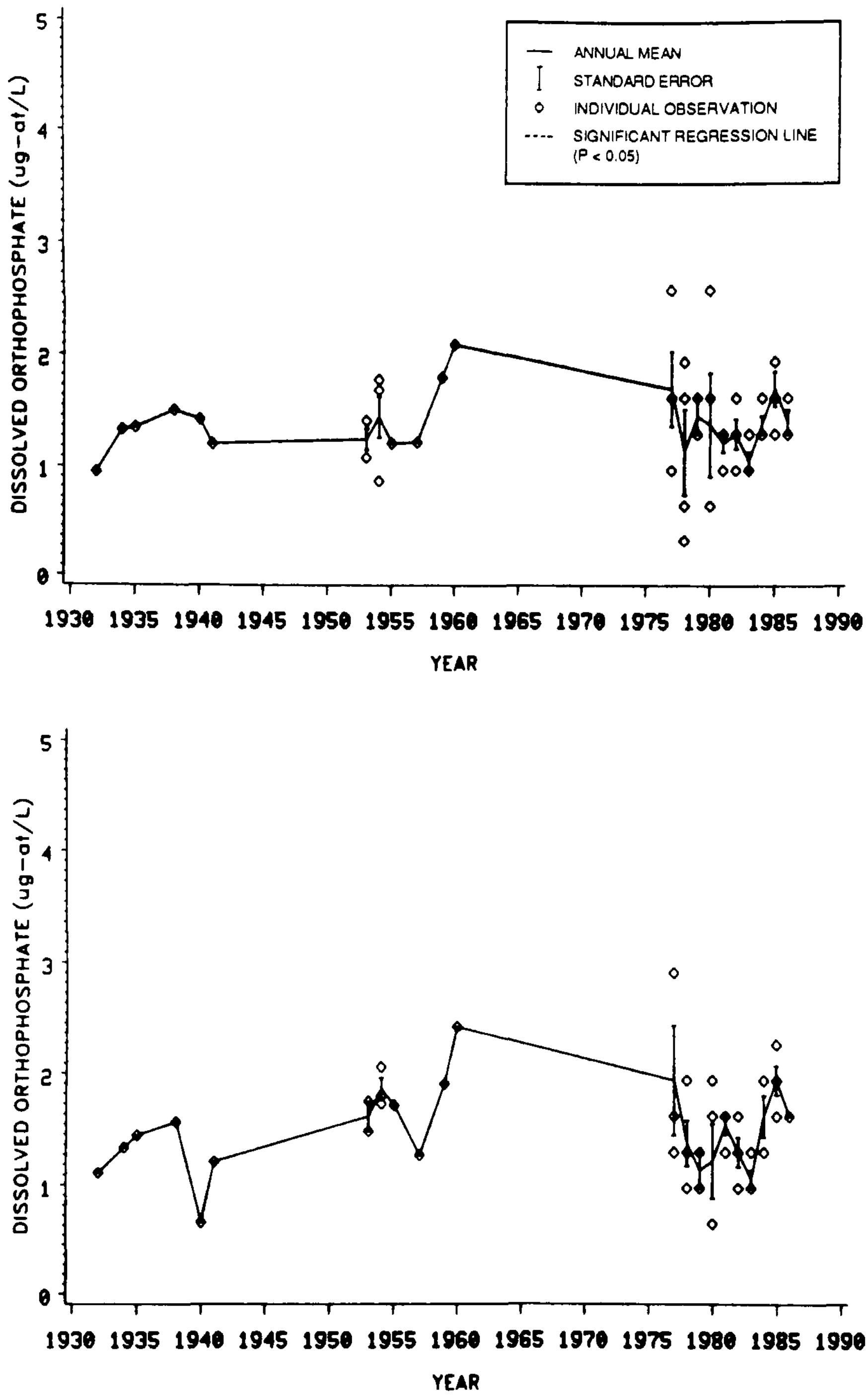


Figure 5.82. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Nisqually Reach study area during the algal bloom season.

techniques used in the 1930s relied upon visual color comparisons, so the early data may be somewhat less accurate (Appendix A).

Indicators of Phytoplankton Growth--No chlorophyll a data are available. An increase in surface percent dissolved oxygen saturation is evident since 1977, although this increase was influenced by the generally high dissolved oxygen concentrations observed in 1986 in the southern sound. Secchi disk depth has not changed significantly since 1977 (Figure 5.83 and Tables 5.11 and 5.12). There is no substantial evidence to suggest that the intensity of algal blooms has changed at Nisqually Reach.

Pollutants--The quantity of sulfite waste liquor data was insufficient for trends analysis. Concentrations of sulfite waste liquor were very low, although the Boise-Cascade pulp mill is located approximately 11 km northeast of Nisqually Reach. Fecal coliform bacteria have been monitored at the surface since 1977 (Figure 5.84). As evidenced by a significant regression against year, concentrations of fecal coliform bacteria have declined ($p<0.05$) over the study period (Table 5.12). Concentrations did not violate Class AA standards, except on 23 August 1978. This single high contamination event probably drove the statistical significance of the declining trend. That day had the heaviest rainfall of that particular month, and the surface salinity recorded on that date was the lowest in the entire data set for Nisqually Reach (15.4 ppt). These two factors suggest that the source of the bacterial contamination was storm runoff from the agricultural areas in the Nisqually River basin.

Budd Inlet

The study area is located in the southern portion of Budd Inlet, a shallow (average depth under 10 m), sluggishly circulating, southern embayment (see Figure 5.63). Budd Inlet is classified as a stratified, partially mixed estuary (URS 1986a). Flushing rates are rather low, particularly near the head of the inlet. Stations are located near Priest Point, from 1.5 to 3 km north of the Port of Olympia. Class A water quality standards apply to the northern portion of the study area. Class B standards apply to the southern portion of the study area, closer to the City of

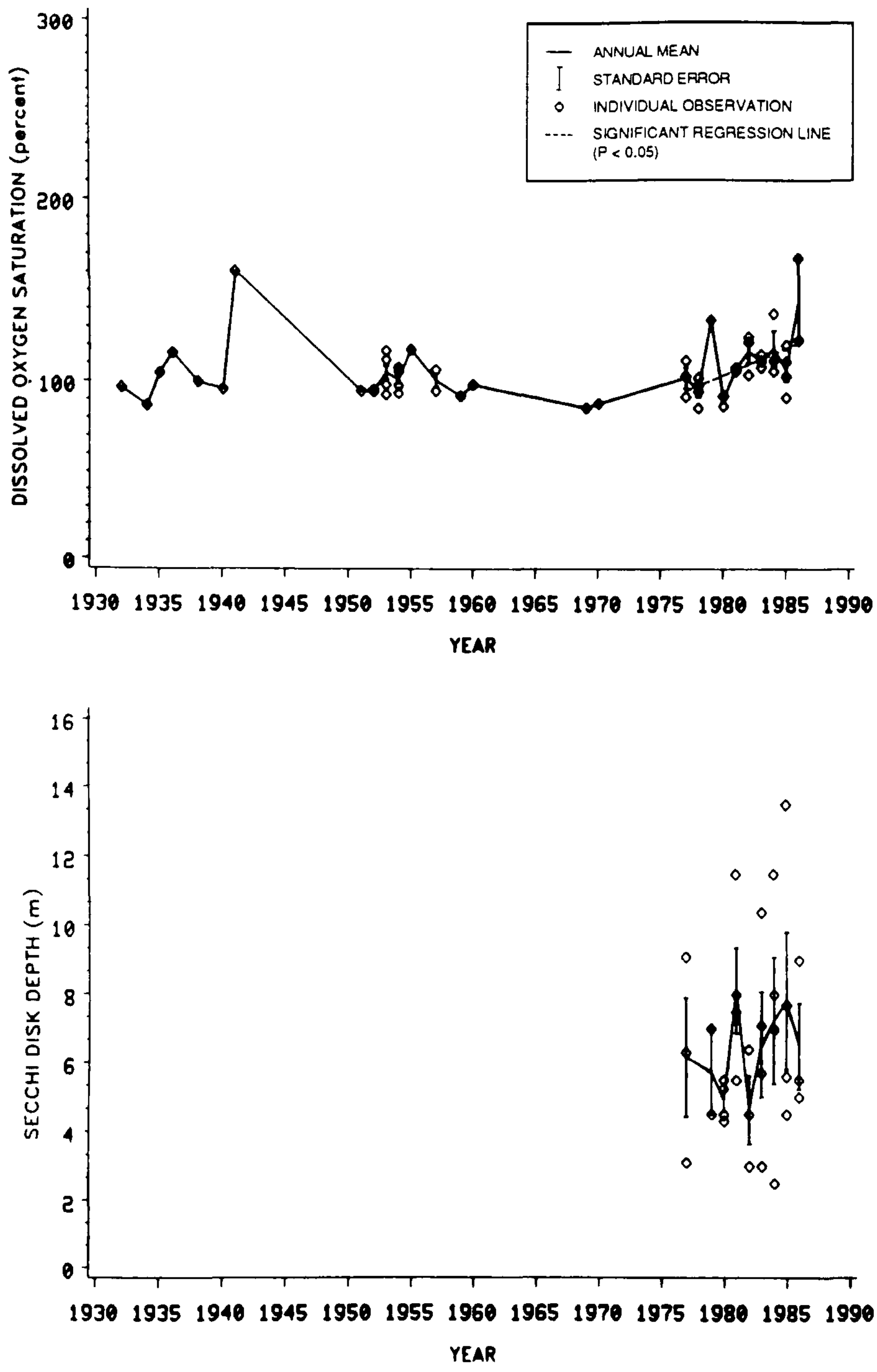


Figure 5.83. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Nisqually Reach study area during the algal bloom season.

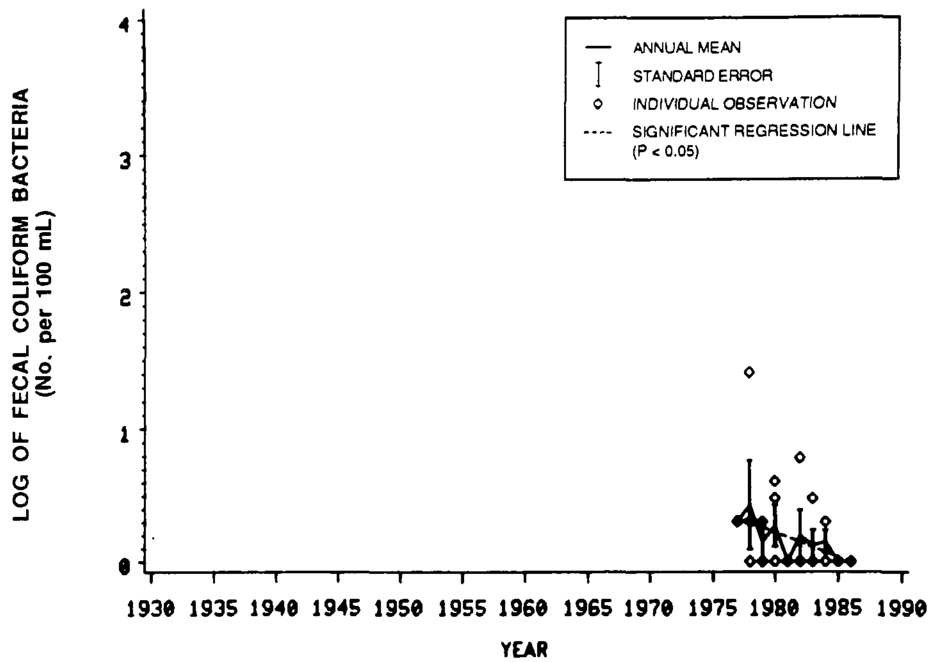


Figure 5.84. Log of concentrations of fecal coliform bacteria at the surface in the Nisqually Reach study area during the algal bloom season.

Olympia. The Deschutes River is an important source of fresh water for Budd Inlet, contributing approximately 1 percent of the total freshwater flow to Puget Sound (Table 2.1). The Deschutes River discharges into Capitol Lake. The depth of Capitol Lake is regulated by a dam that discharges into the head of Budd Inlet. Other sources of fresh water include several small streams.

Environmental Conditions in the Study Area--

The inner portion of Budd Inlet is prone to periods of low dissolved oxygen in near-bottom waters, particularly during the late summer (URS 1986a). In the past, low dissolved oxygen has been attributed to the decay of diatom blooms. Recently, URS (1986a) determined that the spring diatom bloom causes supersaturation of dissolved oxygen throughout the water column in Budd Inlet. Based on the results of limited field and modeling studies, URS (1986a) suggested that low dissolved oxygen concentrations in late summer are caused by a combination of factors, including high temperatures, high sediment oxygen demand, and low flushing rates. However, the influence of the diurnal vertical migration patterns of dinoflagellates had to be included in the URS (1986a) model to account for the depth gradient of oxygen concentrations in the late summer. In this model, the dinoflagellates functioned as an oxygen "pump," producing oxygen near the surface during the day and consuming oxygen near the bottom during the night.

The contribution of anthropogenic sources to the dissolved oxygen problems in Budd Inlet has been investigated recently. Modeling studies have suggested that anthropogenic nitrogen inputs could be increasing the magnitude of spring diatom blooms and summer dinoflagellate blooms by 30-50 percent (URS 1986a). The LOTT plant is the major point source of nitrogen to Budd Inlet (URS 1986a). URS (1986a) has recommended that nitrogen removal be implemented by the LOTT plant during the summer to reduce anthropogenic enhancement of algal blooms in the area.

Point sources of biological oxygen demand do not appear to have a substantial impact on dissolved oxygen concentrations. In 1979, point sources of biological oxygen demand contributed less than 10 percent to the total sediment oxygen demand (Kruger 1979). This figure has declined since 1979 because of improvements to the sewage treatment facilities in the area. The biological oxygen demand discharged from the Olympia primary sewage treatment plant in the summer of 1979 averaged approximately 500 mg/L. The LOTT secondary sewage treatment plant became operational at the same location in 1981. Biological oxygen demand discharged from the new plant in the summer of 1986 averaged approximately 10 mg/L (Singleton, L., 7 August 1987, personal communication). Because the new plant also adds ozone to the effluent, the dissolved oxygen concentration in the effluent typically is 8 mg/L or higher.

Mean salinity and water temperature values during the algal bloom season are depicted in Figure 5.64. Scattered data are available from the 1950s and the 1960s, with nearly continuous coverage from the early 1970s through 1986. Density stratification of the water column was well developed, as salinity values were substantially lower and temperature values were substantially higher at the surface. The difference between the mean temperature values at the surface and at 10-m depth was particularly large, approximately 2.6^{o} C. Mean salinity values were approximately 2.0 ppt lower at the surface than at 10-m depth. The stability of the water column indicates that algal blooms could develop readily, and that excess nutrients might not be readily flushed from the head of the inlet, particularly when the flow rate of the Deschutes River is low during the summer.

The distributions of dissolved oxygen and nutrients over depth were strongly affected by water column stability (Figures 5.65 and 5.66). The mean percent dissolved oxygen saturation was over 114 percent at the surface, but was only approximately 90 percent at 10-m depth (Appendix E). Dissolved oxygen concentrations below 3 mg/L, which can cause mortality in sensitive biota (NOAA 1986a), were rarely seen during the algal bloom season. The consistent presence of dissolved oxygen concentrations above 3 mg/L may be due to several factors related to sampling and station location. Sampling was relatively infrequent (once per month by Ecology) and did not extend to the bottom. Thus, the sampling could have missed short-term low dissolved oxygen events (i.e., the water most likely to be low in dissolved oxygen was not sampled). Also, the sampling stations were not located at the head of the inlet, where the most severe problem exists (URS 1986a).

Water clarity and the vertical distributions of nutrient concentrations suggest that algal blooms were quite intense in the Budd Inlet study area. Water clarity was only about half that of Carr Inlet and Nisqually Reach, as mean Secchi disk depth was only about 3.1 m (Figure 5.67). Nitrate concentrations in the Budd Inlet study area were much lower than in the Nisqually Reach study area. The mean surface nitrate concentration was 1.95 ug-at/L at the Budd Inlet site and 10.8 ug-at/L at the Nisqually Reach site. These results for Budd Inlet resemble the concentrations found in the shallow Totten Inlet and Oakland Bay study areas. Phosphate concentrations were similar to those observed in Carr Inlet (e.g., mean surface concentrations were 1.4 ug-at/L at the Carr Inlet site and 1.5 ug-at/L at the Budd Inlet site).

Nitrate concentrations in Budd Inlet were only 40 percent as high at the surface as at 10-m depth. However, phosphate concentrations were 97 percent as high at the surface as at 10-m depth. The low nitrate concentrations recorded in Budd Inlet, especially at the surface, suggest that anthropogenic enrichment of nitrogen could enhance algal blooms in Budd Inlet by supplementing the supply of available nutrients. This interpretation is consistent with the conclusions of URS (1986a).

The relationships among the water quality variables provide further insight into the role of algal blooms in the Budd Inlet ecosystem (Appendix F). Negative correlations between nitrate concentrations and water temperature values at the surface and at 10-m depth, and between dissolved oxygen concentrations and water temperature values at 10-m depth were probably caused by blooms that occurred during warm, calm, and sunny weather. The positive correlation between percent dissolved oxygen saturation at the surface and water temperature also probably was due to enhanced photosynthetic rates that occurred during warm weather. The positive correlations between surface nitrate concentration and Secchi disk depth, and between nitrate concentrations and dissolved oxygen concentrations at 10-m depth also may be attributable to the waxing and waning of algal blooms. Transparency and nutrients would both be high when blooms were not well developed. Nutrient concentrations and dissolved oxygen concentrations at depth would both be low when a bloom declined.

Pollution in the Budd Inlet study area by sulfite waste liquor and fecal coliform bacteria does not appear to be a severe problem (Figure 5.68). The geometric mean of the concentration of sulfite waste liquor was only 3.9 (Pearl Benson Index). The geometric mean concentration of fecal coliform bacteria was not as high as that found in the City Waterway study area, although it was the highest of any southern sound study area (4.2 organisms/100 mL). URS (1986a) found that a small creek discharging near the head of the inlet (Moxlie Creek) was the major point source of fecal coliform bacteria to Budd Inlet.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.11. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.12.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.85 and 5.86. Significant differences ($P<0.05$) between salinity data collected before and after 1973 were not detected. However, a significant ($P<0.05$) positive slope in the regression of salinity values against year was detected for surface water since 1973. The most plausible explanation for the apparent recent salinity increase in the Budd Inlet study area is that station locations changed over time, and that an unusual low salinity event occurred in 1974, near the beginning of the time period analyzed in the recent regression. During the period when all three Ecology stations (BUD003, BUD004, BUD005) were sampled (1967-1970, 1976-1977), salinity values did not differ significantly ($P<0.05$) among the three stations. However Station BUD003 was the station closest to the mouth of the Deschutes River and to Capitol Lake (Figure 5.63). One very low surface salinity value (12.7 ppt) was detected at this station in August 1974. Because Stations BUD003 and BUD004 were dropped by Ecology after 1977, the

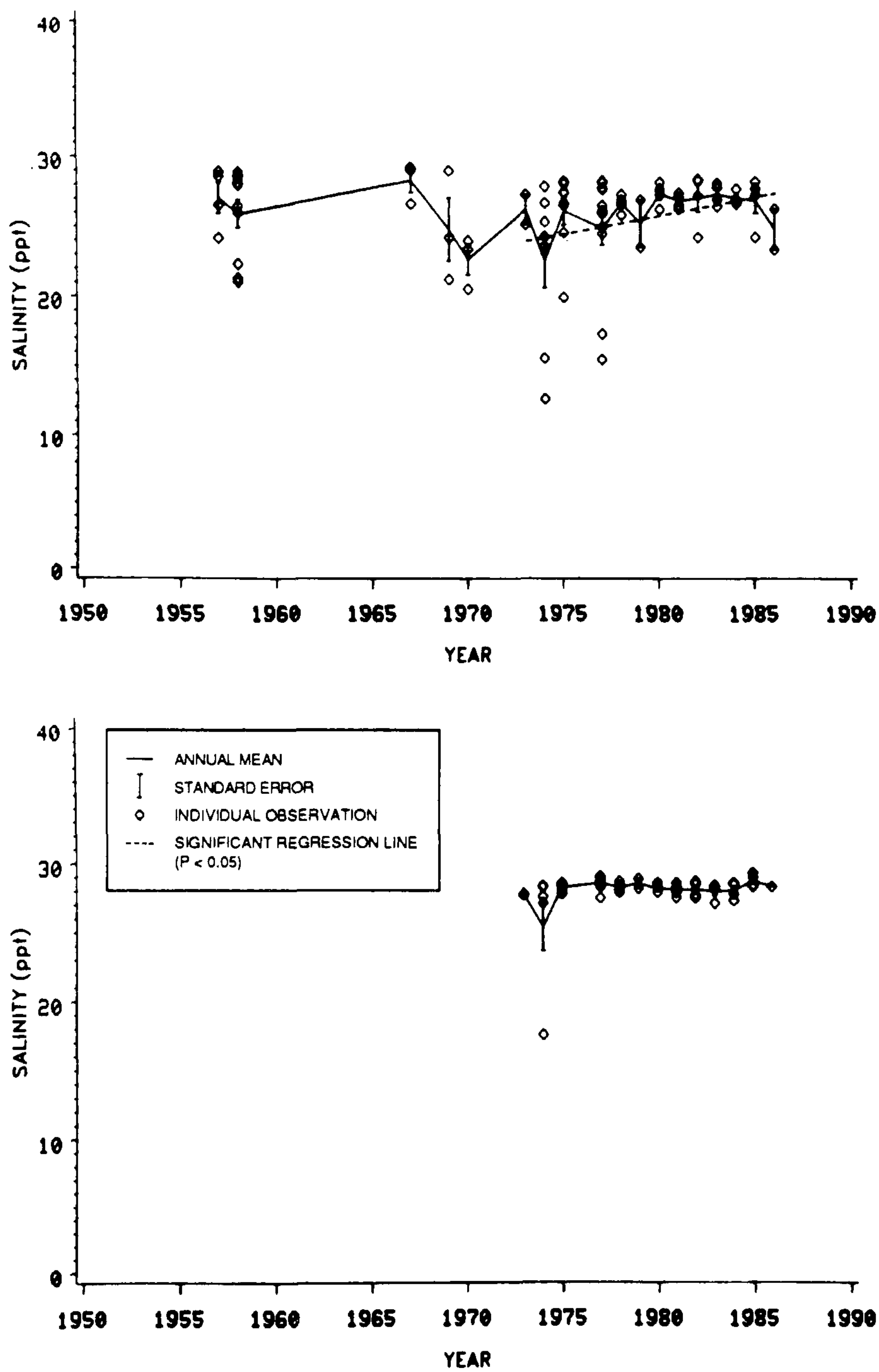


Figure 5.85. Salinity values at the surface and at 10-m depth in the Budd Inlet study area during the algal bloom season.

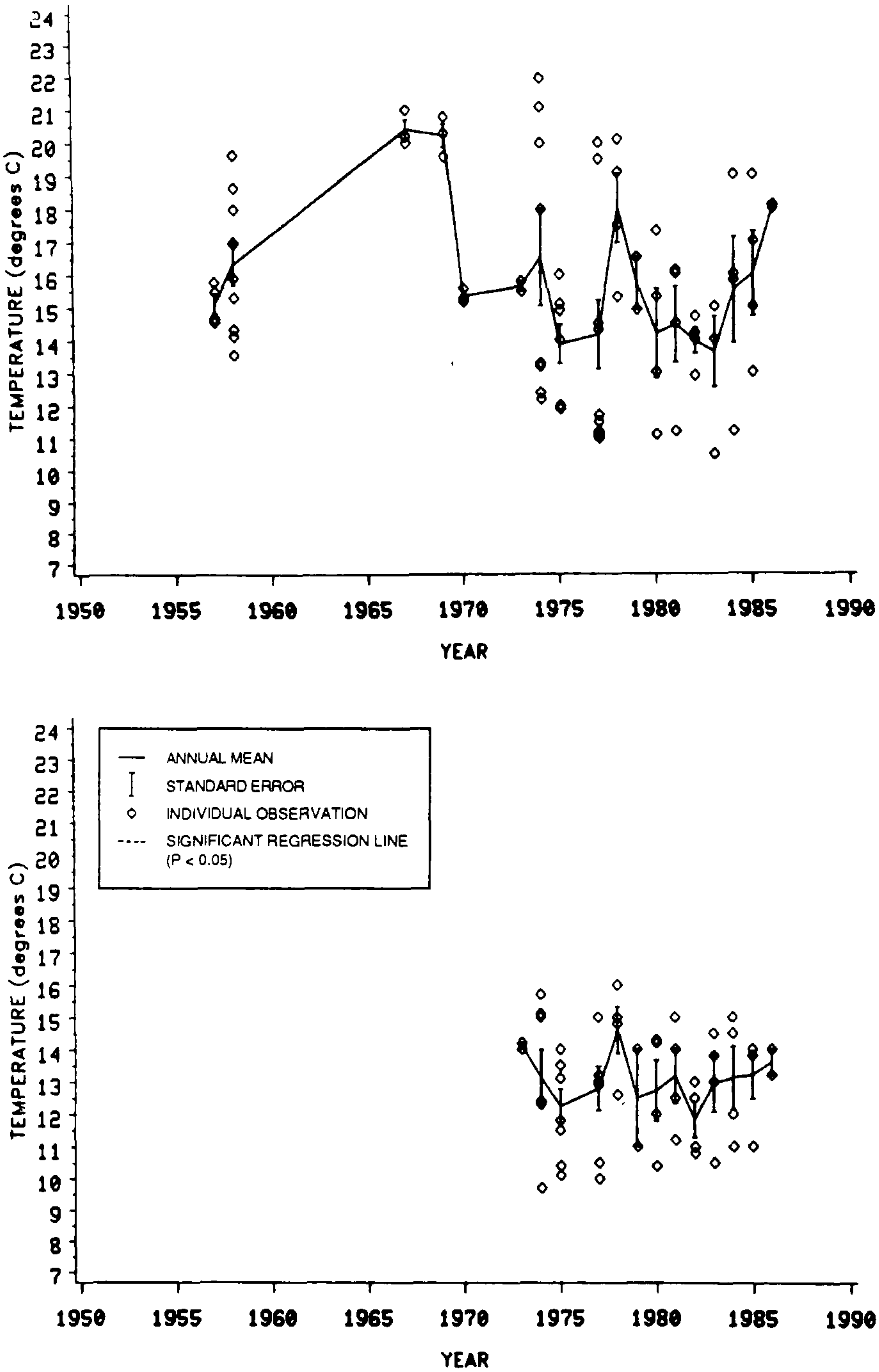


Figure 5.86. Water temperatures at the surface and at 10-m depth in the Budd Inlet study area during the algal bloom season.

only station from which data are available after 1977 is BUD005, which is the station most distant from the principal source of fresh water. The effects of freshwater inputs from the Deschutes River and from the flushing of Capitol Lake on the salinity data were diminished in the more recent data, which could have introduced an apparent increasing trend into the salinity data.

The only change detected for water temperature was from the comparison of data collected before 1973 with data collected from 1973 through 1986 (Table 5.11). That comparison indicated that a decline in surface temperature had occurred. However, the regressions of water temperature by year were not significant ($P>0.05$) (Table 5.12). This contradiction may be resolved by noting that the data collected before 1973 contained data from only a few years, and that data collected in 1968 and 1969 had the highest mean water temperatures recorded for the entire Budd Inlet data set (Figure 5.86). Thus, no substantial temporal change in water temperature was noted for Budd Inlet.

Dissolved Oxygen--Plots of dissolved oxygen concentrations by year are shown in Figure 5.87. Violations of the Class B water quality standard (see Table 4.2) were recorded at the surface and 10-m depth during the 1970s. The mean dissolved oxygen concentration for the period 1973-1986 was approximately 16 percent higher than the mean for the period 1957-1972 (Table 5.11). Statistically significant ($P<0.05$) increasing dissolved oxygen concentrations were detected at the surface in both the long-term and recent regressions (Table 5.12). This increase seems to have been due in part to the absence of very low values after 1977, the last year that Ecology sampled the stations nearest the head of Budd Inlet. Dissolved oxygen concentrations typically are lowest near the head of the inlet (URS 1986a). Because the sampling stations near the head of Budd Inlet were dropped at the same time the low dissolved oxygen values disappeared from the data, the apparent rise in dissolved oxygen concentrations probably was influenced by changing sampling station locations over time. Aside from any apparent effects of changes in sampling station locations, dissolved oxygen concentrations may have continued to increase in the Budd Inlet study area during the 1980s (Figure 5.87). When the LOTT sewage treatment plant became

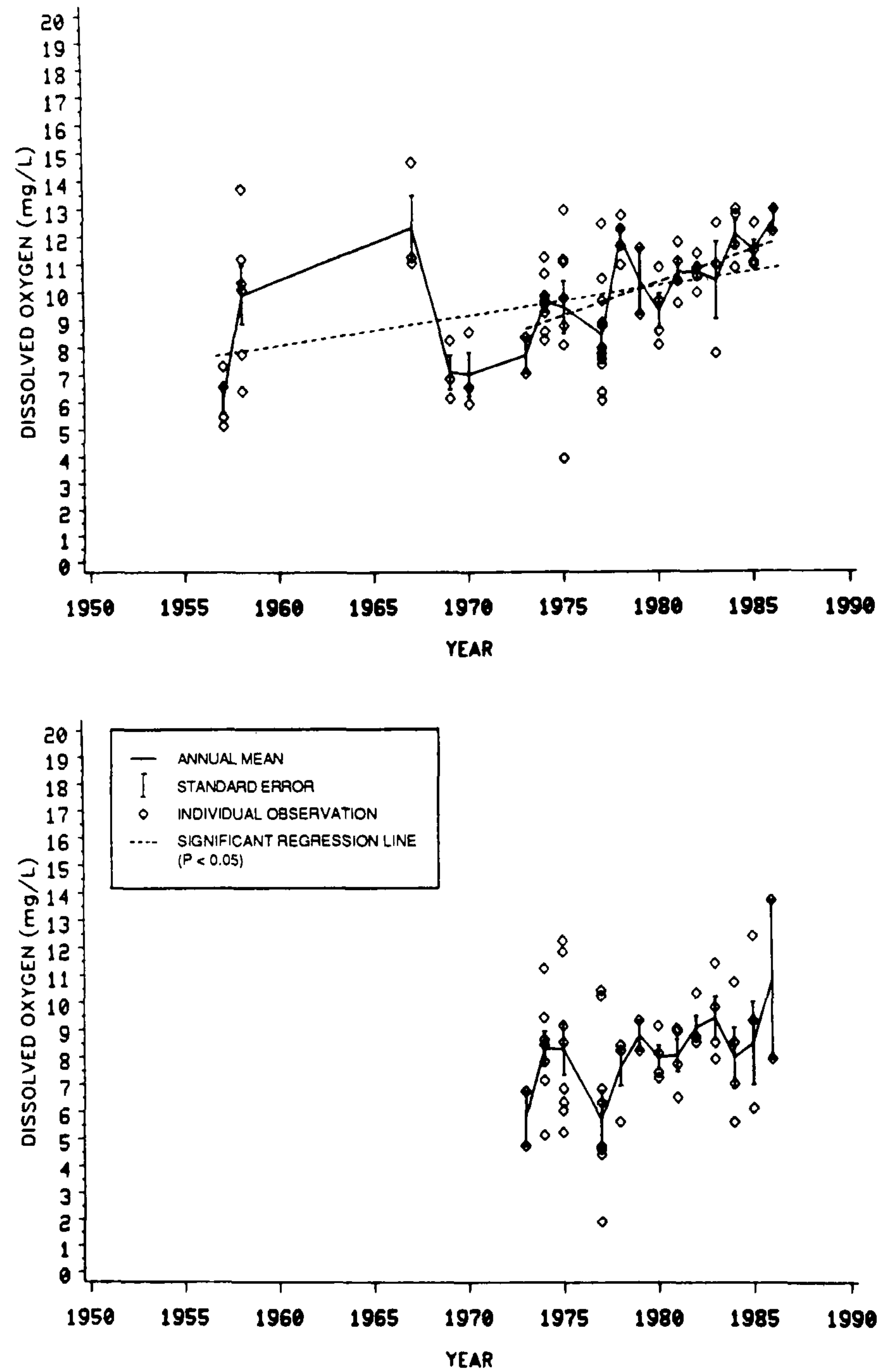


Figure 5.87. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Budd Inlet study area during the algal bloom season.

operational, removal of biological oxygen demand and addition of ozone to the effluent may have contributed to the apparent increase in dissolved oxygen concentrations. Also, as was observed in the other study areas in the southern sound, high dissolved oxygen concentrations, possibly caused by an intense algal bloom, were reported in 1986.

Nutrients--Plots of nitrate concentrations by year are shown in Figure 5.88. Because data are available only since 1977, comparisons between data collected before and after 1973 could not be performed. The regressions of nitrate by year were not significant ($P>0.05$) at either the surface or at 10-m depth (Table 5.12). Plots of phosphate concentrations by year are shown in Figure 5.89. The mean phosphate concentration at the surface was approximately 33 percent lower for the period 1973-1986 than for the period 1957-1972 (Table 5.11). However, the data collected from 1957 to 1972 consist of only five observations taken in only 2 yr, and the long-term regressions of phosphate concentrations against year were not significant ($P=0.35$). Thus, the evidence for decreasing phosphate concentrations since the 1950s in Budd Inlet is weak. The recent regressions (since 1973) of phosphate concentrations against year had a positive slope with a statistical significance probability of $P=0.08$. This result suggests that phosphate concentrations may have increased since 1973.

Indicators of Phytoplankton Growth--No chlorophyll a data are available. Percent dissolved oxygen saturation in surface water is plotted by year in Figure 5.90. Statistically significant ($P<0.05$) positive slopes were found in the long-term and recent regressions of surface dissolved oxygen saturation by year (Table 5.12). The greater net increase, approximately 41 percent, was detected by the recent regression. The increase in surface percent dissolved oxygen saturation was probably influenced by several factors. Some of this increase appears to result from the absence of very low values after 1977 (Figure 5.90), which was the last year that Ecology sampled the stations nearest the head of Budd Inlet. Other factors that could have affected the percent dissolved oxygen saturation include high dissolved oxygen concentrations observed in 1986 (13.7 mg/L on 23 June), and improvements in the sewage treatment facilities used by the City of Olympia and the surrounding region. Thus, the available evidence concerning

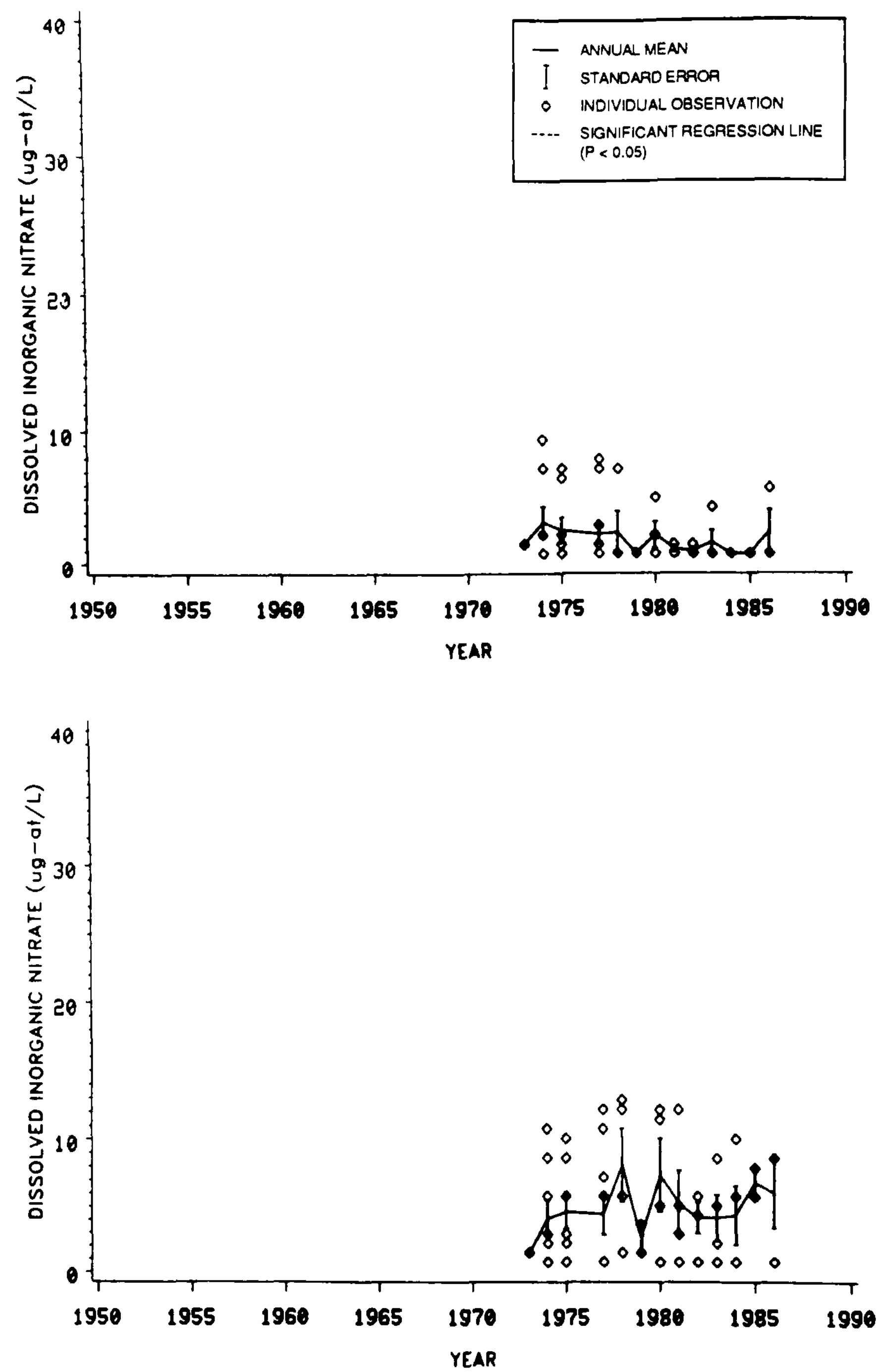


Figure 5.88. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the Budd Inlet study area during the algal bloom season.

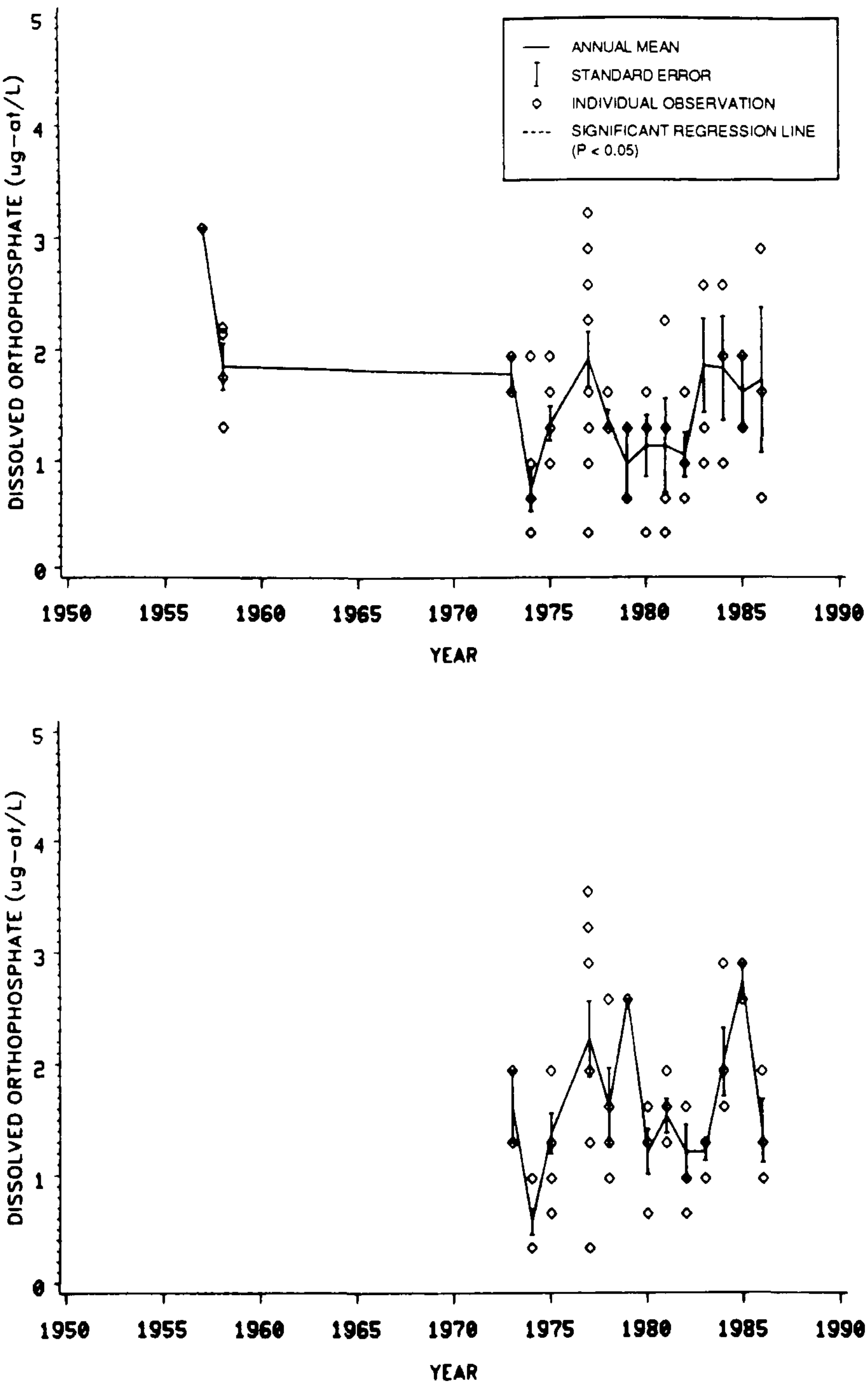


Figure 5.89. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Budd Inlet study area during the algal bloom season.

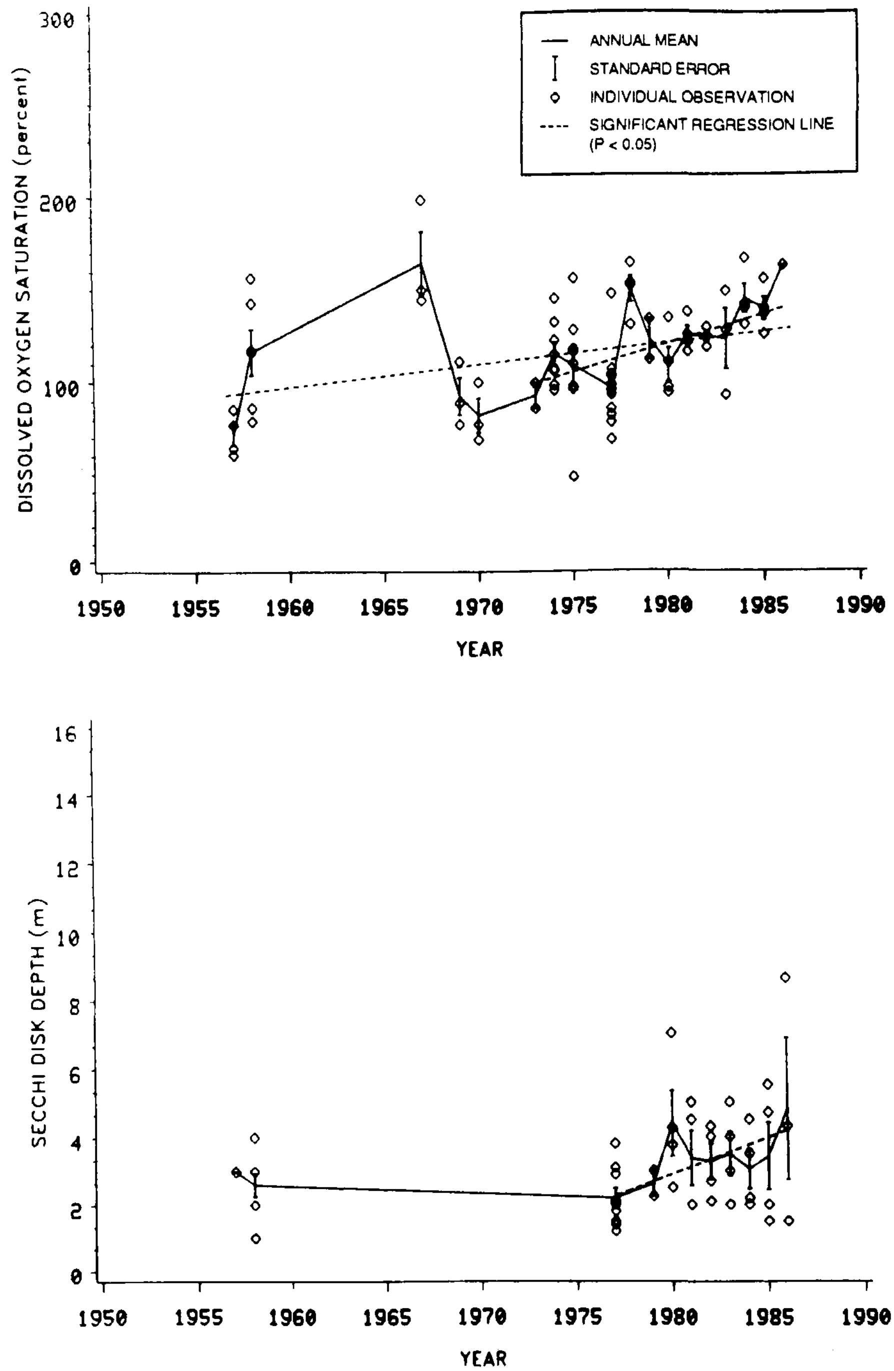


Figure 5.90. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Budd Inlet study area during the algal bloom season.

the intensity of algal blooms does not suggest that changes have occurred in the photosynthetic rates of Budd Inlet. This interpretation is further supported by the Secchi disk data (see below), which did not show declining transparency, as would be expected if phytoplankton density in the water column had increased.

Secchi depth data from the late 1950s and 1977-1986 are plotted by year in Figure 5.90. Mean Secchi disk depths measured before and after 1973 were not significantly different (Table 5.11). However, a positive slope was found in the regression of Secchi disk depth against year since 1973. This positive slope seems to have been caused by both low Secchi disk depth values near the beginning of the recent time period and by occasional high Secchi disk depth values since 1980. In addition, low values are absent from the database after 1977. It appears that changing station locations after 1977 also may have affected the Secchi disk depth data. When the stations near the head of Budd Inlet were dropped from Ecology's ambient monitoring program in 1977, the low Secchi disk depths disappeared from the data. These stations probably would have exhibited lower transparency due to proximity to the head of the inlet.

<u>Pollutants</u>--Data on sulfite waste liquor in the surface waters are available from the late 1950s and from 1969 to 1977 (Figure 5.91). Data for 10-m depth, available only from 1973 to 1977, are not plotted. Values were low [geometric mean surface concentration was 3.9 (Pearl Benson Index)] and no changes were detected at either depth.

Data on concentrations of fecal coliform bacteria for surface waters, available from 1973 to 1986, are plotted by year in Figure 5.91. A significant ($P<0.05$) decrease was detected at the surface. High values, frequently well in excess of Class B water quality standards, were reported from 1973 through 1977. Lower values, generally well below Class A water quality standards, were reported from 1978 through 1986.

The apparent decline in the concentrations of fecal coliform bacteria may have had more than one cause. The trend may be an artifact of changing sampling station locations because the sampling stations nearest the head of

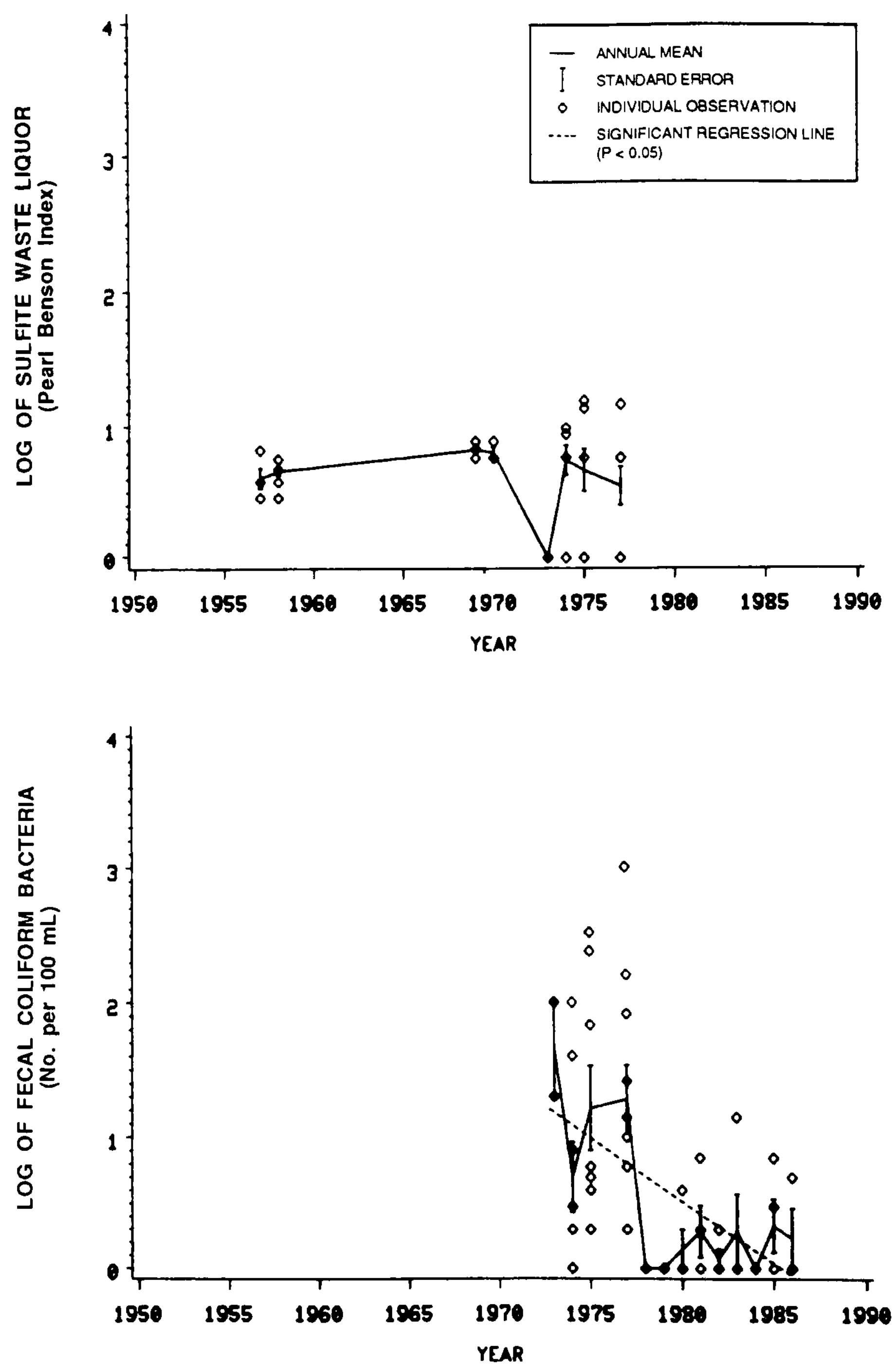


Figure 5.91. Log of concentrations of sulfite waste liquor and fecal coliform bacteria at the surface in the Budd Inlet study area during the algal bloom season.

the inlet and the known point sources of fecal coliform bacteria (URS 1986a) were dropped after 1977. However, the upgrades in the sewage treatment facilities discharging near the head of Budd Inlet may also have contributed to the decreased concentrations of fecal coliform bacteria. Prior to the improvements completed in 1981, a raw sewage lift station on the Deschutes River was known to fail frequently (Singleton, L., 7 August 1987, personal communication).

Totten Inlet

The study area is near Windy Point, in the middle of a shallow (approximately 15 m), sluggishly circulating, southern embayment (see Figure 5.63). Class A water quality standards apply in this rural area (Table 4.2). There is no large source of fresh water for Totten Inlet, although small creeks flow into the heads of each branch of the inlet. Extensive mudflats are found in Oyster Bay, at the southern head of the inlet. Totten Inlet is highly productive for shellfish.

Environmental Conditions in the Study Area--

Mean salinity and water temperature values are depicted in Figure 5.64. Data are available from the late 1950s, sporadically from the 1960s and 1970s, and regularly from 1978 through 1986. Mean salinity values at the surface and 10-m depth were very similar, approximately 28.0 ppt. Surface water was moderately warmer (approximately 1.0^{o} C) than water at 10-m depth. Mean surface temperatures were similar at the Totten Inlet and Budd Inlet study areas (15.5^{o} C), but the difference in the mean temperature values at the surface and 10-m depth was considerably smaller at the Totten Inlet site (1.0^{o} C for Totten Inlet; 2.7^{o} C for Budd Inlet). This difference suggests that more vertical mixing occurred at the Totten Inlet site. Vertical mixing may occur more readily in Totten Inlet than in Budd Inlet because Totten Inlet does not have a large freshwater source that contributes fresh water to the surface layers (i.e., there is no density gradient to inhibit mixing). Solar heating may also be more effective in Totten Inlet than in Budd Inlet because water clarity is greater in Totten Inlet

(Figure 5.67). Mean Secchi disk depth was 4.3 m in the Totten Inlet site and 3.1 m in the Budd Inlet site.

Both dissolved oxygen and nitrate concentrations exhibited only slight concentration gradients between the surface and 10-m depth (Figure 5.65). Mean dissolved oxygen concentrations were 10.0 mg/L at the surface and 10.2 mg/L at 10-m depth. Mean nitrate concentrations were 1.8 ug-at/L at the surface and 2.5 ug-at/L at 10-m depth. The nitrate concentration at the surface was 72 percent of the mean nitrate concentration at 10-m depth. These percentages were only 40 percent at the Budd Inlet site and 34 percent at the Carr Inlet site. These results also suggest that vertical mixing was substantial in the Totten Inlet study area. The higher concentration of dissolved oxygen at 10-m depth than at the surface suggests that there may be a source of dissolved oxygen at depth. This source is unknown, but it could have been photosynthesis by benthic diatoms.

The low nutrient concentrations (especially nitrate; Figures 5.65 and 5.66) and the high mean percent dissolved oxygen saturation (120 percent) at the surface (Figure 5.67) suggest that the water column in the Totten Inlet study area had high rates of nutrient uptake and primary production. Nitrate inputs also may have been low because of the lack of a large freshwater source that could serve as a nitrate source (see Chapter 2). The existing high rate of primary production and the low nitrate concentrations in Totten Inlet suggest that additional inputs of nutrients would be rapidly utilized by algae, causing further increases in the already substantial algal blooms.

Phosphate concentrations were positively correlated with salinity and water temperature values at the surface and at 10-m depth, although the surface correlation was not statistically significant when scaled with the Bonferroni inequality (Appendix F). Nitrate concentrations were not correlated with either salinity or water temperature values. Results of these correlation analyses can be explained by seasonal changes in salinity and water temperature values, and by the contrasting sources of nitrate and phosphate. Phosphate concentrations probably were positively correlated with both salinity and water temperature values because the main source of phosphate replenishment is oceanic water that replaces the existing water in the southern sound in late summer (Collias et al. 1974). (In the Totten Inlet data, phosphate concentrations reached the lowest monthly mean in June, and began to increase in July.) Thus, high phosphate concentrations could occur when both salinity and water temperature values were high. However, nitrate probably is replenished later, after the algal bloom season (see Chapter 2). Nitrate concentrations remained low throughout the entire algal bloom season.

Pollutant concentrations in the Totten Inlet study area were low (Figure 5.68). The geometric mean sulfite waste liquor concentration at the surface was 2.2 (Pearl Benson Index). The geometric mean concentration of fecal coliform bacteria at the surface was 1.04 organisms/100 mL. Both of these values are near analytical detection limits.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.11. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.12.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.92 and 5.93. A decline in salinity values at the surface was detected, but no changes were detected in water temperature values (Tables 5.11 and 5.12). The decline in salinity values could have been a real phenomenon, or it could have been an artifact of changes in station location over time. The early higher salinity samples were collected at the University of Washington's Station TOT472. That station was located somewhat downstream from Ecology's Station TOT001, which is where the recent lower salinity samples were collected. However, the horizontal salinity gradient in Totten Inlet is not steep or consistent (Olcay 1959) because the freshwater inputs into the head of Totten Inlet are small (USGS 1985). Hence, the effect of the changes in station locations on the salinity data cannot be assessed unequivocally.

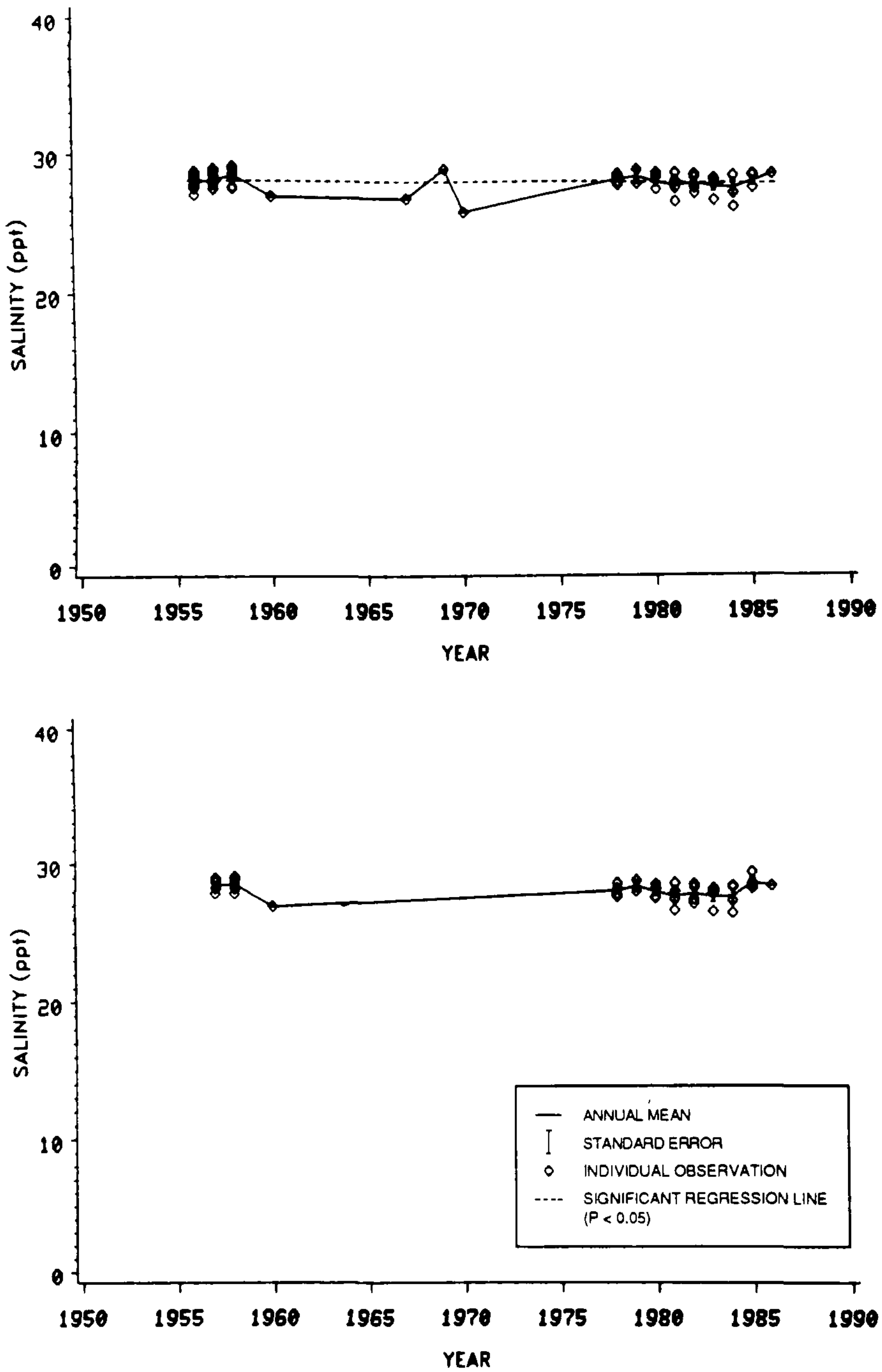


Figure 5.92. Salinity values at the surface and at 10-m depth in the Totten Inlet study area during the algal bloom season.

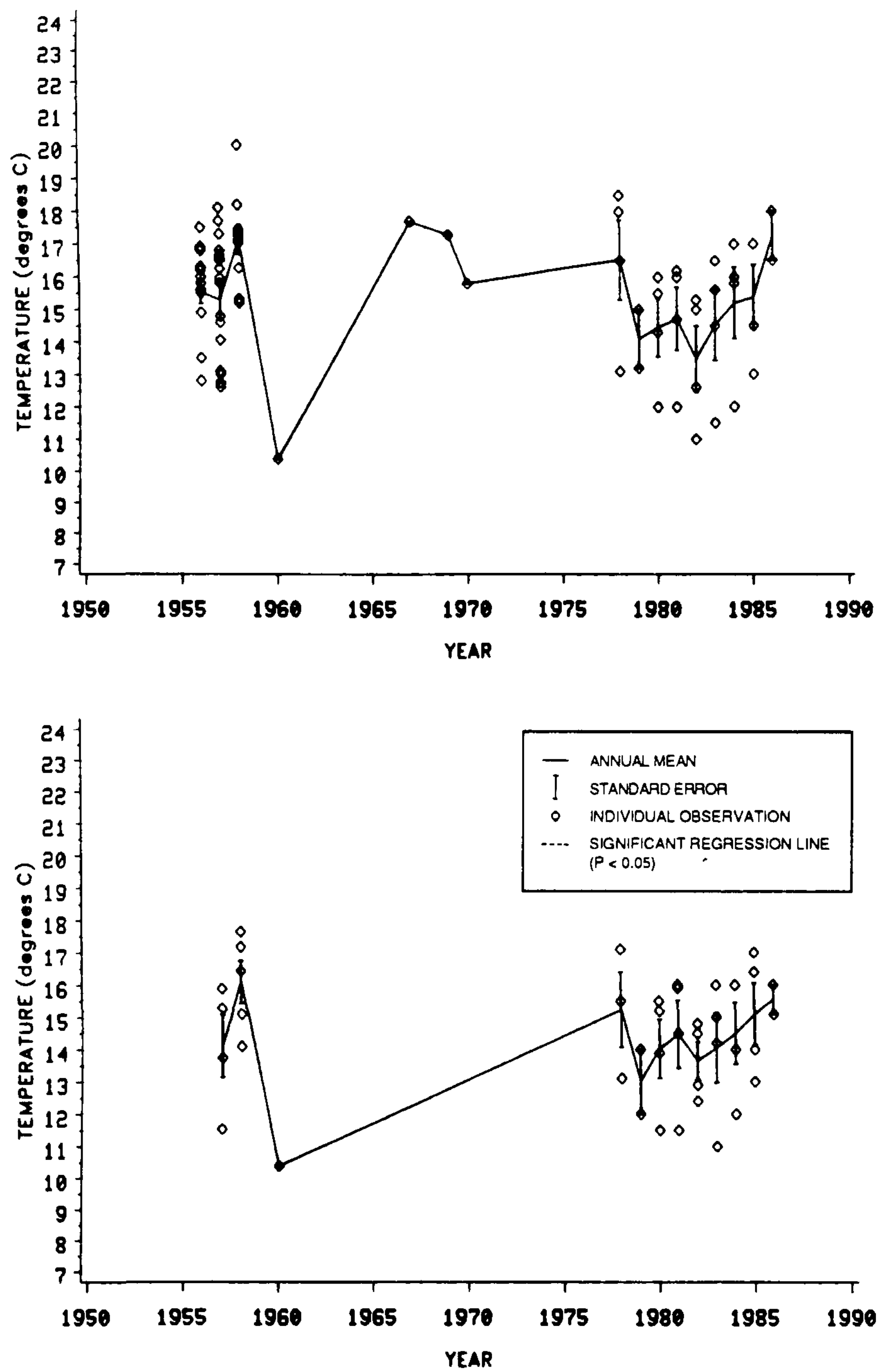


Figure 5.93. Water temperatures at the surface and at 10-m depth in the Totten Inlet study area during the algal bloom season.

Dissolved Oxygen--Plots of dissolved oxygen concentration by year are shown in Figure 5.94. Dissolved oxygen concentrations below the Class A water quality standard (see Table 4.2) were observed only once, in 1970. The only significant temporal trend in dissolved oxygen concentrations in the Totten Inlet study area was an increase at 10-m depth since 1978. This increase appears to have been caused largely by one very high concentration observed in 1986. This high value may be attributed to a particularly intense algal bloom.

Nutrients--Nitrate data are available since 1978. Although no significant changes in nitrate concentrations were detected (Figure 5.95), long-term declines in phosphate concentrations were detected at both the surface and at 10-m depth (Figure 5.96, Tables 5.11 and 5.12). No changes in phosphate concentrations were detected since 1978. No site-specific explanation was available for the long-term declines in phosphate concentrations.

The apparent long-term declines in phosphate concentrations were probably real phenomena. The effect of changing station locations probably would be to increase the apparent phosphate concentrations over time, contrary to the decline that was observed. The more recent samples were taken closer to the head of the inlet (Table 5.9, Figure 5.63), and phosphate concentrations during the bloom season typically are higher closer to the head of the inlet (Olcay 1959). The decline in phosphate concentrations detected over time occurred despite the interfering influence of changing station locations. However, it was not possible to assess the effects of changes in analytical techniques used by University of Washington and Ecology to measure phosphate. Thus, the possibility that changes in the data sources over time that may have influenced the data could not be evaluated.

Indicators of Phytoplankton Growth--No chlorophyll *a* data are available. Percent dissolved oxygen saturation at the surface and Secchi disk depth are plotted by year in Figure 5.97. Because no temporal changes were detected for either variable (Tables 5.11 and 5.12), overall changes in algal abundance do not appear to have occurred.

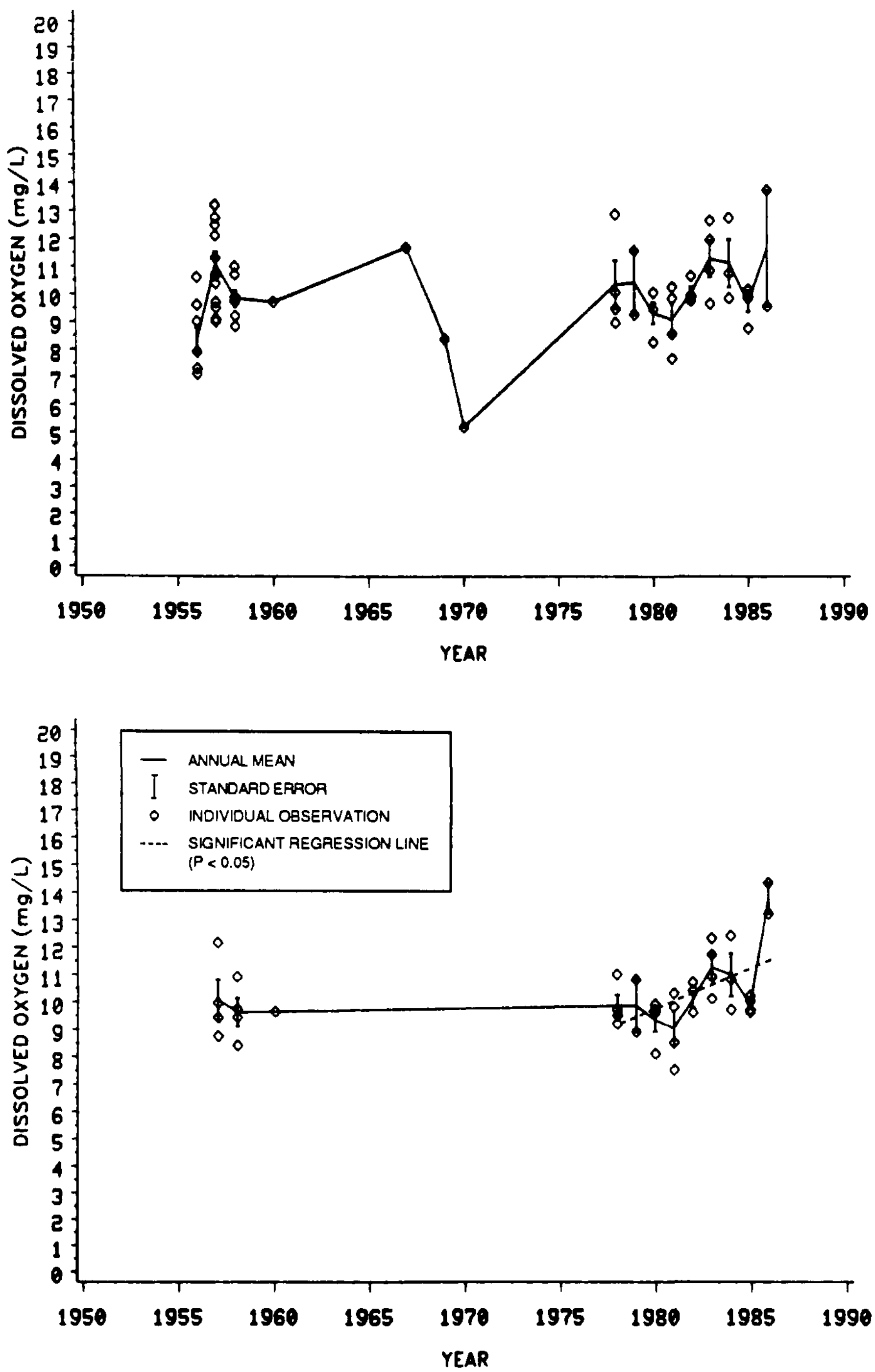


Figure 5.94. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Totten Inlet study area during the algal bloom season.

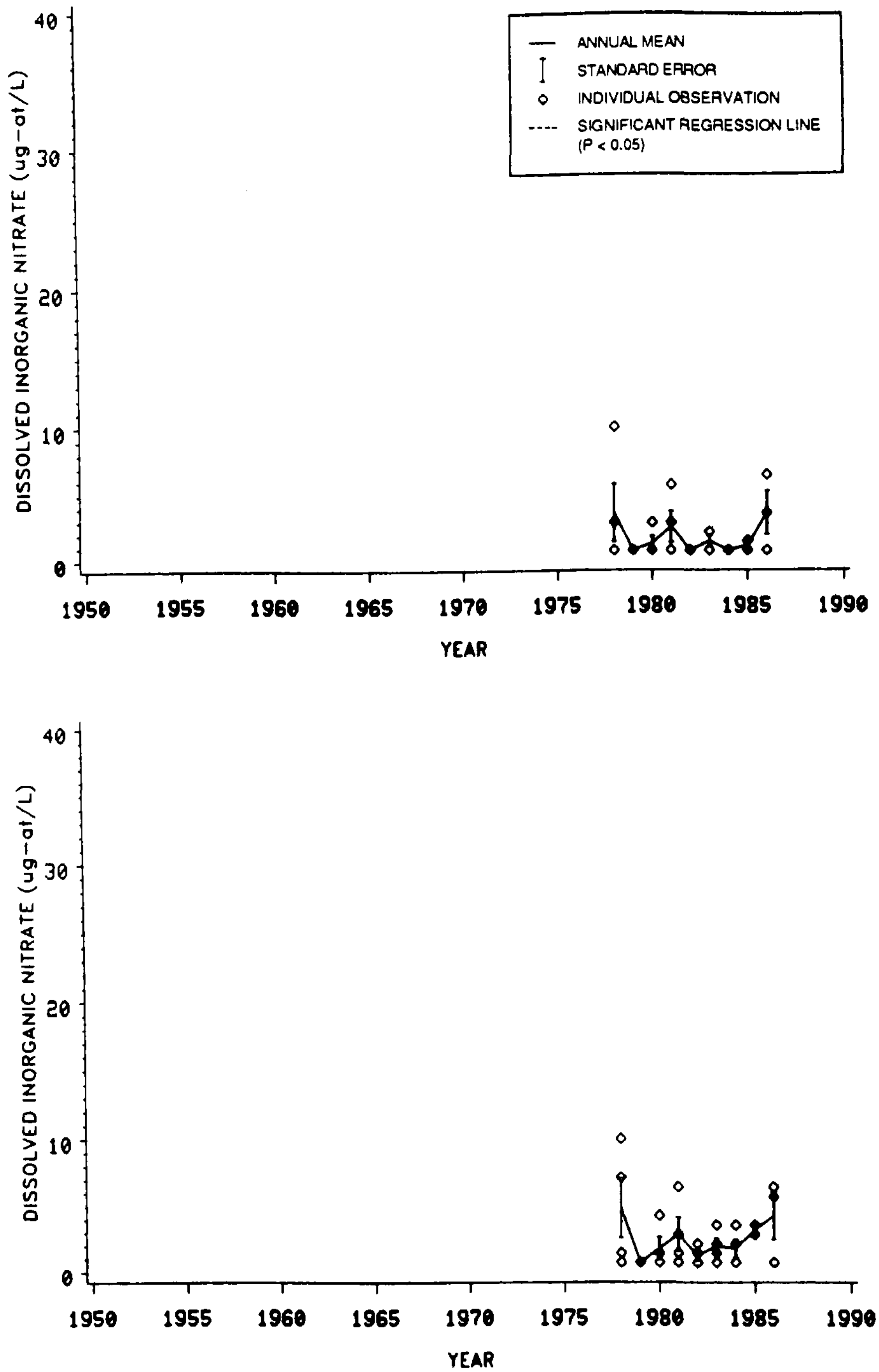


Figure 5.95. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the Totten Inlet study area during the algal bloom season.

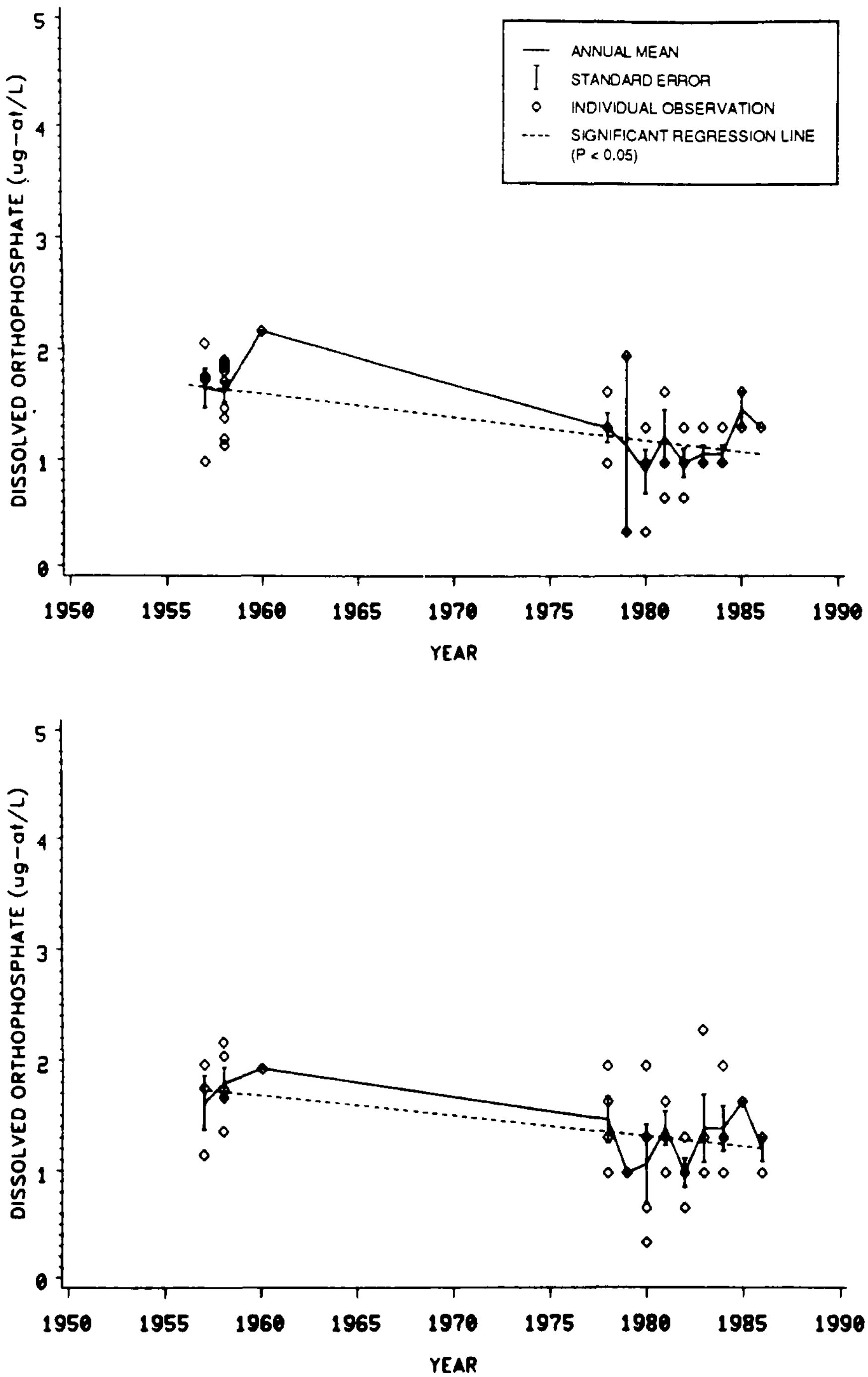
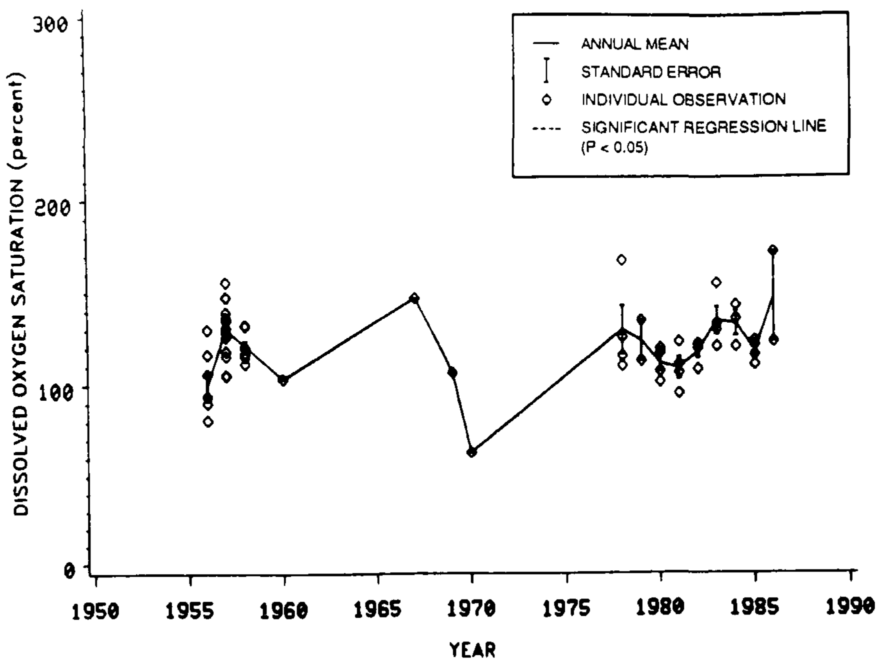


Figure 5.96. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Totten Inlet study area during the algal bloom season.



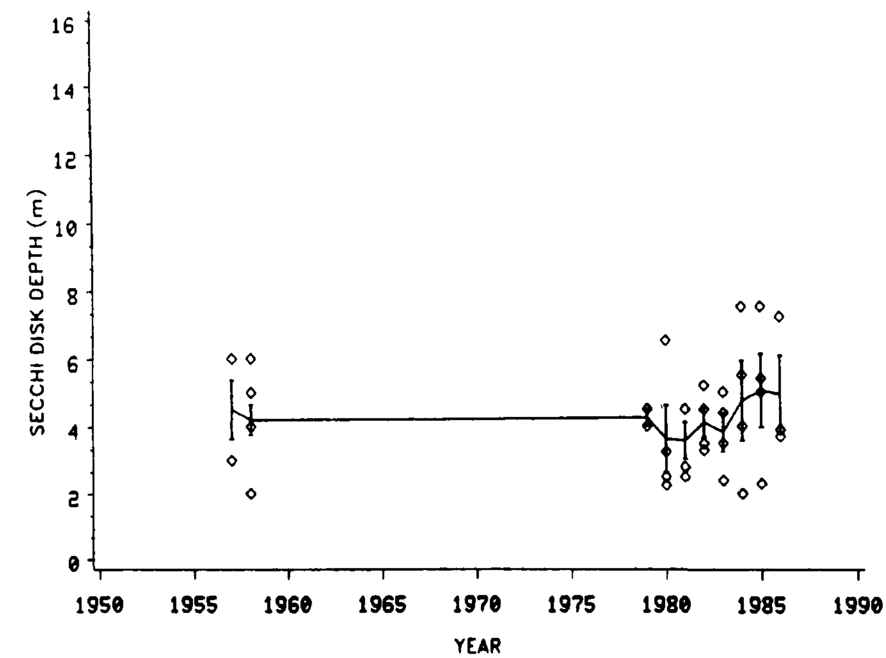


Figure 5.97. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Totten Inlet study area during the algal bloom season.

Pollutants--Values of sulfite waste liquor and fecal coliform bacteria for surface water are plotted by year in Figure 5.98. Temporal trends were not detected for either variable (Tables 5.11 and 5.12).

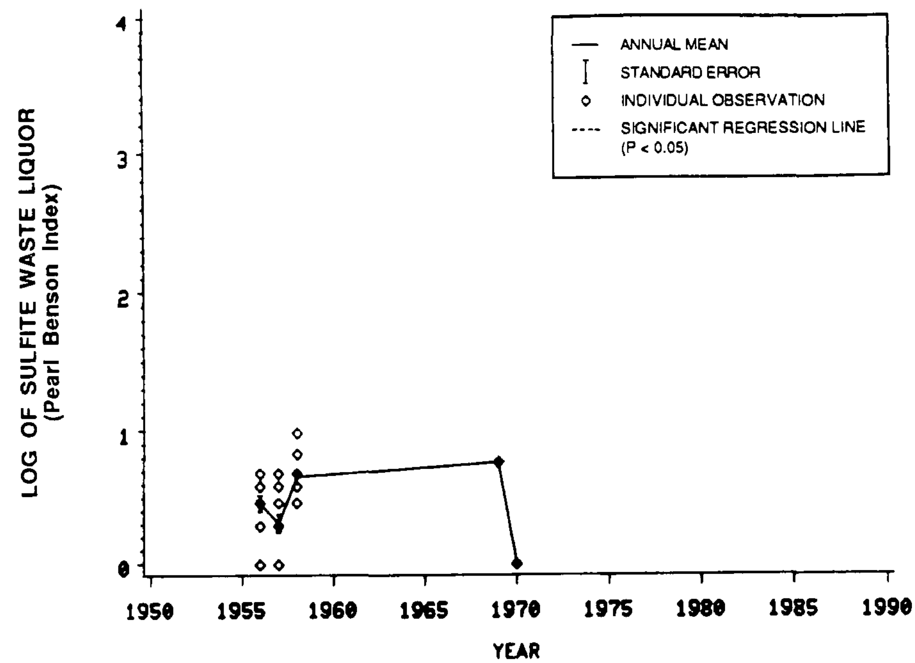
Oakland Bay

The study area is located near the intersection of Oakland Bay and Hammersley Inlet (see Figure 5.63). Sampling stations are located from Eagle Point to southwestern Oakland Bay, near Goldsborough Creek and the City of Shelton. Class B water quality standards apply in the area. Historically the area was affected by the ITT-Rayonier sulfite pulp mill, which operated from 1928 to 1957 (NOAA 1985). A primary sewage treatment plant that discharged into the inner portion of Shelton Harbor was replaced in 1979 by a secondary sewage treatment plant that discharges near Eagle Point (Singleton, L., 20 October 1987, personal communication).

Circulation in the study area is sluggish and erratic because Oakland Bay is connected to Puget Sound only through the shallow and narrow Hammersley Inlet. Oakland Bay is shallow, averaging approximately 3 m deep over much of its area. Extensive mudflats border most of the bay. The study area ranges from 3 to 15 m deep. Two stations were too shallow to have 10-m data (University of Washington's Station OAK484 and Ecology's Station OAK003).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.64. Data are available from 1956 through 1986. Temporal coverage was variable and data for 10-m depth are available only since 1975. Salinity and water temperature values were affected by the timing of the algal bloom period. This period was shorter in duration and occurred earlier in the year in Oakland Bay than in the other southern sound study areas (Table 5.10). Salinity values in the Oakland Bay study area were the lowest of all the southern sound study areas at both the surface and at 10-m depth. The Oakland Bay site also exhibited the steepest



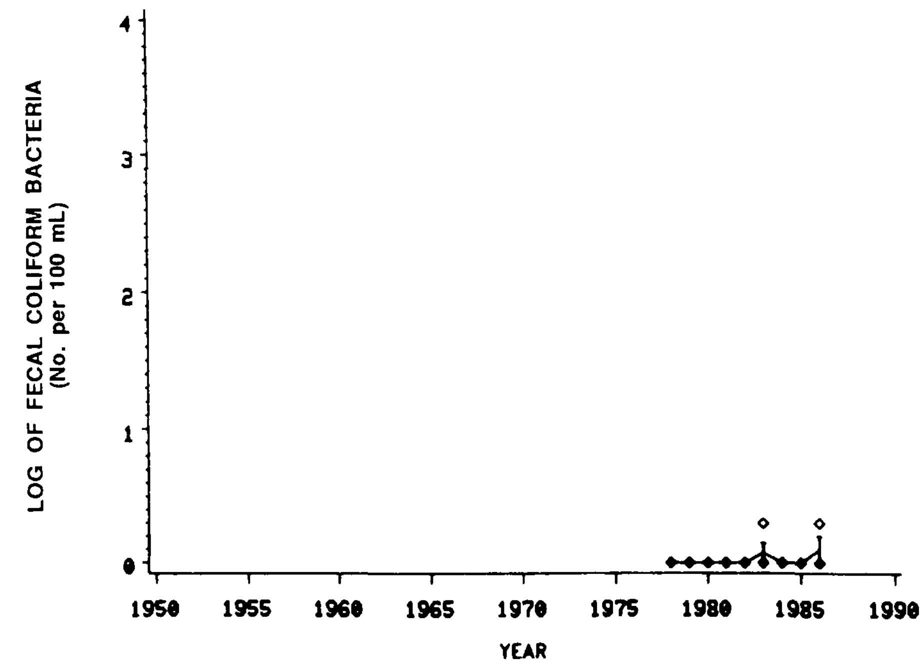


Figure 5.98. Log of concentrations of sulfite waste liquor and fecal coliform bacteria at the surface in the Totten Inlet study area during the algal bloom season.

vertical salinity gradient, a difference of 3.3 ppt between the mean salinity values at the surface and at 10-m depth. Density stratification appears to have been well developed in the study area, possibly because the fresh water from Goldsborough Creek supplied fresh water to the surface in the study area.

The thermal depth gradient in the Oakland Bay study area was not as large as the gradients observed in Carr and Budd Inlets (Figure 5.64). In the Oakland Bay site, the mean water temperature was 0.7^{o} C higher at the surface than at 10-m depth. The equivalent differences in Carr and Budd Inlets were 2.3^{o} C and 2.7^{o} C, respectively. The relatively small thermal depth gradient may be due, in part, to the shallowness and small volume of Oakland Bay. These characteristics would allow solar warming to be effective throughout the water column. The mean water temperatures during the algal bloom season in the Oakland Bay study area were lower than those in the other southern sound study areas (e.g., 13.6^{o} C at the surface at the Oakland Bay site and 15.5^{o} C at the surface at the Totten Inlet site). This temperature difference was probably an effect of the timing of the algal bloom season in the Oakland Bay study area. Algal blooms occurred from April through June in the Oakland Bay site and from May through August in the other southern sound sites. Mean water temperature values increased at the Oakland Bay site during midsummer, after the bloom season, averaging approximately 1.5^{o} C higher in the Oakland Bay site than in the Totten Inlet site.

Figure 5.65 shows a concentration gradient of dissolved oxygen over depth that is reversed from the typical estuarine bloom condition. The mean dissolved oxygen concentration at the surface was approximately 1.4 mg/L lower than the mean dissolved oxygen concentration at 10-m depth. Most of this apparent difference was caused by the presence of sulfite waste liquor in many of the surface water samples collected in 1956 and 1957, when the ITT-Rayonier pulp mill was still in operation. As discussed in Chapter 3, sulfite waste liquor lowers the dissolved oxygen concentration in seawater.

After the ITT-Rayonier pulp mill closed, the depth gradient in dissolved oxygen concentrations observed in the Oakland Bay study area was similar to the gradient observed in the Totten Inlet study area. In both sites, the mean dissolved oxygen concentration was approximately 0.2 mg/L lower at the surface than at 10-m depth. Moreover, the mean dissolved oxygen concentration at 10-m depth was higher in Oakland Bay (9.9 mg/L) than in Budd Inlet (7.9 mg/L), Nisqually Reach (8.1 mg/L), or Carr Inlet (8.4 mg/L). As in Totten Inlet, the cause of the higher dissolved oxygen concentration at 10-m depth is unknown. Possible explanations include high photosynthetic oxygen production by benthic diatoms and advection of high dissolved oxygen water along the bottom through Hammersley Inlet.

Depth gradients of nutrient concentrations were fairly typical of partially stratified estuaries. Mean concentrations at the surface were lower than at 10-m depth (Figures 5.65 and 5.66). At 10-m depth, the mean nitrate concentration in the Oakland Bay study area during the algal bloom period was lower (5.8 ug-at/L) than in the Carr Inlet (10.7 ug-at/L) or the Nisqually Reach (12.9 ug-at/L) study areas. However, it was slightly higher than in the Budd Inlet (4.8 ug-at/L) or the Totten Inlet (2.5 ug-at/L) study areas. Phosphate concentrations in the Oakland Bay study area were slightly lower than in the other southern sound study areas (e.g., mean surface phosphate concentration was 1.2 ug-at/L at the Oakland Bay site and 1.5 ug-at/L at the Budd Inlet site).

The positive correlation between surface phosphate concentrations and Secchi disk depths (Appendix F) probably reflects variation in both variables caused by the waxing and waning of algal blooms. Low nutrient concentrations would tend to occur during blooms, and blooms also would reduce transparency of the water column. When blooms were absent, both nutrient concentrations and transparency would be high.

The algal blooms that occurred in Oakland Bay did not seem to be as intense as those in the other southern sound study areas (Table 5.10). [The limited amount of chlorophyll _a_ data available indicates that similar standing stocks of phytoplankton were found in the Carr Inlet and Oakland Bay sites (Figure 5.66). However, because data were collected during different time periods, a direct comparison is not very meaningful.] The algal bloom in the Oakland Bay study area does not appear to have been limited by nutrient availability. Although nutrient concentrations were always higher in the Oakland Bay site than in the Totten Inlet site, algal blooms appeared to have been more intense in the Totten Inlet site. Higher turbidity of the water column in Oakland Bay is a possible explanation for the more limited intensity of the algal bloom, when compared with Totten Inlet. Both areas probably support extensive populations of benthic diatoms, but the lower transparency of the water column in Oakland Bay may reduce light penetration to the bottom, thereby lowering photosynthetic rates and dissolved oxygen concentrations at the surface.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.11. Slopes of statistically significant long-term and recent regressions of the values of water quality variables by year are given in Table 5.12.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.99 and 5.100. The nonparametric ANOVA detected no significant differences ($P>0.05$) between data collected before 1973 and data collected from 1973 to 1986 for either surface salinity or surface water temperature. The long-term regression of surface salinity values by year had a significant ($P<0.05$) positive slope. This pattern was probably caused by some very low salinity values observed in 1956 and 1957. The low values were observed at Station OAK484, the station closest to Goldsborough Creek and the point of discharge for the ITT-Rayonier pulp mill. Data were not collected at this station after 1957. Salinity values at Station OAK484 did not differ significantly from salinity values at Station OAK485 during periods of overlapping samples, but were lower on average. Therefore, the apparent increase in salinity in the Oakland Bay study area may have been caused at least in part by changing station locations over time.

Dissolved Oxygen--Plots of dissolved oxygen concentrations by year are shown in Figure 5.101. The Class B dissolved oxygen water quality standard (see Table 4.2) has been met since the ITT-Rayonier pulp mill closed in 1957. A long-term increase in dissolved oxygen concentrations was observed

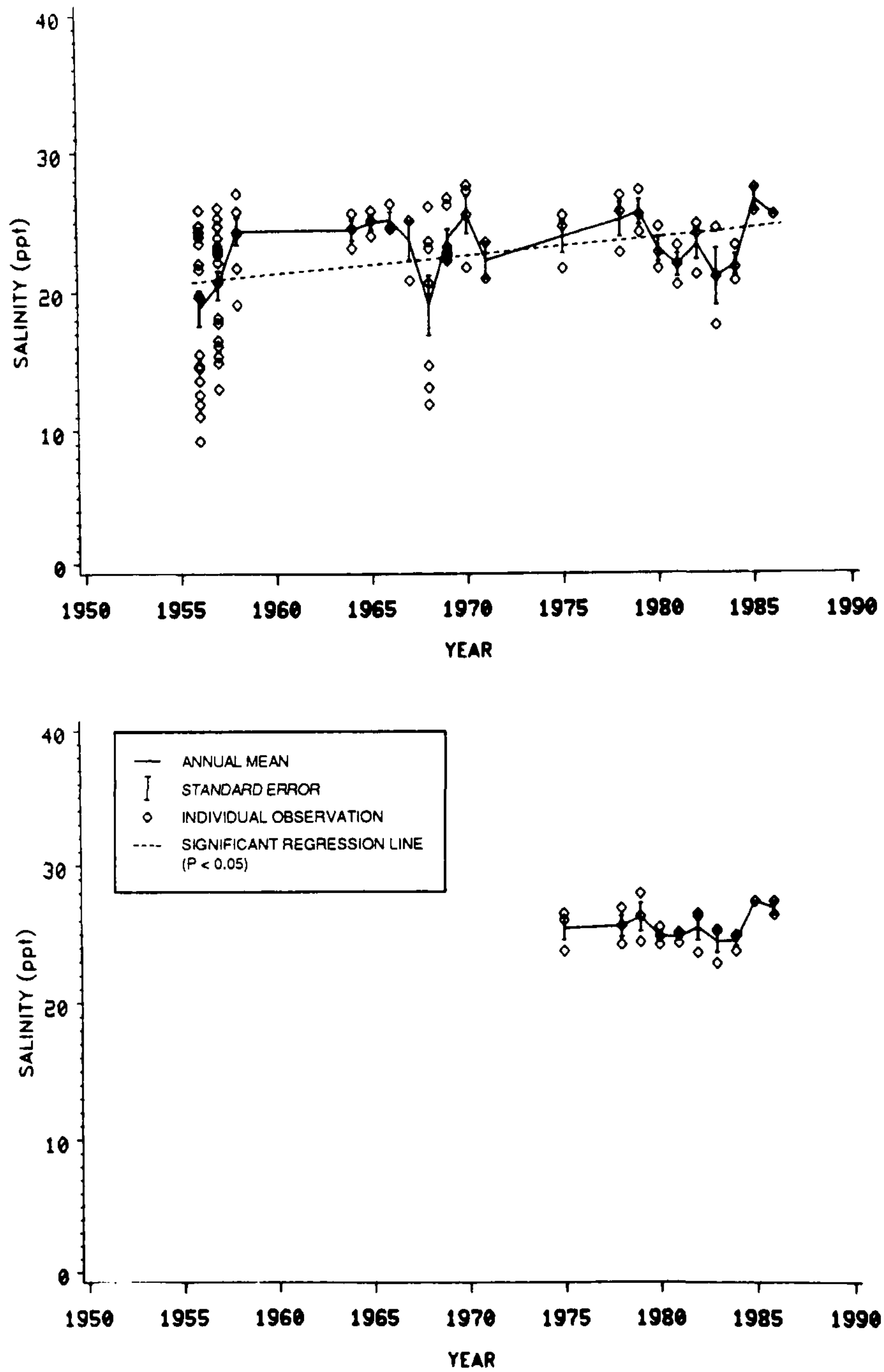


Figure 5.99. Salinity values at the surface and at 10-m depth in the Oakland Bay study area during the algal bloom season.

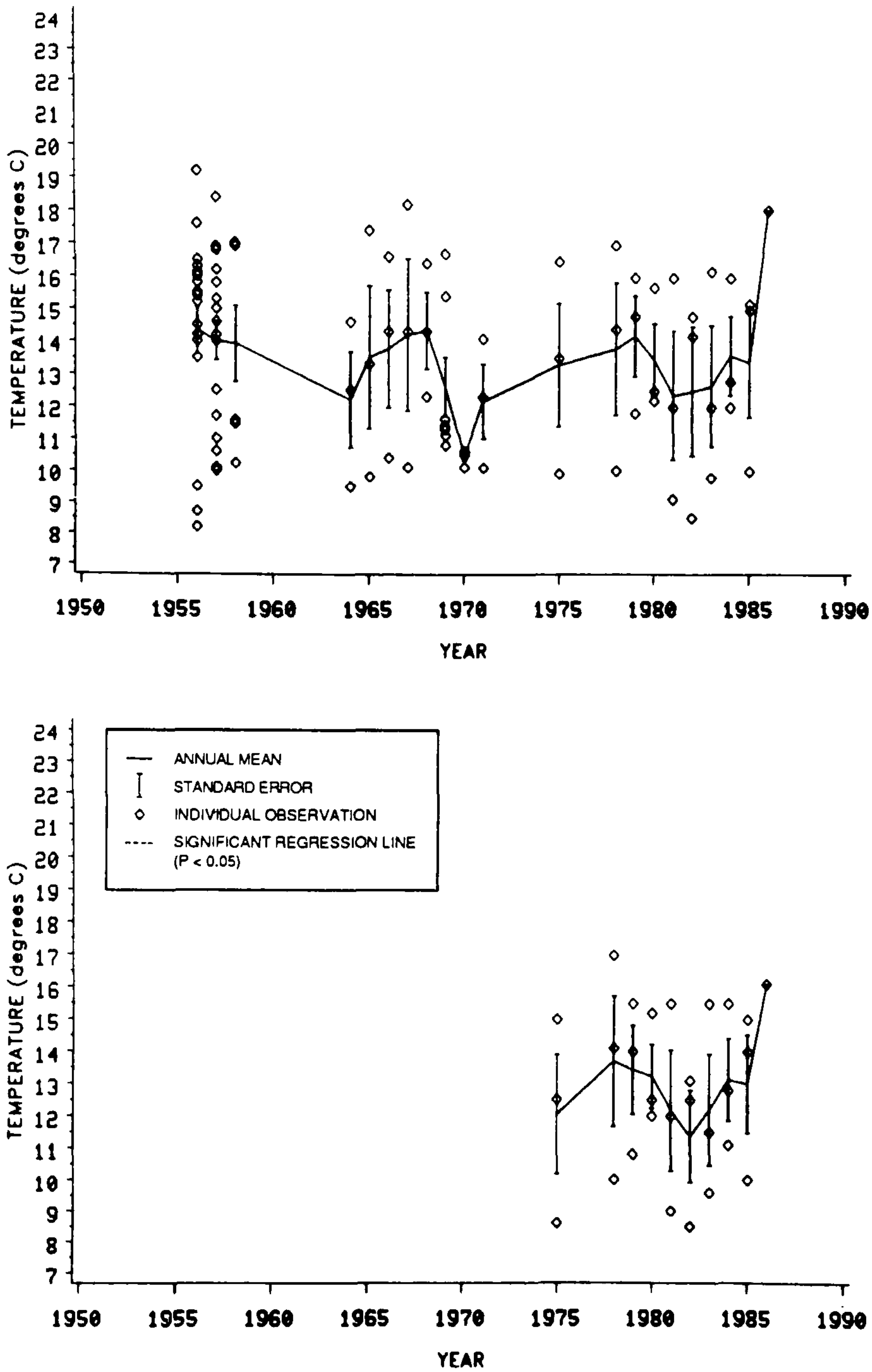


Figure 5.100. Water temperatures at the surface and at 10-m depth in the Oakland Bay study area during the algal bloom season.

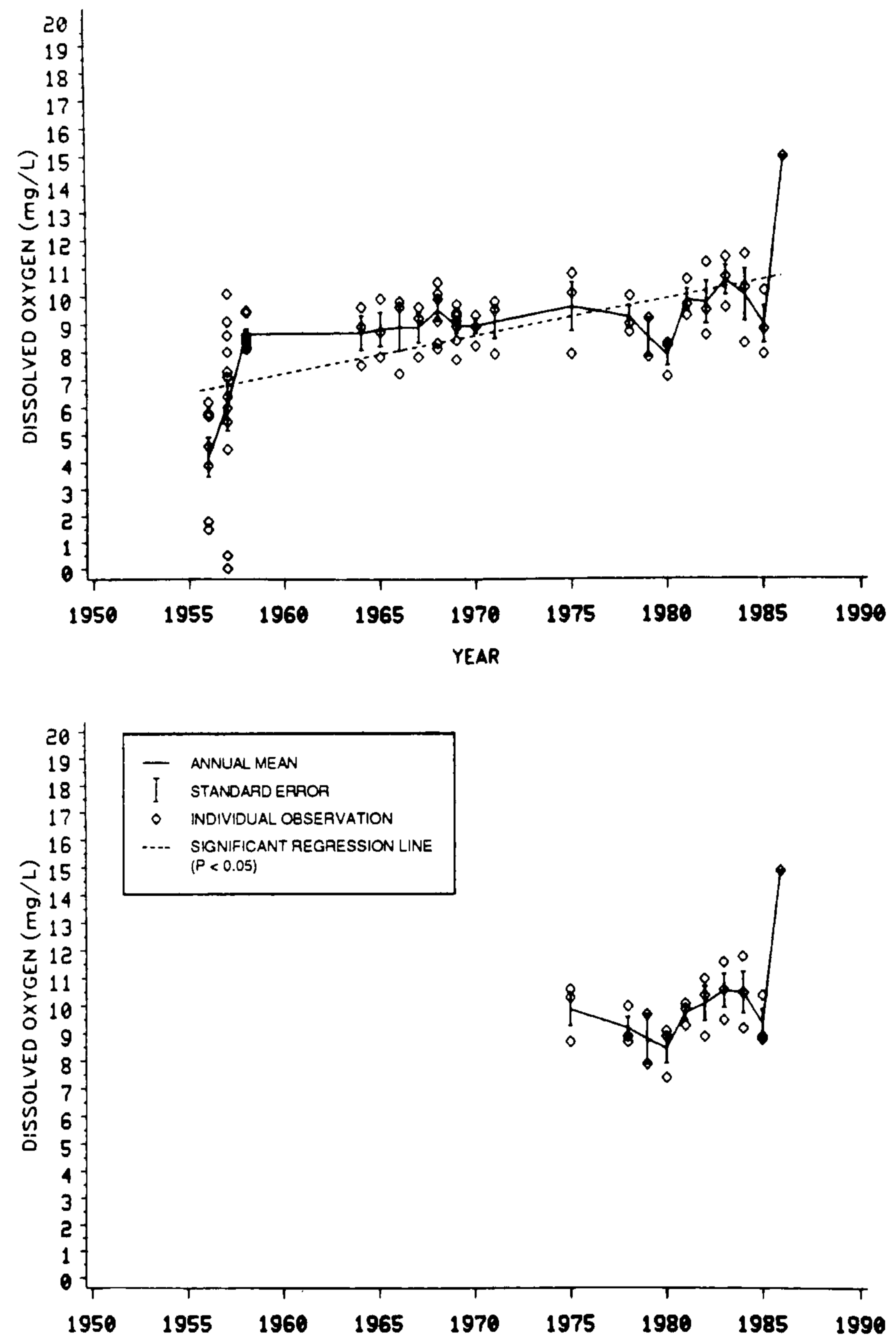


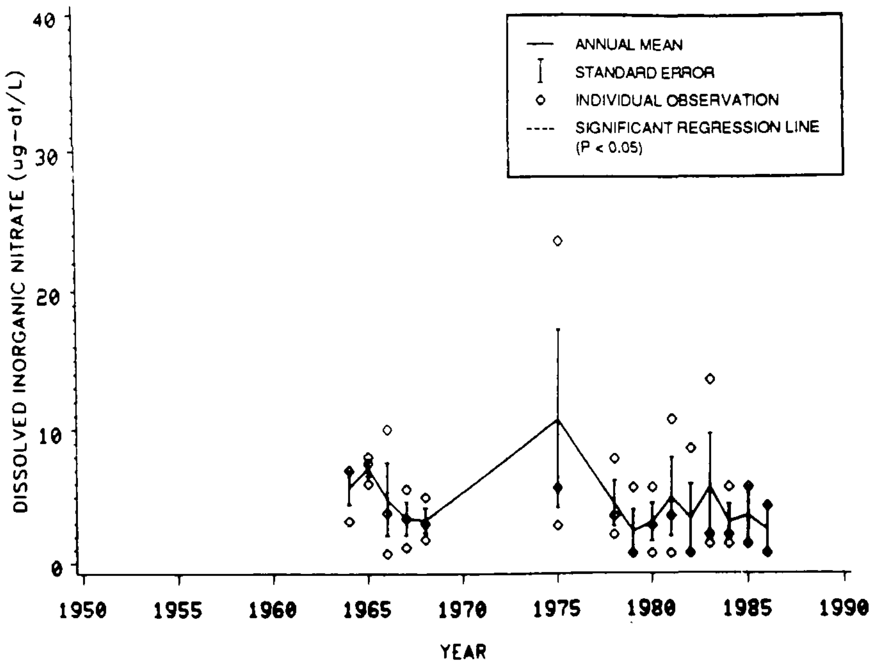
Figure 5.101. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Oakland Bay study area during the algal bloom season.

at the surface (Tables 5.11 and 5.12). This increase appears to have been caused by very low values observed during 1956 and 1957, and by very high values observed in 1986. The high values reported in 1986 may have been caused by an intense algal bloom. The early data actually include some zero values. The same samples that contained no dissolved oxygen had Pearl Benson Index values of sulfite waste liquor in excess of 200. As discussed in Chapter 3, pulp mill wastes react with dissolved oxygen, as well as with the reagents used to measure dissolved oxygen. Therefore, the low early values probably were caused by contamination with pulp mill wastes.

Nutrients--Plots of nitrate and phosphate concentrations by year are shown in Figures 5.102 and 5.103, respectively. No statistically significant changes were detected in nitrate concentrations (Tables 5.11 and 5.12). Results of the nonparametric ANOVA indicated that average surface phosphate concentrations were lower from 1973 through 1986 than from 1958 through 1972 (Table 5.11). The slope of the long-term regression for surface phosphate concentration against year was negative (Table 5.12). Although statistically significant ($P<0.05$), these trends were based on a sparse data set for the period of 1958 through 1975. In contrast to the long-term decline, phosphate concentrations have increased significantly ($P<0.05$) since 1975.

The high phosphate concentrations detected in 1958 probably can be attributed to natural variation in phosphate concentrations. Alternatively, these high concentrations could have been influenced by residual effects of the ITT-Rayonier pulp mill, which closed in 1957. Changing station locations probably did not influence the data substantially. The early phosphate data were obtained from the University of Washington's Station OAK485, which was located near the stations sampled recently by Ecology. Because the analytical techniques used by Washington Department of Fisheries to generate the 1958 data could not be calibrated with Ecology's techniques, analytical differences could have influenced the data. However, the techniques used for phosphate analyses by Washington Department of Fisheries in the late 1950s are considered to provide fairly accurate data (Appendix A).

The recent (since 1975) increase in phosphate concentrations probably was a real phenomenon. No specific factors were identified that could have



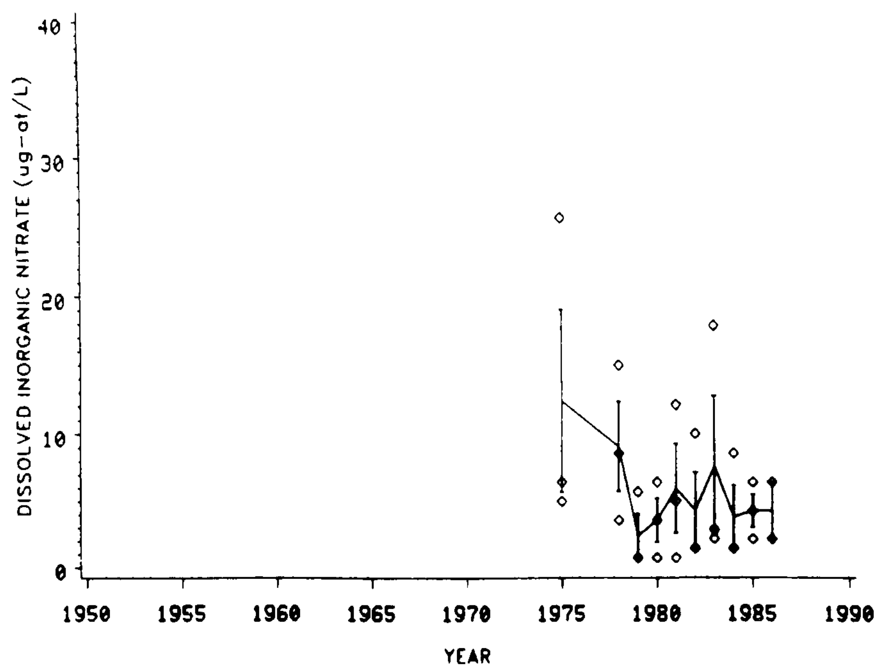


Figure 5.102. Concentrations of dissolved inorganic nitrate at the surface and at 10-m depth in the Oakland Bay study area during the algal bloom season.

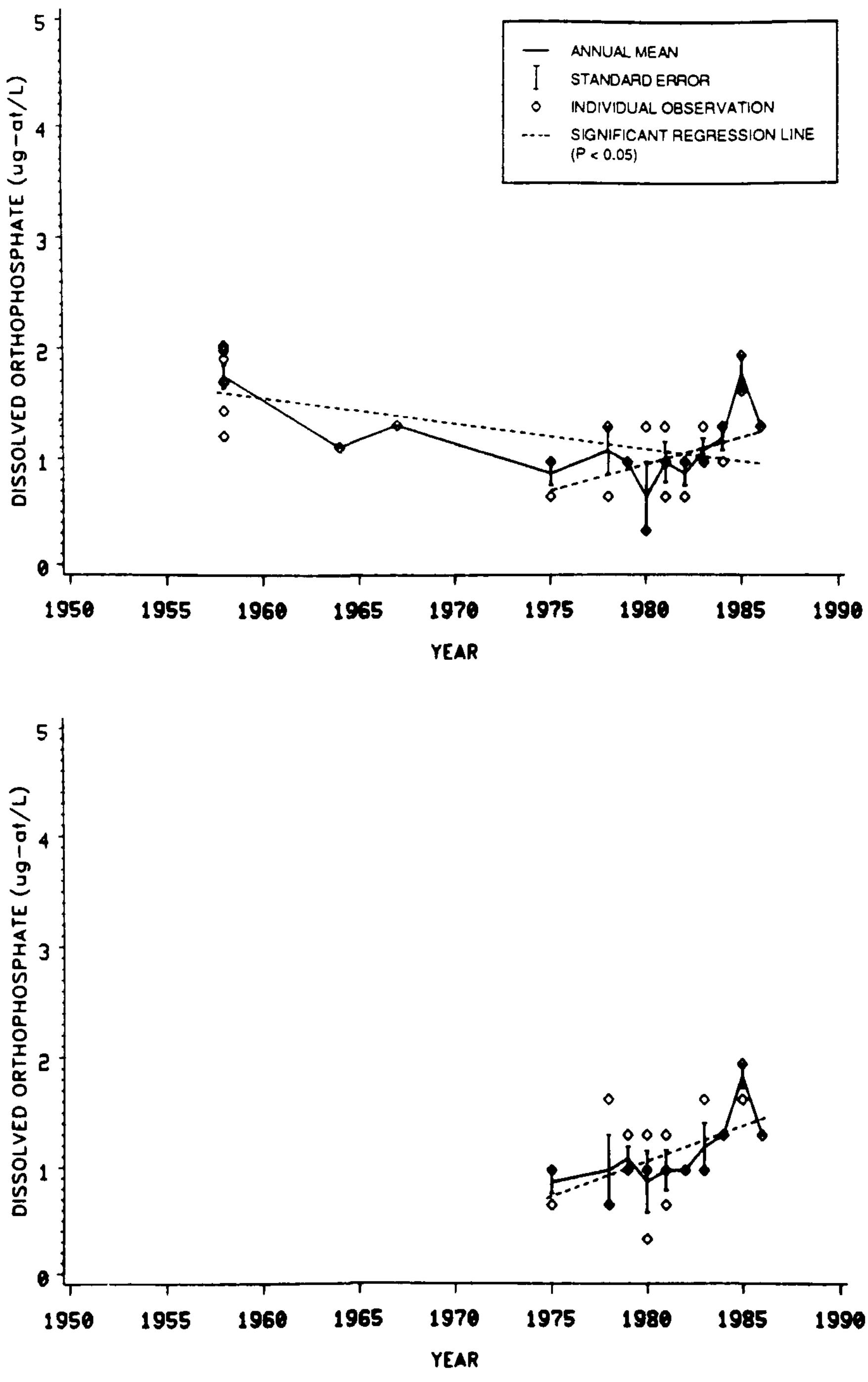


Figure 5.103. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Oakland Bay study area during the algal bloom season.

contributed to this increase. All the samples collected since 1975 were collected at Ecology's Station OAK004, (i.e., changes in station location did not occur). Also, Ecology's analytical techniques have not changed substantially since 1975.

Indicators of Phytoplankton Growth--Chlorophyll a data are available for the Oakland Bay study area from 1964 through 1971 (Figure 5.104). No temporal trend was detected. The percent dissolved oxygen saturation at the surface has increased since 1958 (Figure 5.104). This increase was influenced by low values recorded in 1956 and 1957 (presumably dissolved oxygen saturation percentages near zero percent were due to high concentrations of sulfite waste liquor), and by high values (over 180 percent) recorded in 1986. The highest value for surface percent dissolved oxygen saturation was observed on 23 June 1986. A very high surface temperature and a substantial thermal depth gradient was also observed. These conditions suggest that an intense algal bloom was occurring on that date. The single high data point recorded in 1986 may not have been indicative of a temporal trend. However, it had a substantial influence on the positive slope of the regression because it occurred in the most recent year of the data set.

Secchi disk depth data are plotted by year in Figure 5.105. No long-term change in Secchi disk depths was detected (Tables 5.11 and 5.12). However, the increases in the values observed since 1978 were statistically significant ($P<0.05$). The highest mean Secchi disk depth readings were recorded in 1959 and 1986. These values suggest that transparency may have decreased after 1957 and increased back to earlier levels during the 1980s. Alternatively, the high readings at the beginning and end of the data set could be due to inherent high variability or to changes in station locations.

Pollutants--Sulfite waste liquor data from the surface are plotted by year in Figure 5.105. A very large decline in sulfite waste liquor concentrations coincided with the closing of the ITT-Rayonier pulp mill in 1957. Levels remained low in sporadically collected samples until sampling ceased in 1975. Sulfite waste liquor data (Figure 5.105) indicate that the

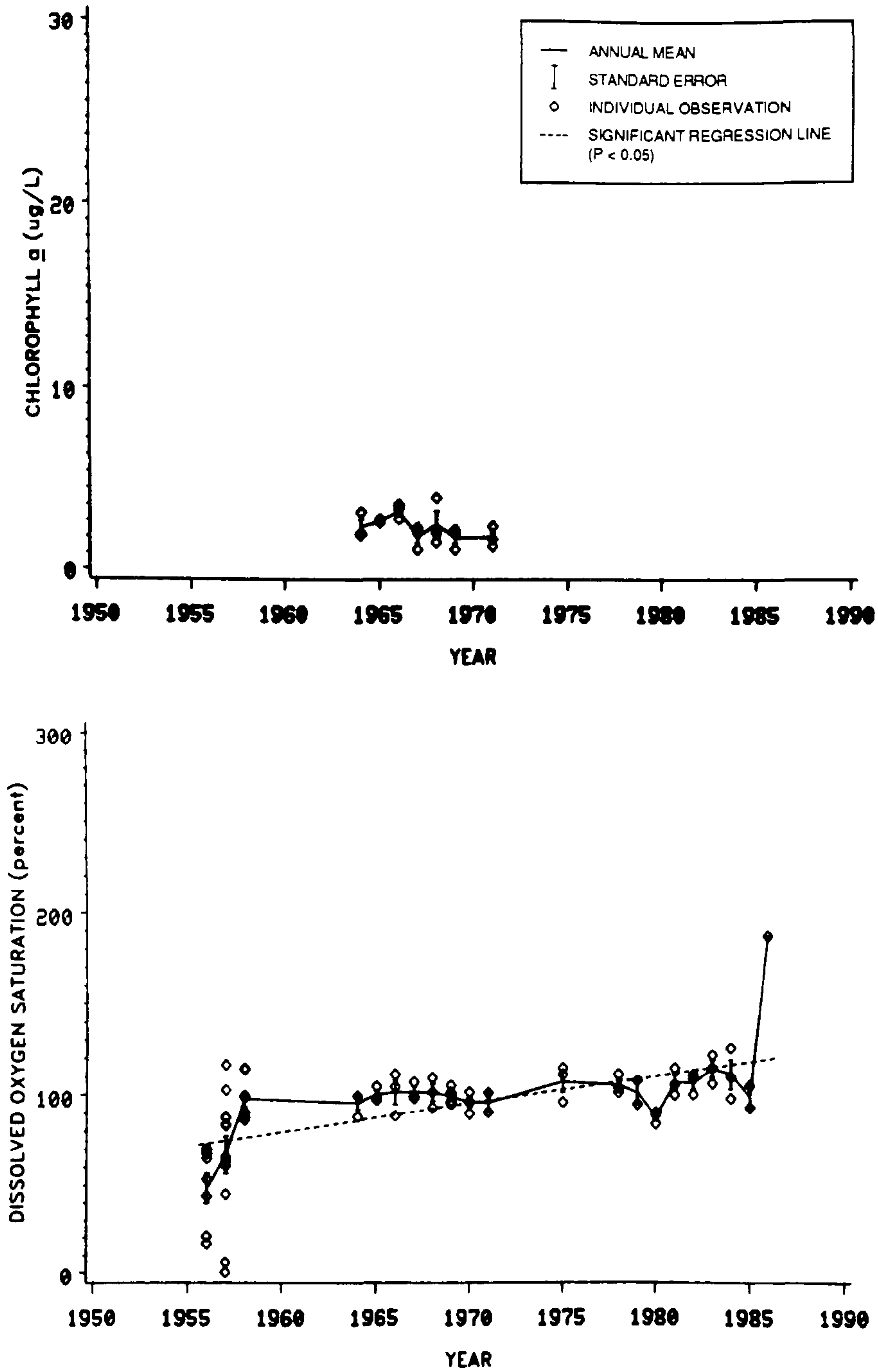


Figure 5.104. Concentrations of chlorophyll a and percent dissolved oxygen saturation at the surface in the Oakland Bay study area during the algal bloom season.

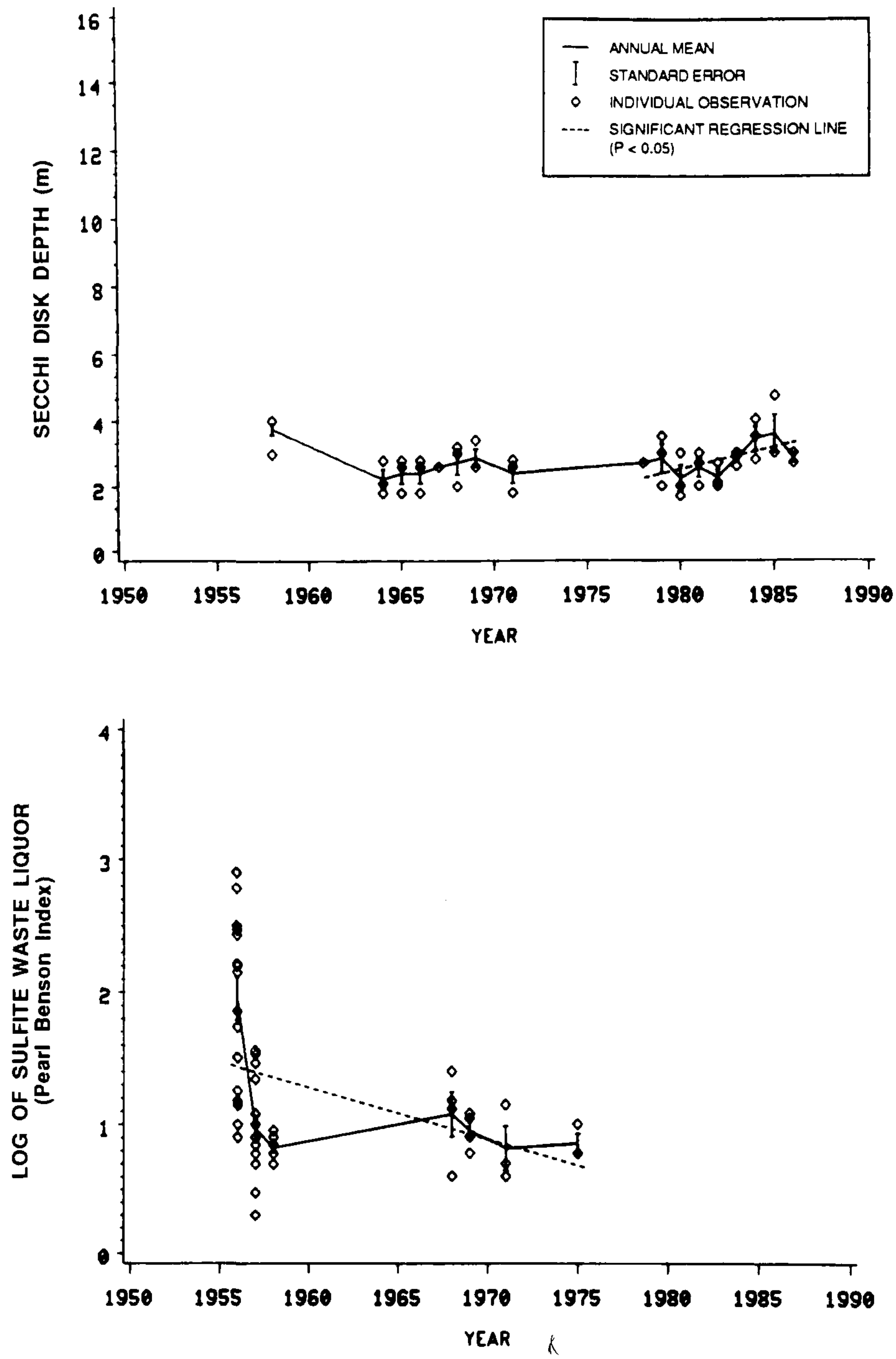


Figure 5.105. Secchi disk depth and log of concentrations of sulfite waste liquor at the surface in the Oakland Bay study area during the algal bloom season.

release of sulfite waste liquor by the ITT-Rayonier pulp mill was episodic (e.g., values of the Pearl Benson Index ranged from 3 to 800 in 1956).

Fecal coliform data from the surface waters are plotted by year in Figure 5.106. The Class B fecal coliform standard was never exceeded during the algal bloom periods of the years for which data are available. Although the negative slope of the regression by year was not statistically significant ($P=0.07$), concentrations generally appeared to be lower in the mid-1980s than they were in the late 1970s and early 1980s. Too few data from 10-m depth were available for analysis.

Summary of Results for the Southern Sound

Major findings for the southern sound are compiled in this section. Environmental conditions in the study areas are summarized and compared. A brief assessment of the sensitivity of the southern sound study areas to pollution is provided. Apparent trends in water quality are also summarized.

Environmental Conditions--

Differences between mean salinity values at the surface and at 10-m depth were >2 ppt in the study areas that have substantial sources of fresh water (i.e., Nisqually Reach, Budd Inlet, and Oakland Bay) and were $\leq$ 0.2 ppt in the other areas (i.e., Carr and Totten Inlets). Vertical gradients of water temperature were present in all five southern sound study areas, and were best developed in Budd and Carr Inlets. The differences between the mean water temperatures at the surface and at 10-m depth exceeded 2.3^{o} C in these two areas. Due to the substantial density stratification in Budd and Carr Inlets, vertical mixing appeared to be limited in both areas. Mean water temperature values at 10-m depth were highest (above 12.8^{o} C) in the Budd Inlet, Totten Inlet, and Oakland Bay sites, which are all quite shallow. Vertical mixing appears to have been well developed at Nisqually Reach. Although the salinity gradient was well developed at the Nisqually Reach site, the thermal gradient was not as large as those in Carr and Budd Inlets. The difference between the mean water temperature values at the surface and 10-m depth was only 0.8^{o} C at the Nisqually Reach site.

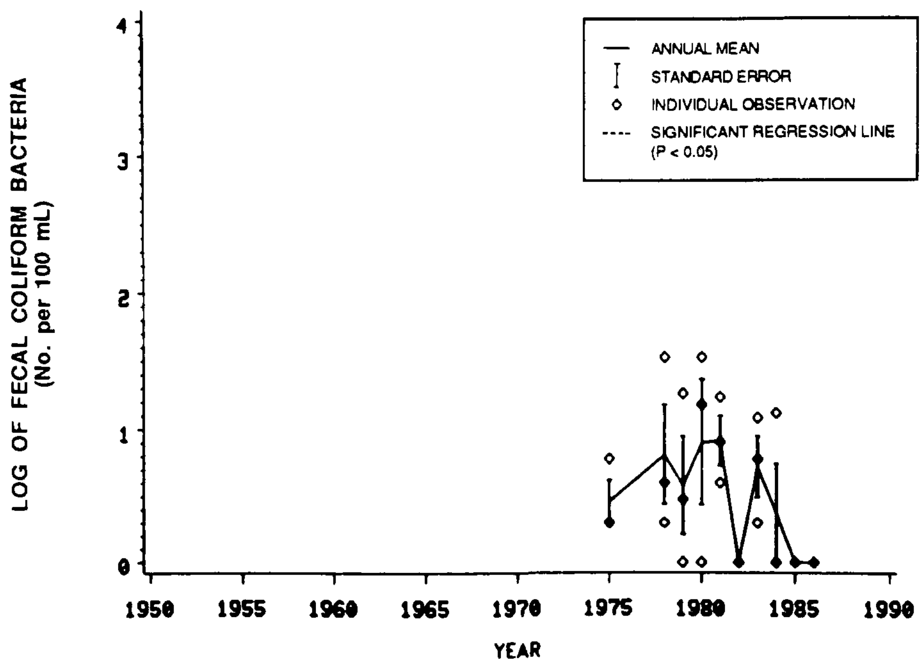


Figure 5.106. Log of concentrations of fecal coliform bacteria at the surface in the Oakland Bay study area during the algal bloom season.

Extremely low dissolved oxygen concentrations at depth were rare, even in Budd Inlet where low dissolved oxygen values have been recorded in other studies (e.g., URS 1986a). Gradients in dissolved oxygen concentrations with depth were steepest in Budd and Carr Inlets, reflecting photosynthetic enhancement of dissolved oxygen near the surface. The mean concentrations of dissolved oxygen were $\leq$1.6 mg/L higher at the surface than at 10-m depth in these two sites. Turbulent mixing apparently reduced the magnitude of the vertical oxygen gradient at Nisqually Reach. Little variation in dissolved oxygen concentrations with depth was detected in the Totten Inlet and Oakland Bay study areas, except when the surface dissolved oxygen concentration was lowered in the Oakland Bay study area by sulfite waste liquor discharge from the ITT-Rayonier pulp mill. The mean dissolved oxygen concentration at 10-m depth was approximately 0.1 mg/L higher than at the surface in the Totten Inlet site and, after the ITT-Rayonier pulp mill closed, 0.2 mg/L higher than at the surface in the Oakland Bay site. The elevated dissolved oxygen concentrations at 10-m depth in these two sites might have been due to the shallowness of these areas, which would have allowed the photic zone to extend to the bottom and to support a photosynthetically active benthic diatom community.

Concentrations of nitrate and phosphate differed noticeably among study areas. Nitrate concentrations were distinctly lower in the Totten Inlet, Budd Inlet, and Oakland Bay study areas than in the Carr Inlet and Nisqually Reach study areas. For example, mean nitrate concentrations at 10-m depth were <6 ug-at/L in the Totten Inlet, Budd Inlet, and Oakland Bay study areas and were >10.6 ug-at/L in the Carr Inlet and Nisqually Reach study areas. A possible explanation is that Budd and Totten Inlets are highly productive, which would account for the lower nutrient concentrations. Also, these two areas are shallower than Carr Inlet and Nisqually Reach, and presumably have less nitrate potentially available from deeper water. Phosphate concentrations did not vary greatly among the areas. Lowest mean concentrations were observed in Totten Inlet and Oakland Bay.

The propensity for algal blooms (based principally on the percent dissolved oxygen saturation at the surface) appears to have been highest in

Carr, Totten, and Budd Inlets. Algal density probably was lower at Nisqually Reach because turbulence tends to remove algal cells from the photic zone, thereby reducing growth rates. The reason for poorly developed algal blooms at the Oakland Bay site is unknown, although low nutrient concentrations and low water transparency may have been contributing factors.

Sensitivity to Nutrient Enrichment--

Based on their limited capacities to export or assimilate pollutants without deleterious ecological effects, Budd Inlet, Totten Inlet, and Oakland Bay appear to be sensitive to inputs of excess nutrients. Nitrate concentrations were low in these areas, and, at least in Budd and Totten Inlets, algal blooms were quite intense. Additional amounts of nutrients probably would increase the magnitude of the algal blooms in these areas. Furthermore, because the volumes of these three areas are rather small, additional nutrients would not be diluted effectively. Tidal flushing is comparatively rapid in these areas, on the order of a few days, even when freshwater inputs are low (URS 1986b). However, considerable refluxing of water occurs at Dana Passage (up to 60 percent), so the rate of net transport out of these embayments is low.

Nisqually Reach is probably the least sensitive of the southern sound study areas to ecological problems caused by nutrient enrichment because it has a greater capacity to export and assimilate excess nutrients. Mixing prevents intense blooms from developing, even though refluxing of southern sound water occurs at the sills of Nisqually Reach and Tacoma Narrows. Assimilative capacity may be substantial at Carr Inlet, which has a large dilution capacity. However, low nitrate concentrations at the surface of Carr Inlet suggest that enrichment of surface waters could further stimulate primary production. Also, the flushing time for Carr Inlet is much longer than the flushing time for any other southern embayment (URS 1986b). Discharges at the head of Carr Inlet might, therefore, have a greater ecological impact because the retention time is greater at the head than at the mouth of the inlet.

Trends in Water Quality--

Although problems caused by changing station locations and data sources limited data interpretation for some of the study areas, some general conclusions may be drawn from the data collected in the southern sound. This section summarizes the interpretation of the statistical data from Tables 5.11 and 5.12. The most informative data for detecting temporal trends were data on physical conditions and dissolved oxygen concentrations. The data on phosphate concentrations were more useful than the data on nitrate concentrations because the phosphate data were collected over a longer time period and were less variable (Appendix E). Data relevant to evaluating algal growth were sparse, while pollutant data were very informative in study areas where known problems were monitored.

Physical Conditions--Declining salinity values were detected in the Carr Inlet, Nisqually Reach, and Totten Inlet study areas, although these results were not unequivocal in the Totten Inlet site. Other salinity trends appeared to have been artifacts of changing stations and data sources. Increased water temperature values were detected in the Carr Inlet and Nisqually Reach sites. These increases apparently were due to the cool temperatures recorded in the early 1950s and 1930s (see Figure 5.1). Data for the other southern sound study areas were not collected until after this cool period, so no major trends in water temperature values were apparent for these areas.

Dissolved Oxygen--There was some evidence that increases in dissolved oxygen concentrations occurred at every study area in the southern sound. Very high concentrations of dissolved oxygen were detected in 1986 at all the southern sound stations. These 1986 elevations in dissolved oxygen concentrations may have been related to intense algal blooms (see below). However, in Budd Inlet the apparent increases may have been influenced by changes in station location and data sources. In Oakland Bay, increased concentrations were partially attributable to reduced contamination from sulfite waste liquor.

Nutrients--Nitrate data are generally available only since the 1970s. The only temporal trend detected was a negative slope in the regression for surface data from Carr Inlet. This decline may have been caused by increased algal abundance. Changes in phosphate concentrations were detected in all the southern sound study areas except Nisqually Reach.

The changes consisted of long-term decreases and recent increases. The long-term decreases appear to have resulted from a few high phosphate concentrations (e.g., over 2 ug-at/L at 30-m depth) that were recorded in the 1950s. The analytical techniques used to measure phosphate concentrations were reasonably good in the 1950s, but the data were fairly sparse. Thus, the few high values from the 1950s exerted a strong effect on the statistical analyses in all the southern sound study areas except Nisqually Reach where data are available from the 1930s. The only statistically significant ($P<0.05$) recent temporal trends in phosphate concentrations detected in the southern sound are increases that have occurred since 1975 at the surface and 10-m depth in the Oakland Bay study area. An increase in phosphate concentrations since 1973 was detected at the Budd Inlet study area, with a statistical probability of $P=0.08$.

Indicators of Phytoplankton Growth--Carr Inlet is the only study area in the southern sound for which evidence was found that suggested that algal densities have changed systematically. Since 1977, Secchi disk depths and nitrate concentrations have decreased in the Carr Inlet study area, while values of percent dissolved oxygen saturation at the surface have increased.

Elevated values of percent dissolved oxygen saturation at the surface were detected during 1986 at all study areas located in the southern sound. These high concentrations of dissolved oxygen may have been caused by intense algal blooms that occurred during 1986. The highest dissolved oxygen saturation values of 1986 occurred during May in the Carr Inlet and Nisqually Reach study areas. Unfortunately, dissolved oxygen data from May 1986 were not available for the Budd Inlet, Totten Inlet, and Oakland Bay study areas. It cannot be determined whether the highest dissolved oxygen saturation values occurred simultaneously in all the southern sound study areas. Nonetheless, dissolved oxygen concentrations were generally high in the southern sound during 1986.

With the exception of the Carr Inlet study area, values of Secchi disk depth and percent dissolved oxygen saturation at the surface were not significantly correlated ($P \geq 0.3$) in the southern sound study areas. Therefore, with the exception of the Carr Inlet study area, variation in Secchi disk depth was not closely associated with variation in algal abundance. Recent increases in Secchi disk depth were detected in the Budd Inlet and Oakland Bay study areas. The increase in Budd Inlet was driven, in part, by changes in station location and data sources, and by a few very high values recorded in the 1980s. The recent increases in Oakland Bay brought the Secchi disk readings back to levels recorded in the 1950s, but the cause of these increases cannot be determined from the available data.

Pollutants--The only significant change ($P < 0.05$) in sulfite waste liquor concentrations was a sharp decline in Oakland Bay that coincided with the closure of the ITT-Rayonier sulfite pulp mill in 1957. The other southern sound study areas lacked nearby sources of sulfite waste liquor. Declines in counts of fecal coliform bacteria were detected in the Carr Inlet, Nisqually Reach, and Budd Inlet study areas. In the Budd Inlet site, the fecal coliform data may have been influenced by improvements in the sewage treatment facilities and by changes in sampling station locations. The decline in Nisqually Reach appears to have been driven by a high value detected in 1978, at the beginning of the fecal coliform data set for this site. The source of this contamination probably was storm runoff carried in the Nisqually River. No cause of the decline observed in Carr Inlet is apparent as the contaminated water samples collected early in the surveys of this area did not appear to have been collected during, or shortly after, storms.

HOOD CANAL

Hood Canal is defined herein as the portion of Puget Sound west of Admiralty Inlet and south of Tala Point, including Dabob Bay, The Great Bend (where southern Hood Canal bends to the east and north), and Lynch Cove (see Figure 2.1). Hood Canal is generally narrow (roughly 3 km) and deep. The area around the Hood Canal is primarily rural. The region contains 15 percent of the surface area, 15 percent of the volume, 16 percent of the shoreline, and 14 percent of the tidelands of all of Puget Sound south of Admiralty Inlet (Burns 1985).

Circulation is less complex in Hood Canal than in the rest of Puget Sound because of the relatively simple shape of the shoreline and the absence of large islands that could constrain the flow of water. Several small rivers flow into Hood Canal (see Table 2.1). The lack of vigorous circulation in Hood Canal allows well-developed density stratification to persist along most of its length. Density stratification is particularly well-developed during the summer, when solar heating of surface water reinforces salinity stratification (Collias et al. 1974). A 50-m deep sill approximately 15 km south of the entrance to Hood Canal restricts the circulation of seawater at depth. The deepest portion of Hood Canal (up to approximately 200 m) extends from Dabob Bay south to The Great Bend. The mouth of Dabob Bay has a sill at approximately 120-m depth. East of The Great Bend the basin is less than 50-m deep, and it becomes progressively shallower approaching Lynch Cove.

Three of the study areas in this characterization study are located in Hood Canal: Dabob Bay, Mid-Hood Canal, and South Hood Canal. Station locations are shown in Figure 5.107. Data sources are given in Table 5.13. The algal bloom seasons for the study sites are given in Table 5.14. Histograms summarizing the water quality variables are given in Figures 5.108-5.112. Back-up tables of the summary data given in Appendix E. The ANOVAs comparing the water quality variables before and after 1973 are summarized in Table 5.15. Long-term and recent regressions are summarized in Table 5.16.

Based on the percent dissolved oxygen saturation at the surface, algal blooms were most prevalent in Hood Canal in April through July. However, photosynthetic rates remained fairly high through late summer (Table 5.14).

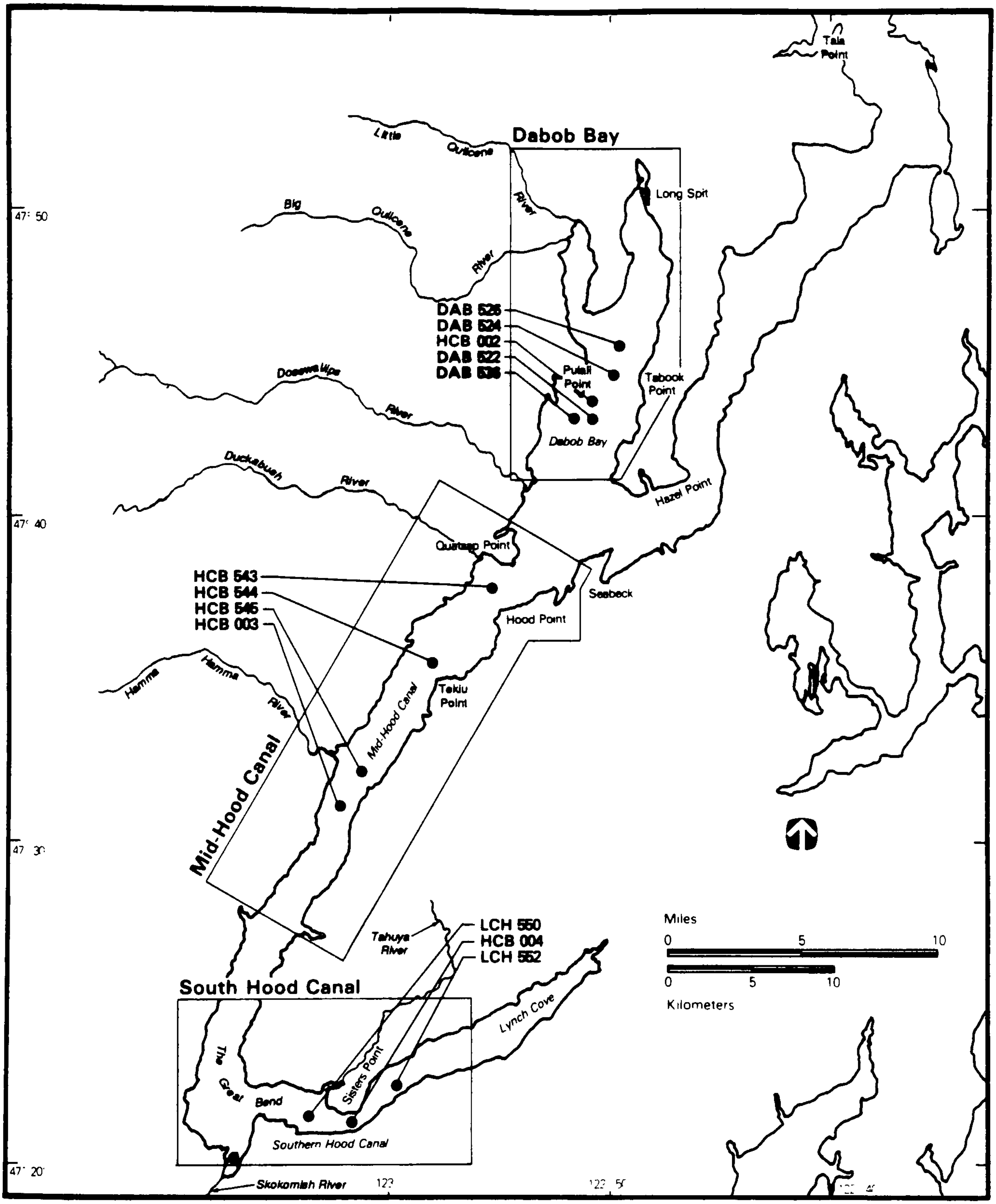


Figure 5.107. Locations of study areas and sampling stations in Hood Canal.

TABLE 5.13. SAMPLING STATION NUMBERS, DATA SOURCES, AND SAMPLING PERIODS FOR THE STUDY AREAS IN HOOD CANAL

Study Area	Station	Data Source	Sampling Period
Dabob Bay	DAB522	UW[a]	1952, 1960, 1965-66
	DAB524	UW	1949-50, 1952-63, 1965-66
	DAB526	UW	1952, 1960, 1962, 1965
	DAB536	UW	1962, 1965
	HCB002	Ecology	1968-70, 1976, 1978-86
Mid-Hood Canal	HCB543	UW	1932-33, 1939, 1952, 1966
	HCB544	UW	1933, 1952-63, 1965-67
	HCB545	UW	1933, 1939, 1952-54, 1966
	HCB003	Ecology	1968-70, 1975-86
South Hood Canal	LCH550	UW	1952-63, 1965-66
	LCH552	UW	1952-63, 1965-66
	HCB004	Ecology	1968-70, 1975-86

[a] UW = University of Washington.

TABLE 5.14. ALGAL BLOOM SEASONS FOR HOOD CANAL STUDY AREAS, AS DEFINED BY MONTHLY MEAN AND STANDARD ERROR OF PERCENT DISSOLVED OXYGEN SATURATION IN SURFACE WATER

	Percent Dissolved Oxygen Saturation		
Month	Dabob Bay	Mid-Hood Canal	South Hood Canal
April	120 +/- 4[a]	106 +/- 6	116 +/- 3[a]
May	122 +/- 3[a]	120 +/- 3[a]	117 +/- 2[a]
June	117 +/- 2[a]	117 +/- 3[a]	112 +/- 2[a]
July	123 +/- 8[a]	114 +/- 3[a]	115 +/- 3[a]
August	113 +/- 2	110 +/- 3	109 +/- 3
September	114 +/- 3	107 +/- 3	100 +/- 4

[a] Months included in the algal bloom season.

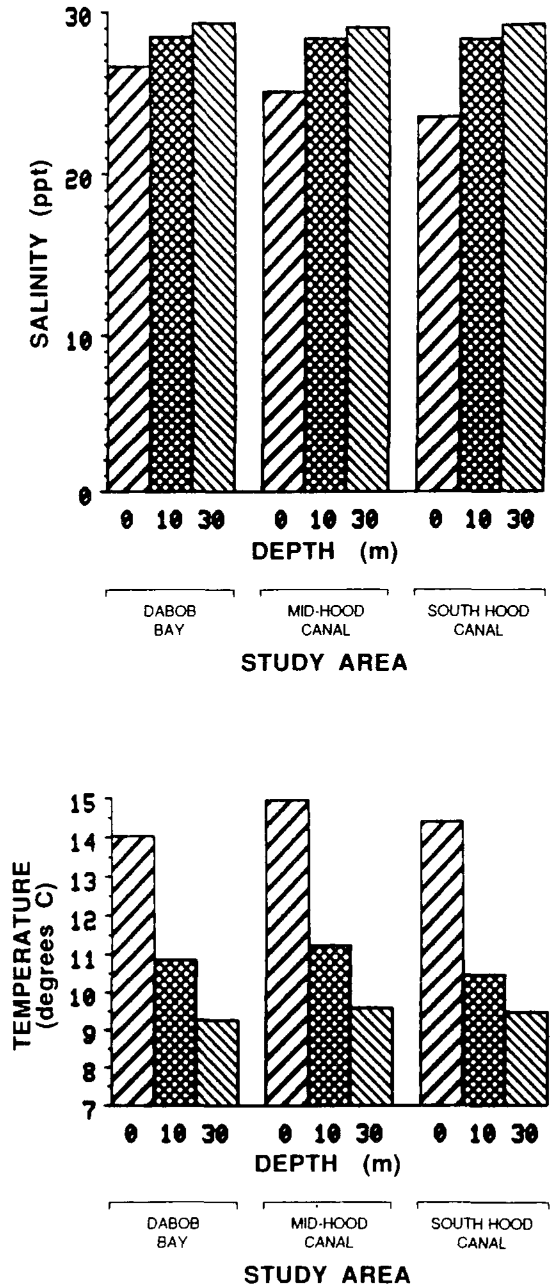


Figure 5.108. Mean salinity and water temperature values in the Hood Canal study areas during the algal bloom season.

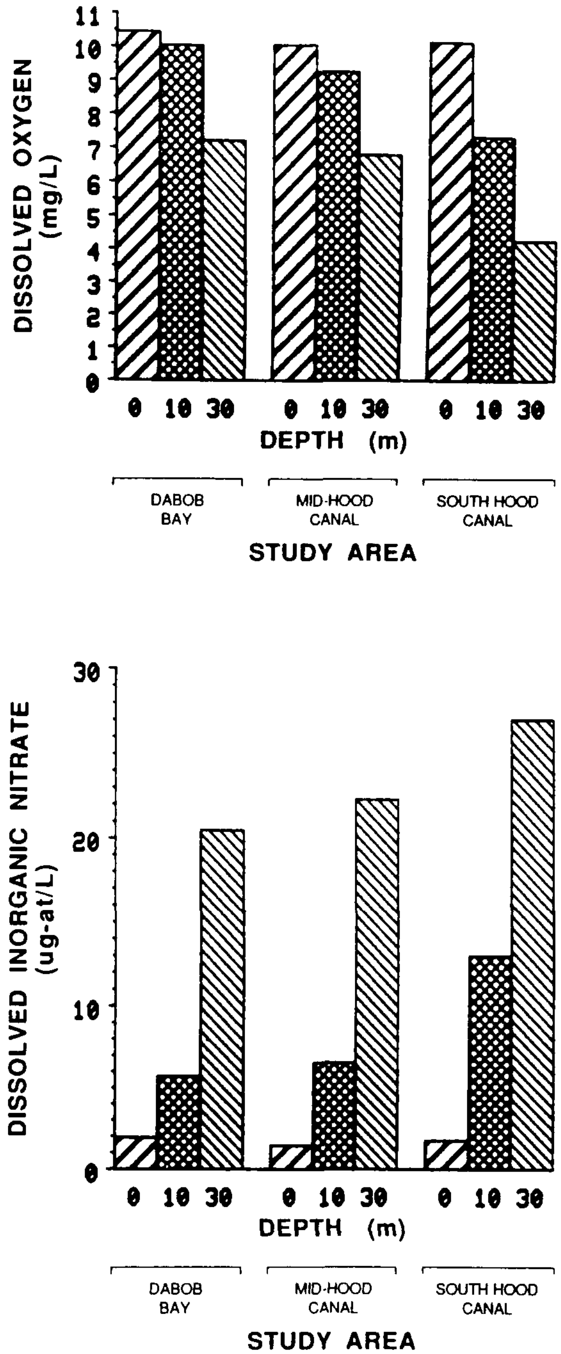


Figure 5.109. Mean concentrations of dissolved oxygen and dissolved inorganic nitrate in the Hood Canal study areas during the algal bloom season.

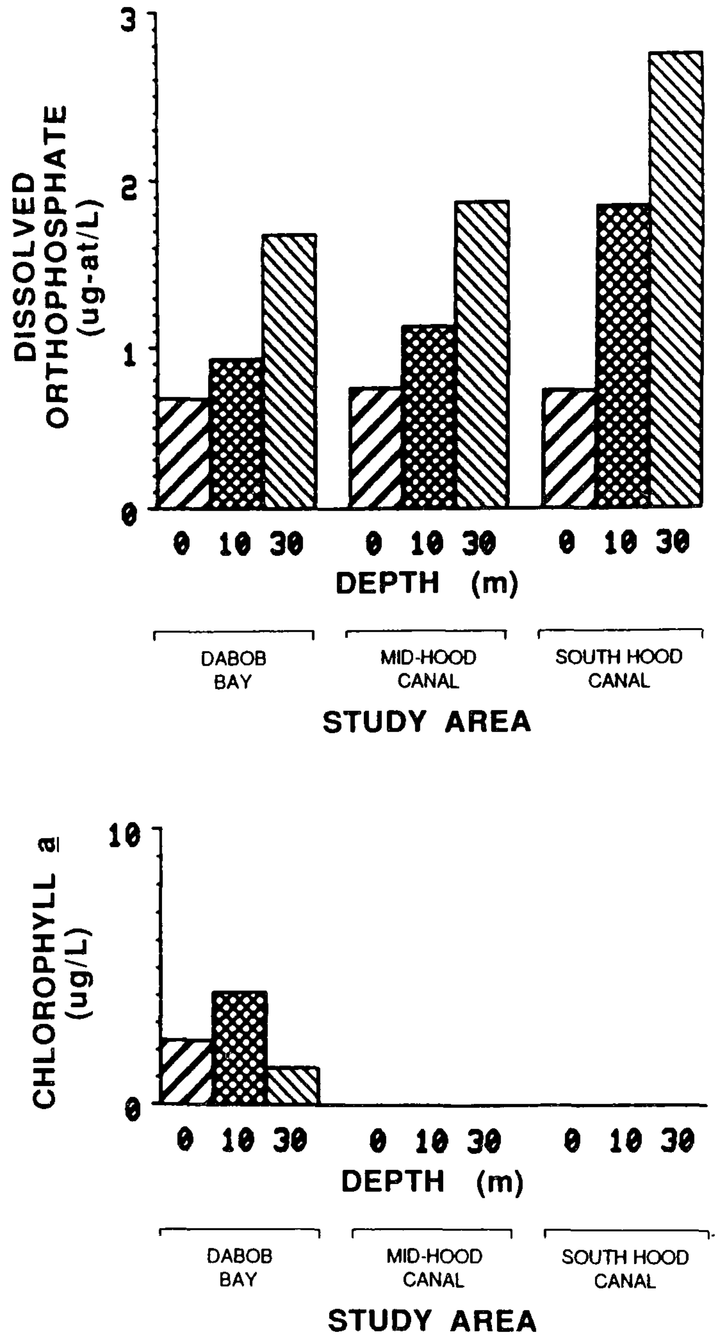


Figure 5.110. Mean concentrations of dissolved orthophosphate and chlorophyll a in the Hood Canal study areas during the algal bloom season.

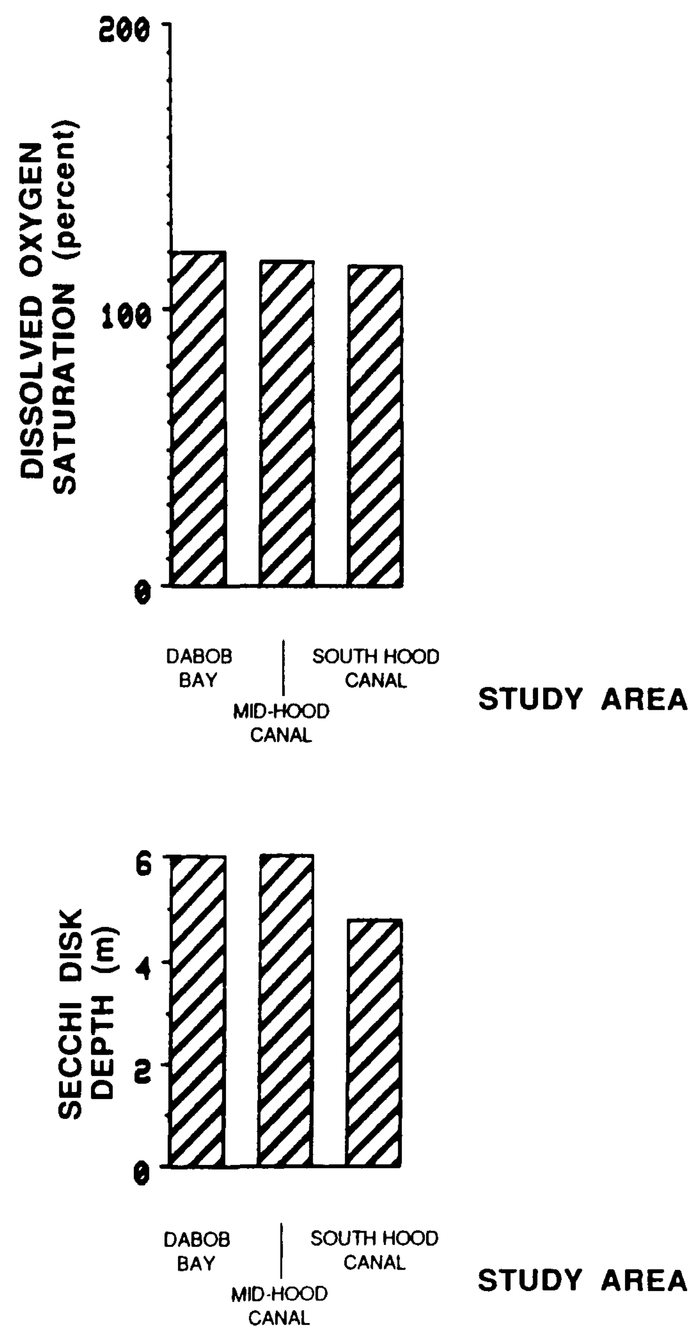


Figure 5.111. Mean percent dissolved oxygen saturation at the surface and Secchi disk depth in the Hood Canal study areas during the algal bloom season.

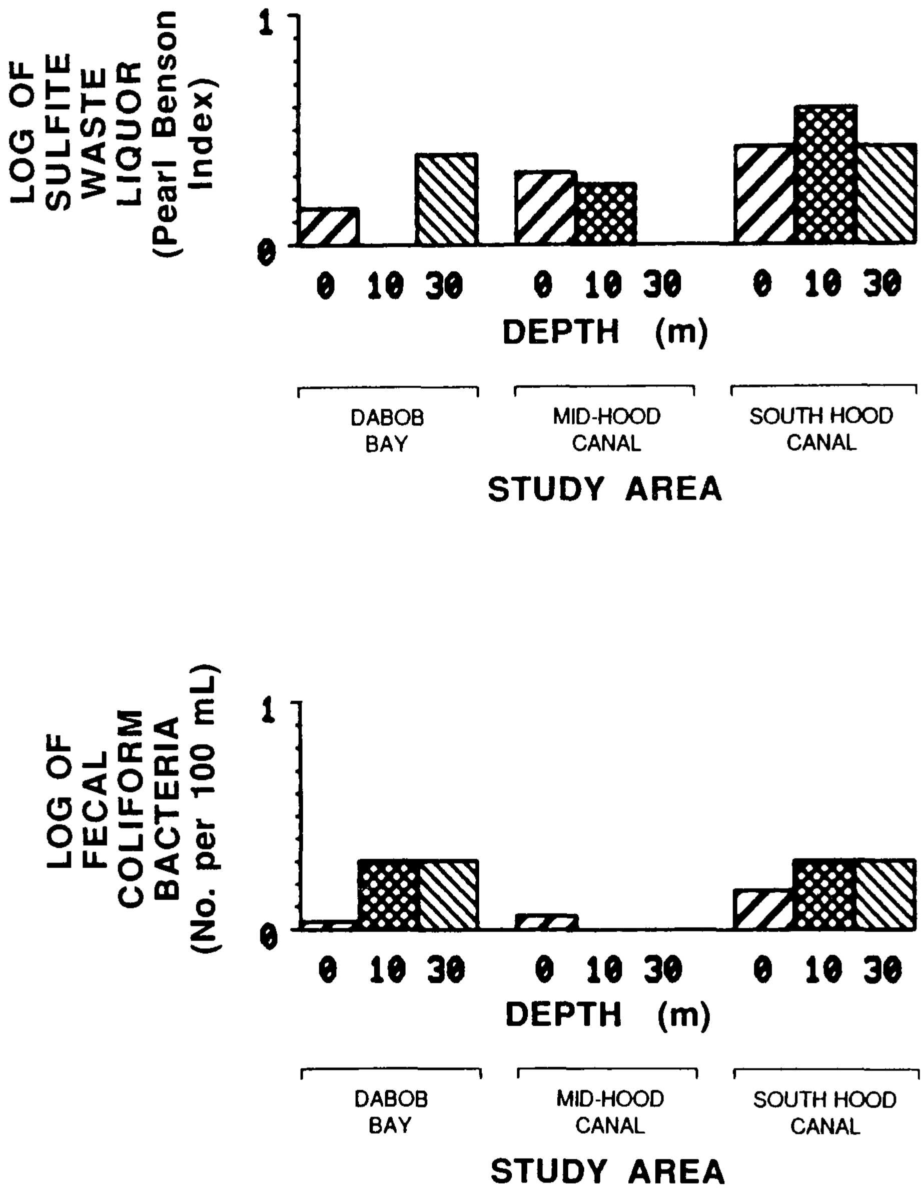


Figure 5.112. Log of geometric mean concentrations of sulfite waste liquor and fecal coliform bacteria in the Hood Canal study areas during the algal bloom season.

TABLE 5.15. NET CHANGE AND PERCENT CHANGE IN THE MEAN VALUES OF WATER QUALITY VARIABLES IN HOOD CANAL, BASED ON ANOVA COMPARISONS OF DATA TAKEN BEFORE 1973 WITH DATA TAKEN FROM 1973 TO 1986

Depth (m)	Dabob Bay Change		Mid-Hood Canal Change		South Hood Canal Change	
	Net	Percent	Net	Percent	Net	Percent
			Salinity (ppt)			
0	NS[a]		-1.58	6.1	NS	
10	-0.51	1.8	-0.87	3.0	-0.84	2.9
30	-0.63	2.1	-1.10	3.7	-0.64	2.2
			Water Temperature (^{o} C)			
0	NS		NS		NS	
10	+1.02	9.9	+1.35	12.9	+1.32	13.6
30	+0.80	9.1	+0.97	10.8	NS	
			Dissolved Oxygen (mg/L)			
0	NS		NS		NS	
10	+1.49	16.1	+1.69	20.4	+1.63	25.1
30	+1.16	17.6	+1.41	23.5	+1.47	44.5
			Nitrate (ug-at/L)			
0	na[b]		na		na	
10	na		na		na	
30	na		na		na	
			Phosphate (ug-at/L)			
0	NS		NS		-0.28	27.7
10	-0.81	46.6	-0.50	30.9	-0.80	30.4
30	-1.16	46.7	-0.45	19.4	-0.64	19.0
			Chlorophyll <u>a</u> (ug/L)			
0	na		na		na	
10	na		na		na	
30	na		na		na	
			Dissolved Oxygen Saturation (Percent)			
0	NS		NS		NS	
10	+19.96	20.1	+23.03	25.9	+21.19	30.7
30	+14.89	21.7	+17.57	28.0	+16.63	48.1
			Secchi Disk Depth (m)			
	na		na		NS	
			Sulfite Waste Liquor (Pearl Benson Index)			
0	na		na		NS	
10	na		na		na	
30	na		na		na	
			Fecal Coliform Bacteria (No./100 mL)			
0	na		na		na	
10	na		na		na	
30	na		na		na	

[a] NS = The pre-1973 and 1973-1986 values were not significantly different at P<0.05, based on a nonparametric one-way ANOVA.

[b] na Results of the statistical test were not available because of a lack of data.

TABLE 5.16. SLOPES OF STATISTICALLY SIGNIFICANT LONG-TERM AND RECENT REGRESSIONS OF WATER QUALITY VARIABLES AS A FUNCTION OF YEAR FOR HOOD CANAL

	Slopes					
Depth	Dabob Bay		Mid-Hood Canal		South Hood Canal	
(m)	Long-term	Recent	Long-term	Recent	Long-term	Recent
	Salinity (ppt)					
0	NS[a]	NS	-0.057	NS	NS	NS
10	-0.017	NS	-0.029	NS	-0.038	NS
30	-0.025	NS	-0.041	-0.189	-0.026	NS
	Water Temperature (° C)					
0	NS	NS	NS	NS	NS	NS
10	0.039	NS	0.047	NS	0.062	NS
30	0.036	NS	0.037	NS	0.027	NS
	Dissolved Oxygen (mg/L)					
0	NS	NS	NS	NS	NS	NS
10	0.058	NS	0.058	0.282	0.093	0.417
30	0.040	NS	0.047	NS	0.063	NS
	Nitrate (ug-at/L)					
0	na[b]	NS	na	NS	na	NS
10	na	NS	na	NS	na	NS
30	na	NS	na	NS	na	-0.662
	Phosphate (ug-at/L)					
0	NS	NS	NS	NS	-0.011	NS
10	-0.029	NS	NS	NS	-0.029	NS
30	-0.032	NS	NS	NS	-0.023	NS
	Chlorophyll a (ug/L)					
0	na	NS	na	na	na	na
10	na	NS	na	na	na	na
30	na	NS	na	na	na	na
	Dissolved Oxygen Saturation (Percent)					
0	NS	NS	NS	NS	NS	NS
10	0.773	NS	0.805	3.456	1.161	4.809
30	0.534	NS	0.598	NS	0.709	NS
	Secchi Disk Depth (m)					
	na	NS	na	NS	NS	NS
	Sulfite Waste Liquor[c] (Pearl Benson Index)					
0	na	na	na	na	na	na
10	na	na	na	na	na	na
30	na	na	na	na	na	na
	Fecal Coliform Bacteria[d] (No./100 mL)					
0	na	-0.018	na	NS	NS	NS
10	na	na	na	na	na	na
30	na	na	na	na	na	na

[a] NS Not significant at $P<0.05$.

[b] na Results of the statistical test were not available because of a lack of data.

[c] Data were subjected to a log(X+1) transformation for the regressions.

[d] Data were subjected to a log transformation for the regressions.

Algal blooms appeared to have been most intense in Dabob Bay, although differences among the three study sites were not large.

Dabob Bay

The study area is located off Pulali Point, about 6.5 km north of the mouth of Dabob Bay (Figure 5.107). Dabob Bay is a large embayment on the western side of Hood Canal. It is approximately 185 m deep, although a 120-m deep sill at Pulali Point inhibits deeper circulation north of the study area. The Big Quilcene and Little Quilcene Rivers are local sources of fresh water (Table 2.1). Class AA water quality standards apply to the Dabob Bay site. There are no major urban influences in the area. However, the sill and the resultant sluggish circulation at depth make the deep water in Dabob Bay prone to low dissolved oxygen concentrations (Collias et al. 1974).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.108. Data are available from 1950 through 1986. Depth gradients of salinity and water temperature were well developed, with lower salinity values and higher temperature values recorded at the surface. The mean salinity value was approximately 1.8 ppt lower at the surface than at 10-m depth. The thermal gradient between the mean temperatures at the surface and at 10-m depth was approximately 3.2^{o} C, which is larger than the thermal gradient in all other sites except Bellingham Bay and the other Hood Canal sites. Negative correlations between salinity and water temperature values (Appendix F) suggest that salinity values were lower during warmer weather, presumably because snowmelt lowered salinity values in the late spring and early summer. Density stratification and heating of low salinity surface waters, both of which are conditions that would be conducive to the development of intense algal blooms, were prominent features of the water column at the Dabob Bay study area.

The depth gradients for dissolved oxygen concentrations were quite distinct from those in study areas outside Hood Canal (Figure 5.109, see also

Figures 5.6, 5.22, 5.65). In Dabob Bay, the difference between the mean dissolved oxygen concentrations at the surface and at 10-m depth was only 0.4 mg/L, while the difference between the mean dissolved oxygen concentrations at 10 and 30-m depth was approximately 2.8 mg/L (Appendix E). In most of the other deep study areas, the mean dissolved oxygen concentration at 10-m depth was roughly half the difference between the mean concentrations at the surface and at 30-m depth. The similarity between dissolved oxygen concentrations at the surface and at 10-m depth in Dabob Bay may have been due to similarity in the amounts of dissolved oxygen that are produced by photosynthesis at the surface and at 10-m depth (see discussion of chlorophyll a below).

Depth gradients for nutrient concentrations were highly developed in the Dabob Bay study area (Figures 5.109 and 5.110). Extremely low concentrations of nutrients, often below the analytical detection limits, were recorded at the surface. Mean nitrate concentration at the surface was less than one-tenth the mean concentration at 30-m. The depth gradient in phosphate concentration also was substantial, as the mean concentration at the surface was approximately one-third of the mean concentration at 30-m depth. The low concentrations at the surface suggest that algal production near the surface could be limited by low nutrient concentrations more frequently in the Dabob Bay study area [and other Hood Canal study areas (see below)] than in the other study areas in Puget Sound.

Significant negative correlations ($P<0.05$, scaled with the Bonferroni inequality) between nutrient concentrations and both dissolved oxygen concentrations and water temperature values were not found for the surface waters, as would be expected in a highly stratified system subject to algal blooms (Appendix F). However, significant negative correlations were found between these variables and nutrient concentrations at depths of 10-m and 30-m. The lack of significant correlations at the surface may have been caused by the insensitivity of the analytical methods used to analyze the water samples for nutrient concentrations. Because the nutrient concentrations at the surface typically were below the detection limits, variations in nutrient concentrations caused by fluctuations in algal blooms may not have been detected. Therefore, correlations between nutrient concentrations and the other variables at the surface would not have been found.

The vertical distribution of chlorophyll a differed between the Dabob Bay and Point Jefferson areas. The mean concentration of chlorophyll a was higher at the surface than at 10-m depth at the Point Jefferson site. This relationship was reversed at the Dabob Bay site. (Point Jefferson was the only other site in the characterization study for which a substantial amount of chlorophyll a data are available for both the surface and 10-m depth.) This result suggests that maximum phytoplankton densities occurred deeper in the water column at the Dabob Bay site than at the Point Jefferson site. The lack of vertical mixing in Dabob Bay may allow diatoms, which are non-motile but constitute the major type of phytoplankton causing many of the blooms in spring and early summer, to sink out of surface waters.

Because Dabob Bay is highly stratified and has very sluggish circulation, it would be expected to be highly productive. However, based on the data for percent dissolved oxygen saturation at the surface, the intensity of algal blooms in the Dabob Bay study area appeared to have been relatively high (Figure 5.111), but not as high as the intensity of algal blooms in the Sinclair Inlet and Carr Inlet areas (Figures 5.24 and 5.67). As discussed above, it appears that low nutrient concentrations near the surface may have limited algal production in the Dabob Bay study area.

The mean Secchi disk depth in the Dabob Bay study area (6.0 m) was among the highest observed in any of the characterization study areas. This observation supports the interpretation that productivity in the surface waters of Dabob Bay was low. Secchi disk depth was negatively correlated ($P<0.05$ scaled with the Bonferroni inequality) with the values of three variables at the surface: chlorophyll a concentration, dissolved oxygen concentration, and percent dissolved oxygen saturation (Appendix F). [The negative correlation between Secchi disk depth and percent dissolved oxygen saturation was not quite significant ($P=0.09$), scaled with the Bonferroni inequality.] Therefore, the Secchi disk measurements appeared to reflect turbidity in the near-surface water caused by phytoplankton rather than by other suspended material. However, the mean concentration of chlorophyll a was nearly twice as high at 10-m depth (4.1 ug/L) than at the surface (2.4 ug/L). Because the mean Secchi disk depth was only 6.0 m, a considerable amount of phytoplankton must have existed below the Secchi disk depth. Unfortunately, variation in algal density in the deeper layer was not reflected by variation in the Secchi disk depth data.

Geometric means of the concentrations of sulfite waste liquor and fecal coliform bacteria were low (near the detection limits) in the Dabob Bay site (Figure 5.112). These results are reasonable, as there are no large sources of these contaminants near the Dabob Bay site.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.15. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.16.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.113-5.115. No significant ($P<0.05$) temporal changes in salinity were detected at the surface. However, at depths of 10- and 30-m, mean salinity values for the period 1976-1986 were lower than mean salinity values from 1950 to 1966 (Table 5.15). Significant declines ($P<0.05$) in salinity values since 1950 were also detected at 10- and 30-m depths in the regressions of salinity data against year (Table 5.16). Similar regressions for the period of 1976 through 1986 were not statistically significant ($P>0.05$). The reason(s) for the apparent decreases in subsurface salinity are unknown, but inputs of high salinity oceanic water may have declined. Rainfall data from the Seattle-Tacoma International Airport suggest that rainfall has generally decreased in the area since the 1950s (Figure 5.2), which would be expected to cause increases, rather than decreases, in salinity values over time.

The decreased salinity values appear to have been real phenomena that occurred in the field. Possible effects of changes in station locations and data sources on the data appear to have been minimal. The Ecology station

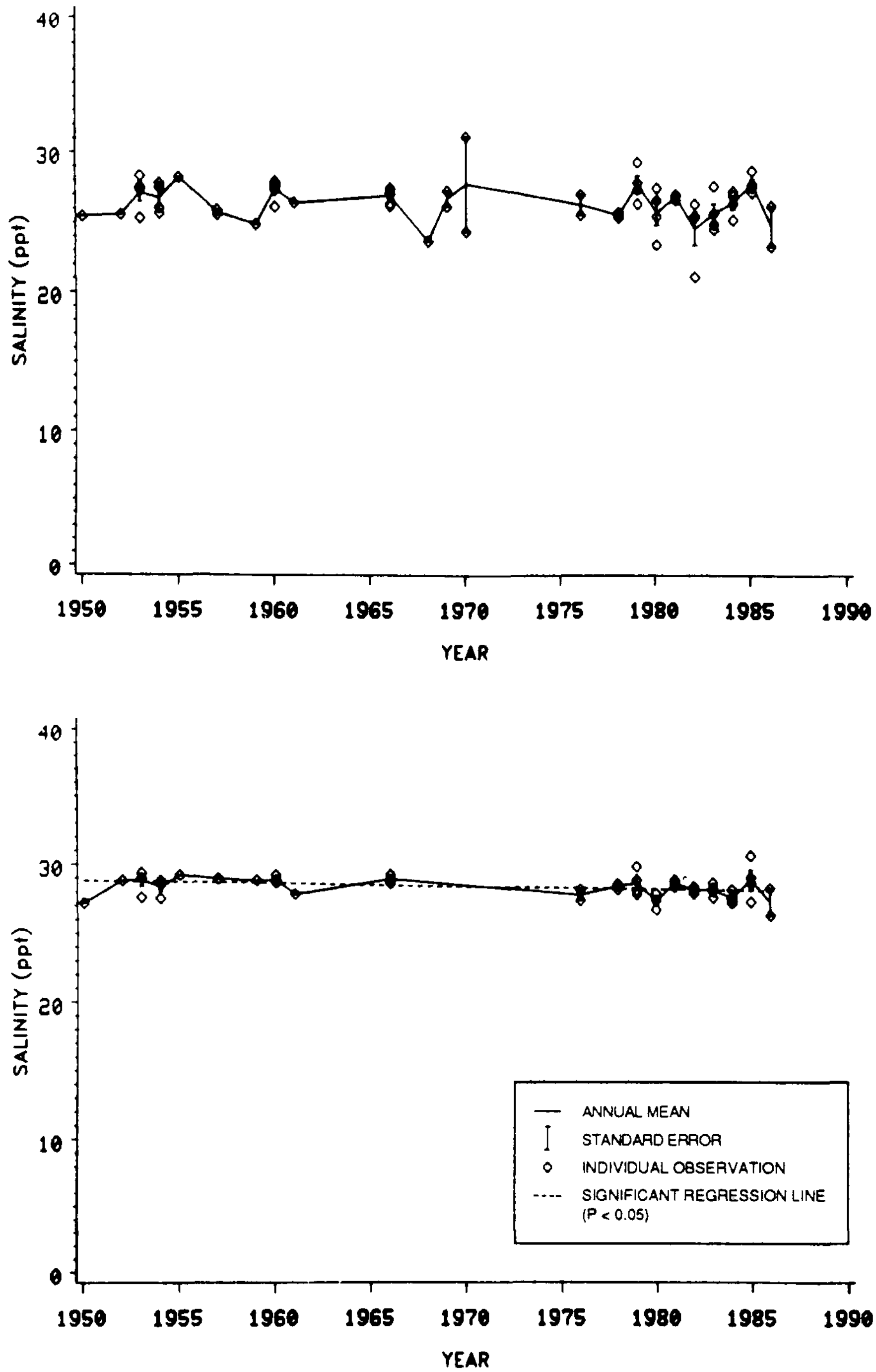


Figure 5.113. Salinity values at the surface and at 10-m depth in the Dabob Bay study area during the algal bloom season.

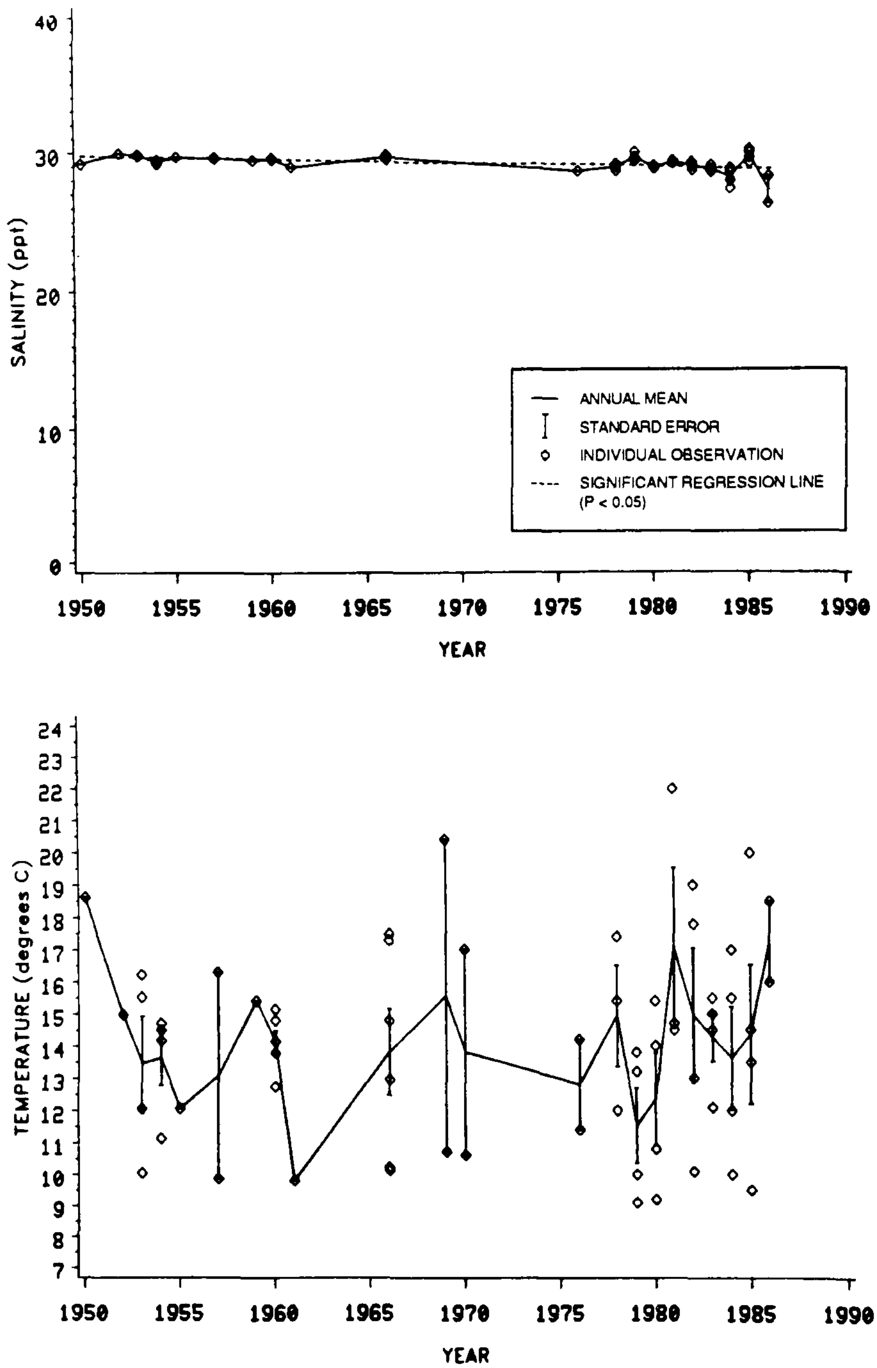
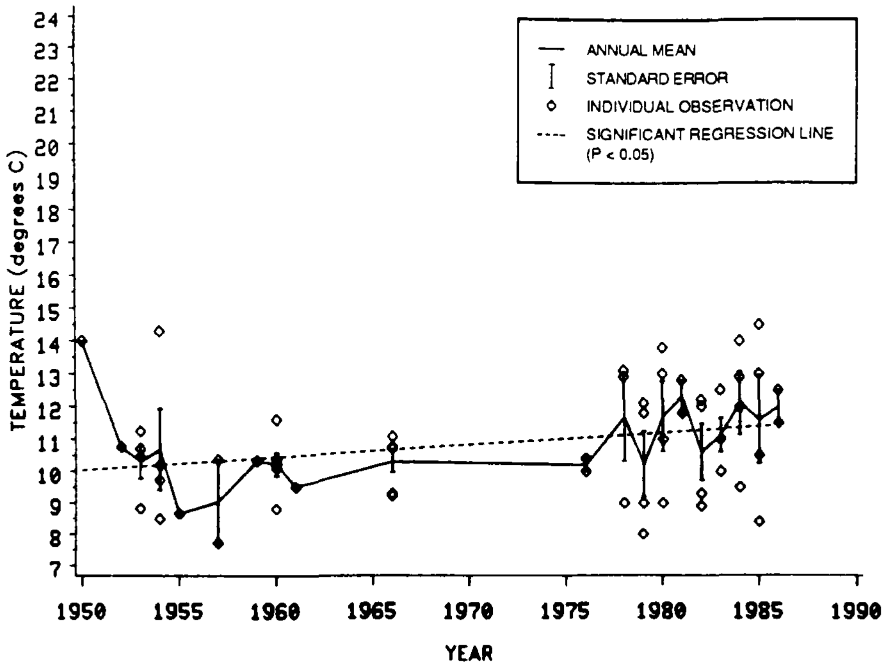


Figure 5.114. Salinity values at 30-m depth and water temperatures at the surface in the Dabob Bay study area during the algal bloom season.



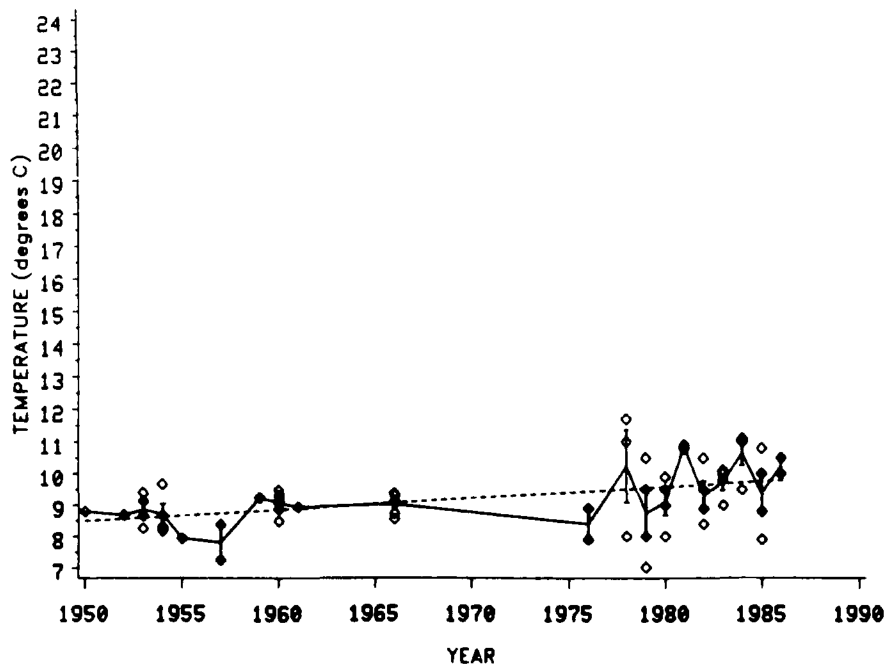


Figure 5.115. Water temperatures at 10- and 30-m depths in the Dabob Bay study area during the algal bloom season.

sampled since the mid-1970s is located near the center of the group of University of Washington stations sampled earlier, and no substantial freshwater source exists in the area that might have distorted the salinity pattern when station locations were changed. Contour maps of salinity values plotted by Collias et al. (1974) also do not suggest that changes in station locations would have introduced apparent declines in salinity values into the data. Salinity values depicted in Collias et al. (1974) near the Ecology site did not appear to be systematically lower than the salinities either north or south of the Pulali Point area. Also, as discussed in Chapter 4 and Appendix D, salinity determinations by the University of Washington and Ecology did not differ systematically.

Water temperatures at 10- and 30-m depths apparently have increased in the Dabob Bay study area since the 1950s (Tables 5.15 and 5.16). These increases are similar to the increases in air temperature values that have been recorded at the Seattle-Tacoma International Airport (Figure 5.1), which showed that the period 1948-1955 was relatively cool. Based on data compiled by Collias et al. (1974), changes in station location do not appear to have introduced apparent increases in water temperature values into the data. Only long-term increases in water temperature values, which were derived from early University of Washington data and recent Ecology data (Table 5.13, Figure 5.107), were statistically significant ($P<0.05$). This observation raises the possibility that differences in analytical techniques between University of Washington and Ecology could have introduced apparent increased values into the data. Measurements of water temperature by the University of Washington were lower than the measurements by Ecology at the site where both agencies sampled during the same period of time (Chapter 4 and Appendix D). Hence, differences in the data sources also could have contributed to the apparent increases in water temperature. In summary, water temperatures at depth appear to have increased in the Dabob Bay study area since the 1950s, but the validity of those increases may be suspect.

<u>Dissolved Oxygen</u>--Plots of dissolved oxygen concentrations by year are shown in Figures 5.116 and 5.117. There was no evidence that the Class AA water quality standard (see Table 4.2) was violated in surface waters. One violation at 10-m depth was recorded in 1983. Many violations at 30-m depth

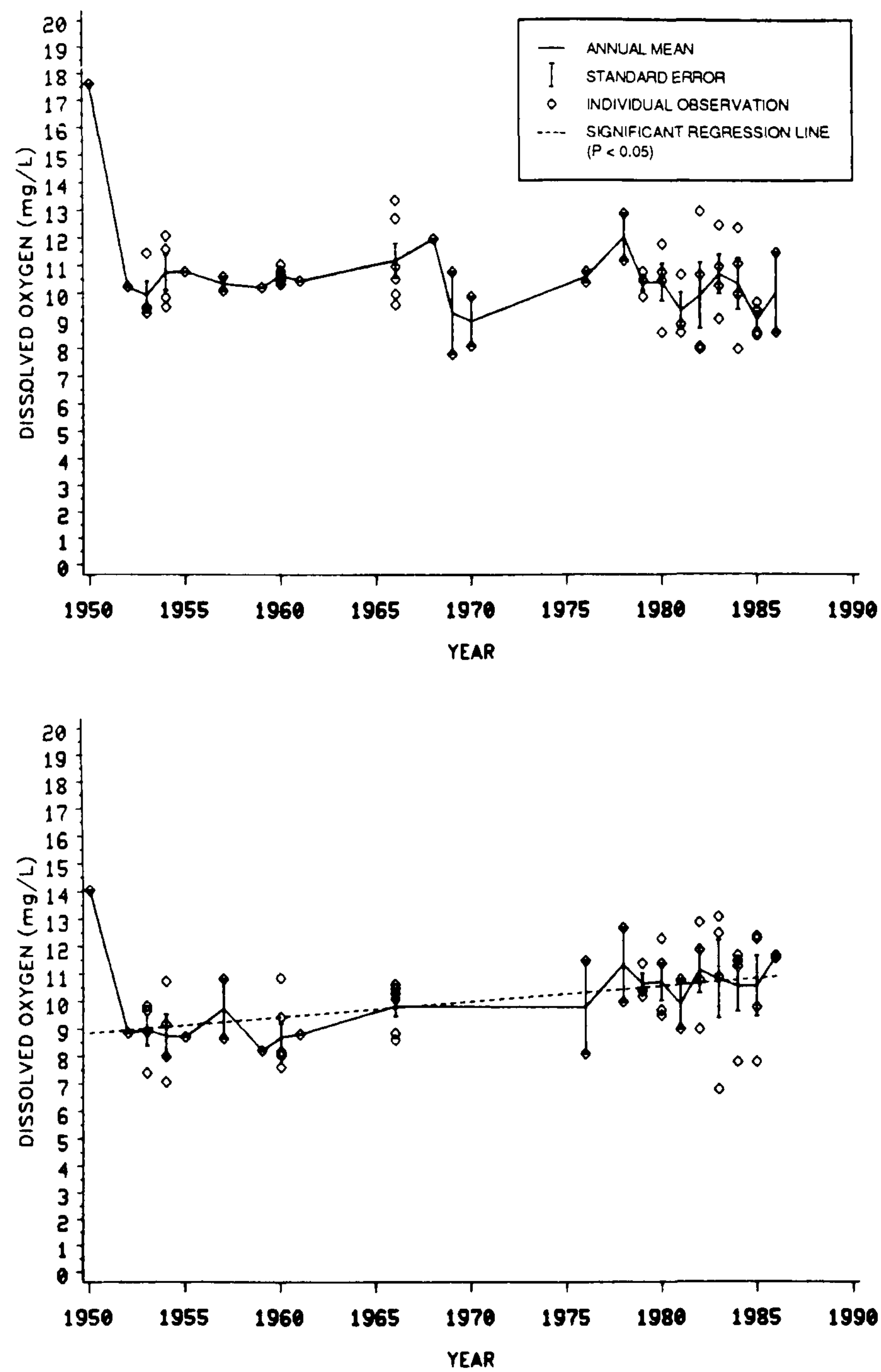


Figure 5.116. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Dabob Bay study area during the algal bloom season.

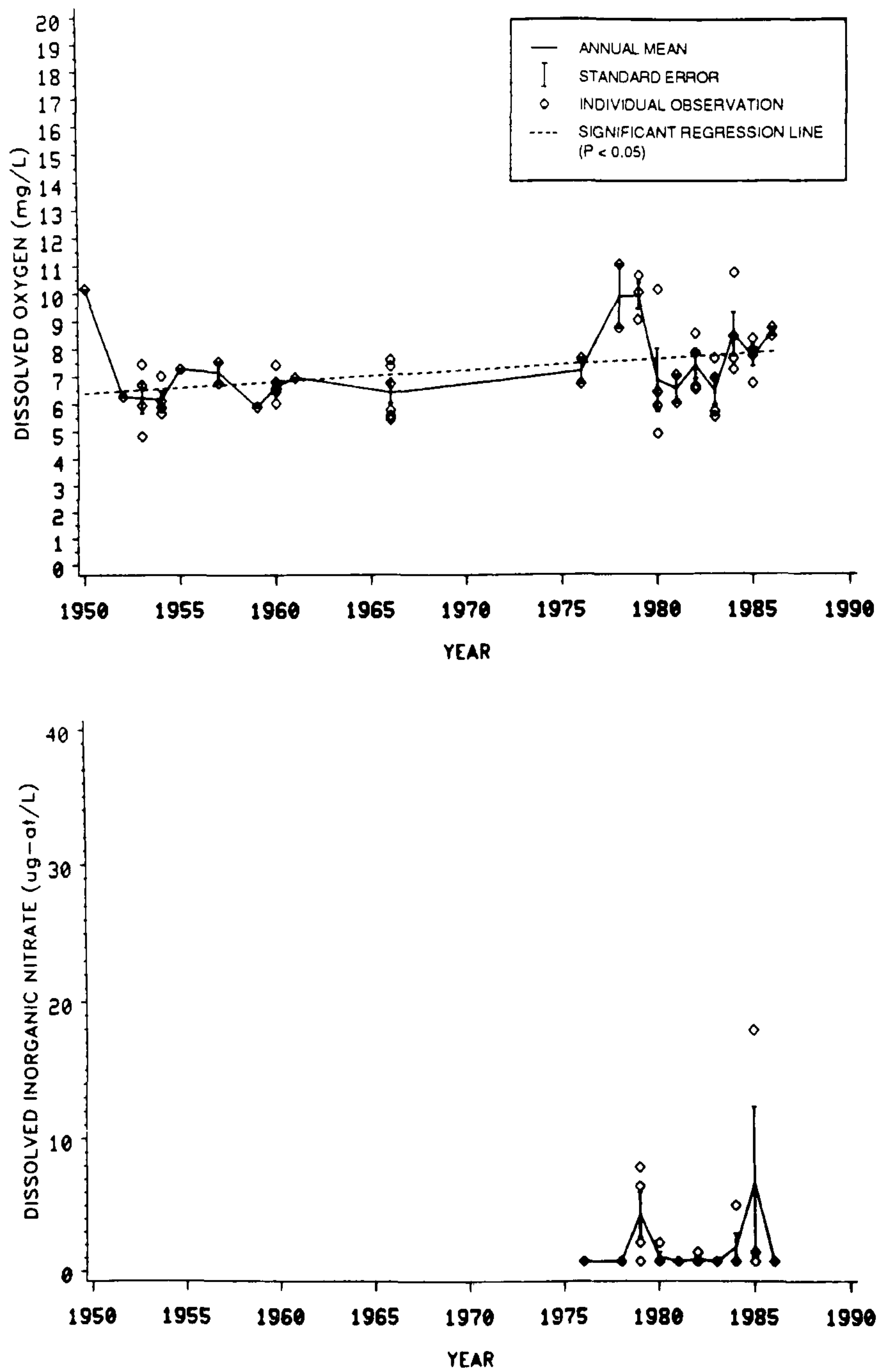


Figure 5.117. Concentrations of dissolved oxygen at 30-m depth and dissolved inorganic nitrate at the surface in the Dabob Bay study area during the algal bloom season.

were recorded. The mean dissolved oxygen concentration at this depth was only 0.2 mg/L above the standard. Significant long-term increases ($P<0.05$) in dissolved oxygen concentrations were found at 10- and 30-m depths (Tables 5.15 and 5.16). Increases since 1976 were not significant. Based on data compiled by Collias et al. (1974) and on the comparisons of dissolved oxygen data collected by the University of Washington and Ecology (Chapter 4 and Appendix D), changes in station locations and sources of data do not appear to be likely explanations for the apparent increases in dissolved oxygen concentrations at depth in the Dabob Bay study area. Although it was not possible to determine why dissolved oxygen concentrations increased since the 1950s at 10- and 30-m depths, one explanation is that photosynthetic rates may have increased at these depths (see following discussion of indicators of phytoplankton growth).

Nutrients--Plots of nitrate concentrations by year are shown in Figures 5.117 and 5.118. Because data are only available since 1976, comparisons of data collected before and after 1973, and long-term regressions could not be performed. No statistically significant ($P<0.05$) temporal trends were detected in nitrate concentrations, although the negative slope of the regression by year was nearly significant ($P=0.12$) at 30-m depth. The sensitivity of these statistical analyses is questionable for surface waters because many of the observations were below the analytical detection limits.

No statistically significant changes in phosphate concentrations were detected at the surface. However, statistically significant ($P<0.05$) declines were detected at 10- and 30-m depths (Figures 5.119 and 5.120, Tables 5.15 and 5.16). In general, the values recorded between 1953 and 1961 were higher than the values recorded between 1976 and 1986. Changes in station locations do not appear to have contributed to these apparent declines in phosphate concentrations because phosphate profiles near the Dabob Bay study area apparently do not vary systematically with location (Collias et al. 1974). Although it was not possible to assess the possibility that differences in analytical techniques over time could have influenced the apparent decreases, data collected since 1953 were probably reasonably accurate (Appendix A).

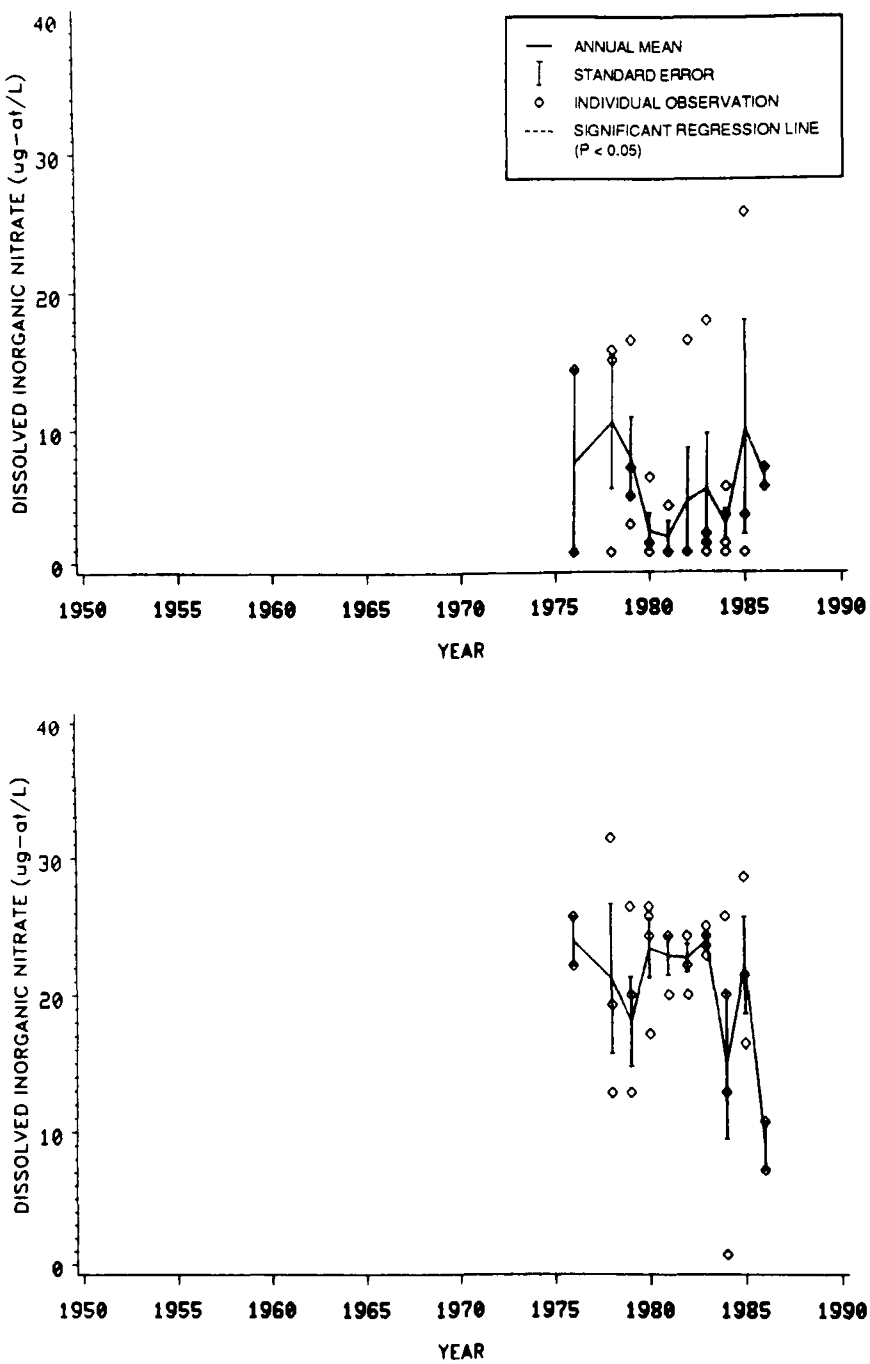


Figure 5.118. Concentrations of dissolved inorganic nitrate at 10- and 30-m depths in the Dabob Bay study area during the algal bloom season.

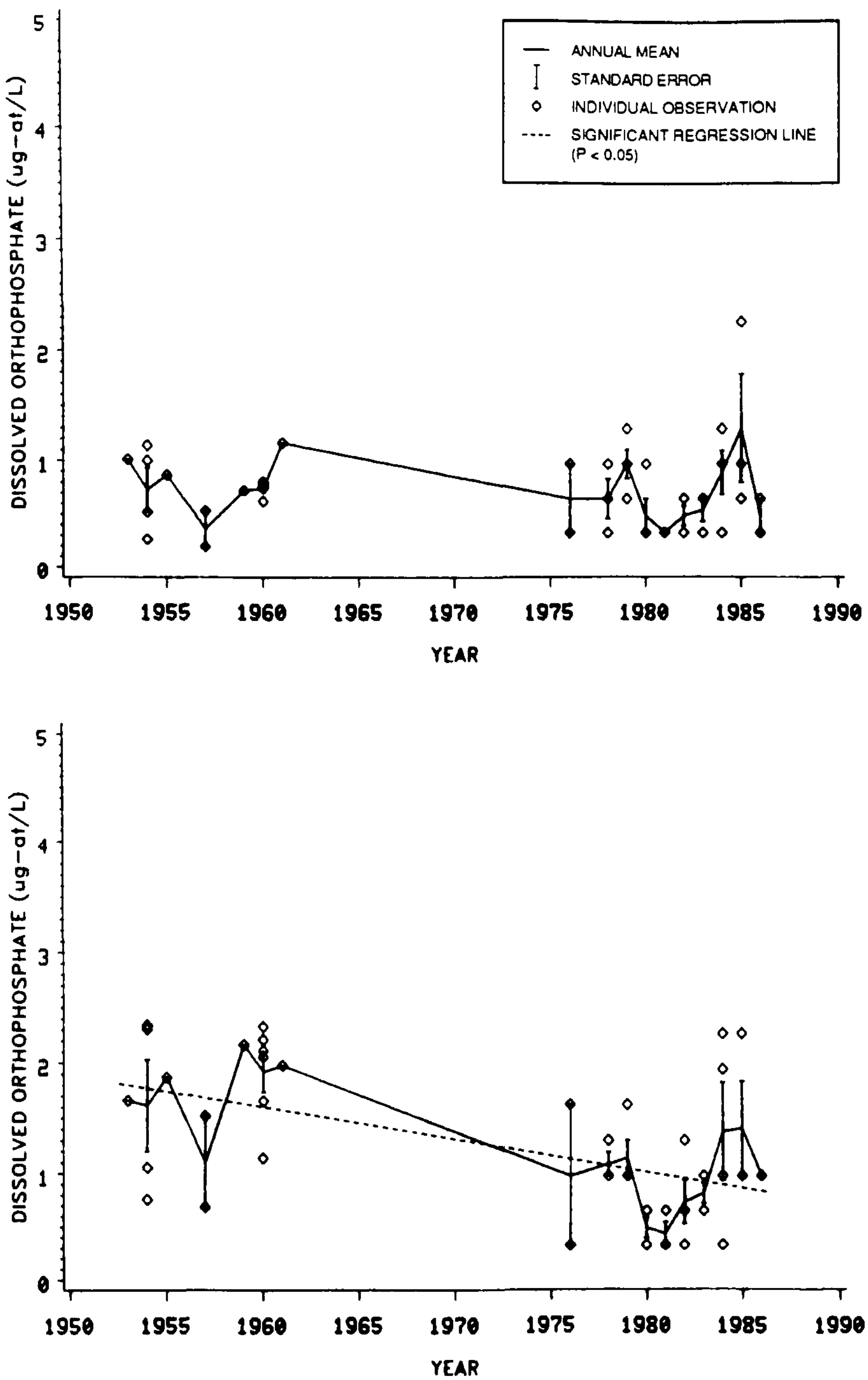


Figure 5.119. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Dabob Bay study area during the algal bloom season.

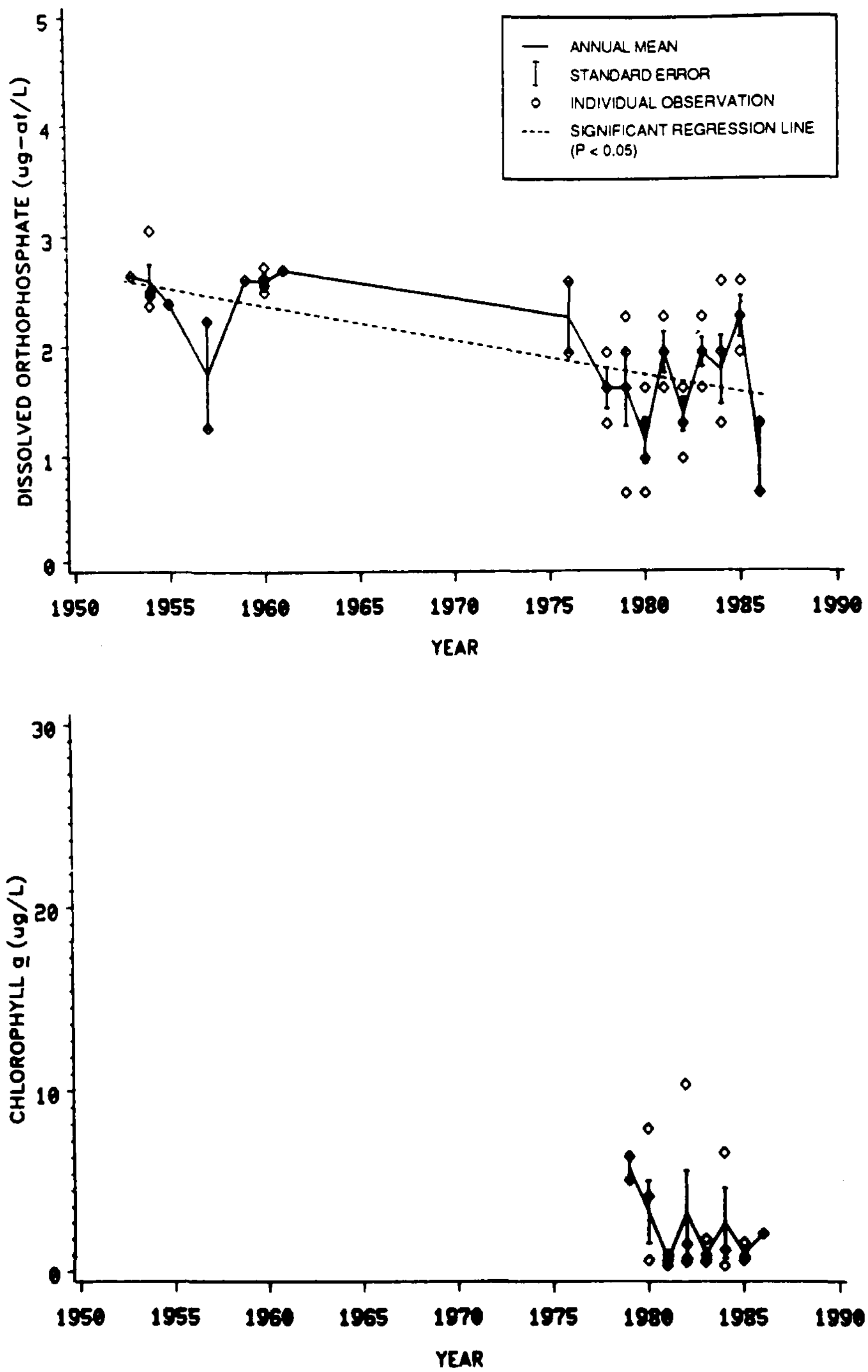


Figure 5.120. Concentrations of dissolved orthophosphate at 30-m depth and chlorophyll a at the surface in the Dabob Bay study area during the algal bloom season.

It was not possible to determine why phosphate concentrations declined since the 1950s at 10- and 30-m depths. One explanation is that rates of consumption of phosphate by phytoplankton could have increased (see following discussion of indicators of phytoplankton growth). Alternatively, oceanic inputs of phosphate may have declined.

Indicators of Phytoplankton Growth--Chlorophyll *a* data from 1979 through 1986 are plotted by year in Figures 5.120 and 5.121. No temporal changes were evident. Percent dissolved oxygen saturation at the surface and Secchi disk depth are plotted by year in Figure 5.122. No statistically significant changes were detected for either variable. However, the transparency of the water column is high in the Dabob Bay area (mean Secchi depth was 6.0 m) and statistically significant increases in percent dissolved oxygen saturation at depth since 1950 were found (Tables 5.15 and 5.16) (10-m depth: slope=+0.77 percent/yr, $P=0.0003$; 30-m depth: slope=+0.53 percent/yr, $P=0.001$). Regressions of percent dissolved oxygen saturation at depth since 1973 were not statistically significant ($P>0.05$). The long-term increases in oxygen saturation at depth suggest that increasing photosynthetic rates may have influenced oxygen concentrations. The long-term declines in phosphate concentrations at 10- and 30-m depths support this interpretation because these declines may be attributable to increased rates of nutrient uptake by phytoplankton at these depths. Unfortunately, the chlorophyll *a* data only covered the most recent 7 yr, which was not sufficient to detect long-term trends.

Pollutants--Too few data on concentrations of sulfite waste liquor are available to warrant analysis. However, large pulp mills do not exist in the area. A statistically significant ($P<0.05$) decline in the concentrations of fecal coliform bacteria was detected at the surface (Figure 5.123). This trend appears to have been driven by a few low values that were reported from 1976 through 1980. All values since 1981 were at the detection limit (i.e., an overall decline was apparent in the data). All the concentrations were well below Class AA water quality standards.

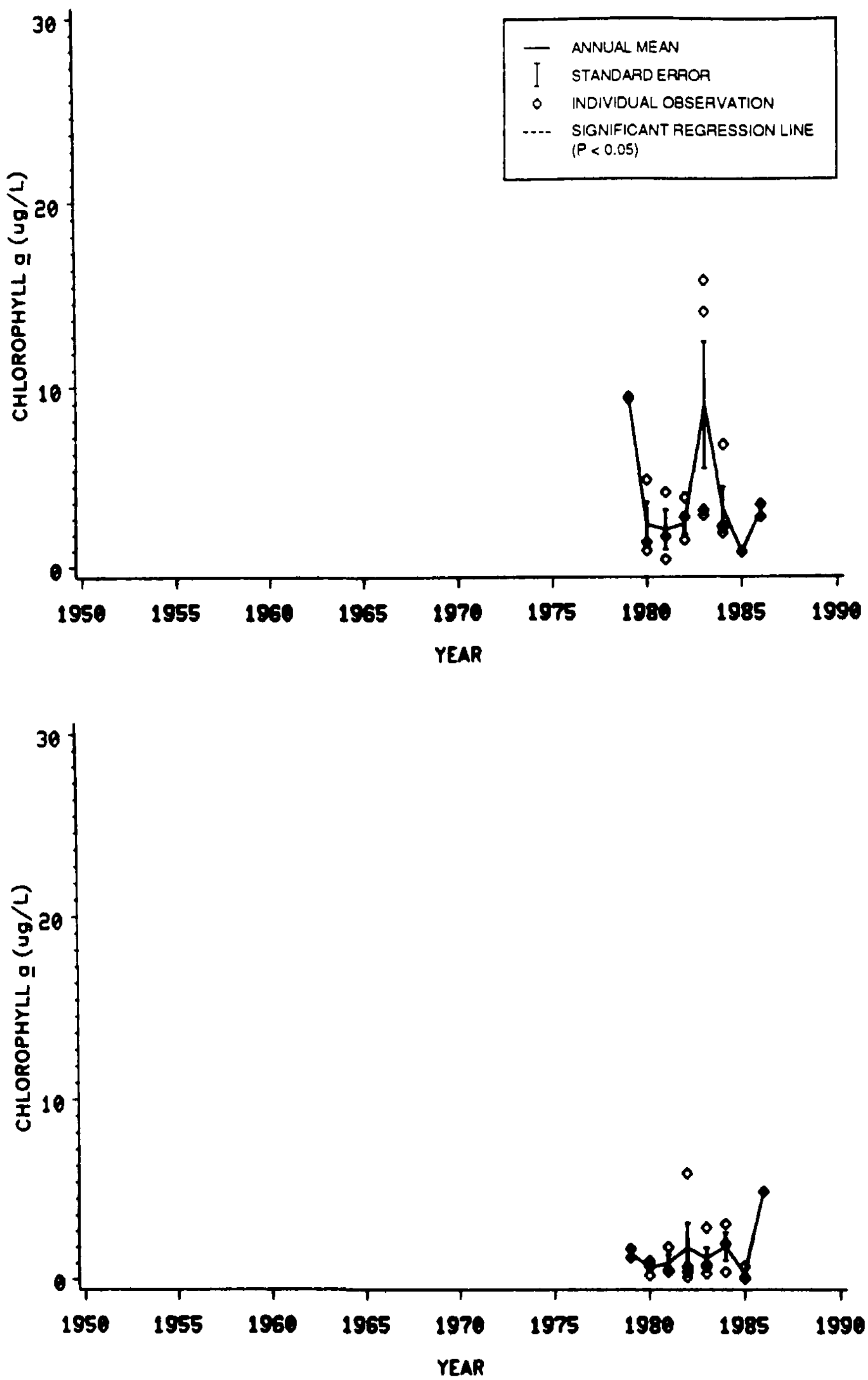


Figure 5.121. Concentrations of chlorophyll a at 10- and 30-m depths in the Dabob Bay study area during the algal bloom season.

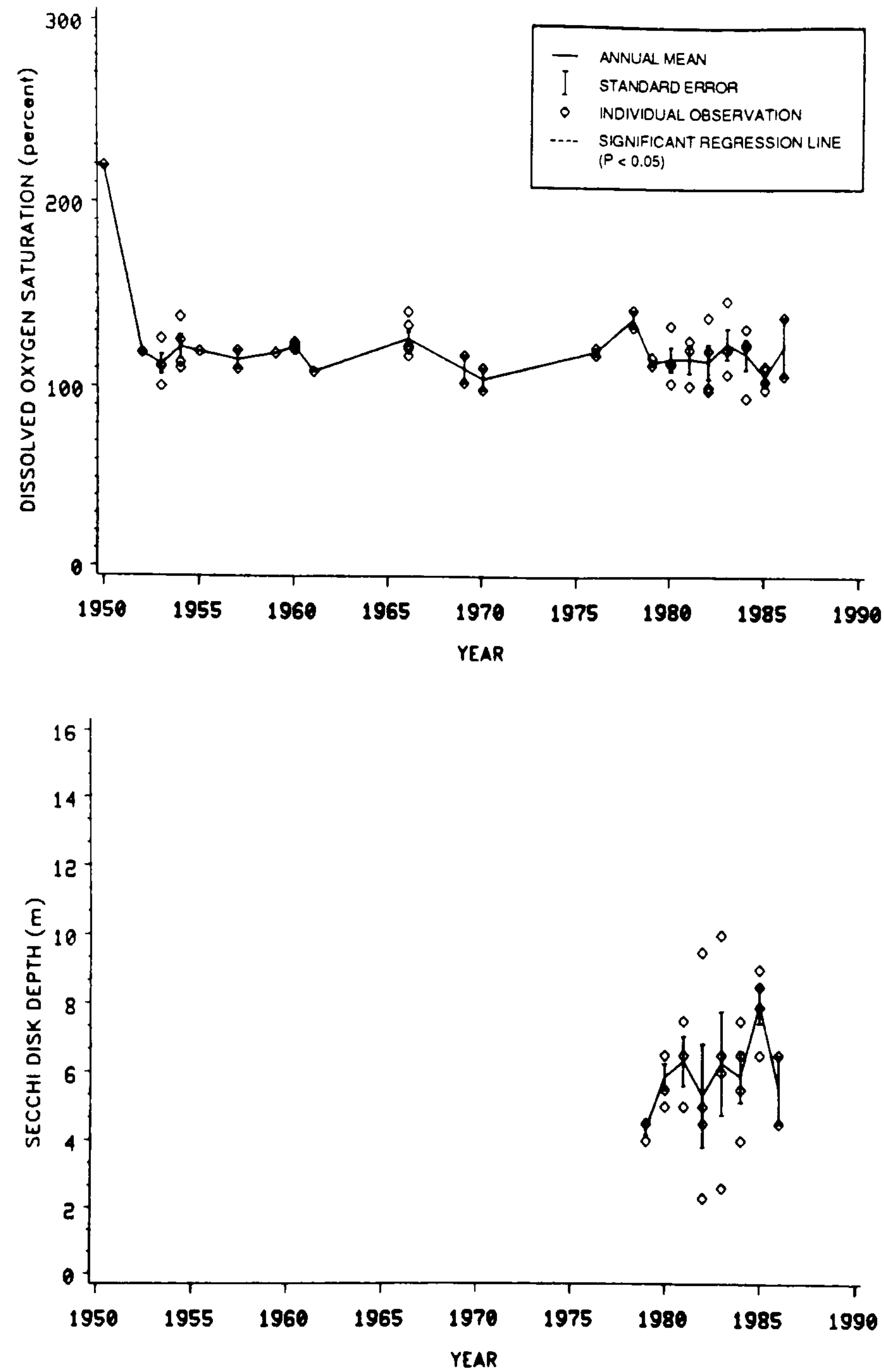


Figure 5.122. Percent dissolved oxygen saturation at the surface and Secchi disk depth in the Dabob Bay study area during the algal bloom season.

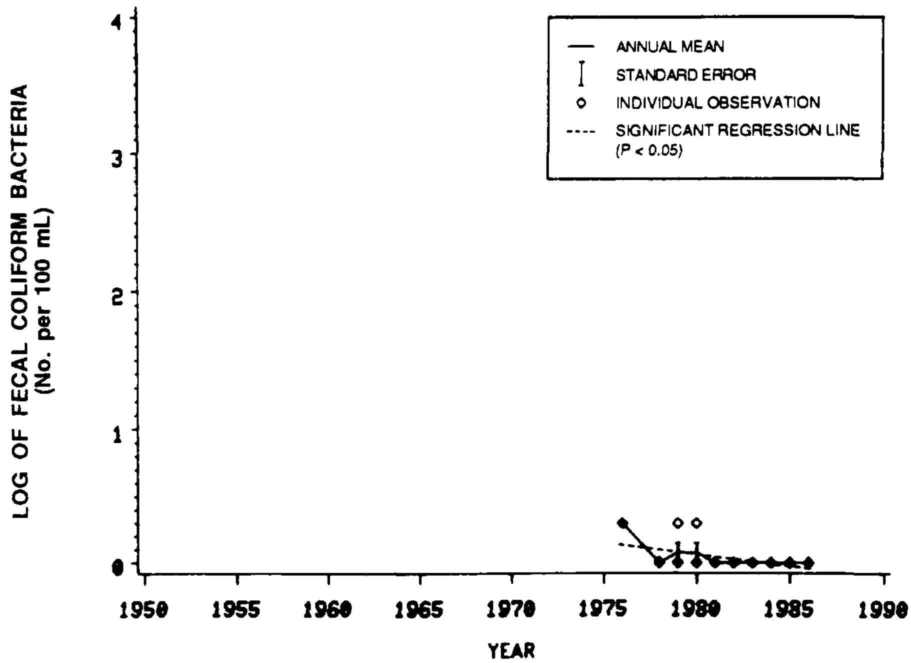


Figure 5.123. Log of concentrations of fecal coliform bacteria at the surface in the Dabob Bay study area during the algal bloom season.

Mid-Hood Canal

The study area includes the region between Hamma Hamma River and Hood Point (see Figure 5.107). Class AA water quality standards apply in the region, which lacks major urban influences. The largest source of fresh water to the study area is the Skokomish River, the two outlets of which combine to be the seventh largest river flowing into Puget Sound (see Table 2.1). The Skokomish River contributes approximately 4 percent of the total freshwater input to the sound. Other sources of freshwater are the Dosewallips, Duckabush, and Hamma Hamma Rivers, each of which contributes approximately 1 percent of the freshwater flow entering Puget Sound (see Table 2.1). The Mid-Hood canal study area is narrow and averages about 165 m in depth. Circulation is sluggish because the volumes of freshwater inputs and tidal flows, which are the major forces driving water movements in Hood Canal, are small relative to the total volume of the system.

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom period are depicted in Figure 5.108. Data are available from 1952 through 1986. Depth gradients of salinity and water temperature were well developed. The mean salinity value was 3.3 ppt lower at the surface than at 10-m depth. The mean water temperature value was 3.7^{o} C higher at the surface than at 10-m depth. The salinity gradient was somewhat greater at the Mid-Hood Canal site than at the Dabob Bay site. Lower mean surface salinity values at the Mid-Hood Canal site (25.0 ppt vs. 26.6 ppt at the Dabob Bay site) probably reflect the closer proximity to substantial freshwater sources. The thermal gradient in the Mid-Hood Canal site was very steep. This gradient is partly attributable to high surface temperatures. The mean water temperature at the surface was 14.9^{o} C, which was the highest surface mean temperature observed in any study site except at Totten Inlet. The magnitude of the density stratification in the Mid-Hood Canal study area suggests that physical factors in the area would be conducive to the development of intense algal blooms.

The vertical distributions of concentrations of dissolved oxygen and nutrients resembled those in the Dabob Bay study area (Figures 5.109 and 5.110). Mean dissolved oxygen concentration was highest at the surface (10.1 mg/L), and relatively small differences between mean dissolved oxygen concentrations at the surface and at 10-m depth were observed (0.8 mg/L). Nutrient concentrations at the surface were frequently below analytical detection limits. The depth gradient in nitrate concentrations was very substantial. Nitrate concentrations at the surface averaged less than 6 percent of the nitrate concentrations at 30-m depth. Phosphate concentrations at the surface averaged approximately one-third of the phosphate concentrations at 30-m depth. As in the Dabob Bay study area, the low concentrations of nutrients at the surface suggest that algal production at the surface frequently could be limited by low nutrient concentrations.

Based on the percent dissolved oxygen saturation at the surface, the intensity of algal blooms in the Mid-Hood Canal study area was relatively high (Figure 5.111). However, algal bloom intensity was slightly lower at this site than at the Dabob Bay site. The mean percent dissolved oxygen saturation at the surface was 116 percent in the Mid-Hood Canal site and 120 percent in the Dabob Bay site. Too few data on the concentrations of chlorophyll a were available to warrant interpretation (Appendix E).

Although the mean Secchi disk depth was high (6.0 m) at the Mid-Hood Canal site, the only statistically significant ($P<0.05$, scaled with the Bonferroni inequality) correlation with Secchi disk depth was a positive correlation with surface water temperature values. This correlation indicates that water clarity was high when the water column was warm. Such conditions are typically conducive to the development of algal blooms. However, such a scenario probably would lead to a negative correlation between Secchi disk depth and temperature values, which is contrary to the observed pattern. The cause of the positive correlation between Secchi disk depth and water temperature values cannot be determined from the available data. However, contributing factors could include high turbidity during periods of cool water, such as occurs during the early spring. Another contributing factor could be that low turbidity is associated with warm water, presumably because suspended sediments and/or phytoplankton densities were low near the surface during the warmer months. Low phytoplankton densities could occur near the surface in Hood Canal, even during the bloom season, if, as in the Dabob Bay study area, maximum algal densities were well below the surface. Also, growth rates at the surface could have been limited by low nutrient concentrations. Depth profiles of the composition of suspended material, algal density, and rates of primary productivity would be useful for assessing the relative importance of these factors as determinants of water clarity.

The absence of statistically significant ($P<0.05$, scaled with the Bonferroni inequality) correlations between nutrient concentrations and other variables at the surface probably was due to a lack of analytical sensitivity in the laboratory analyses of nutrient concentrations. The analytical detection limits probably were not sufficiently low to allow detection of most of the variation in the nutrient concentrations at the surface. As in the Dabob Bay study area, nutrient concentrations were higher at depth, and the negative correlations at 10-m depth between nutrient concentrations and both dissolved oxygen concentrations and water temperature values were statistically significant ($P<0.05$, scaled with the Bonferroni inequality). These relationships would be expected at a stratified site where algal blooms well below the surface waxed and waned in intensity.

Geometric means of the concentrations of sulfite waste liquor and fecal coliform bacteria were near analytical detection limits in the mid-Hood Canal study area (Figure 5.112). These results are reasonable because there are no large sources of these contaminants near the study area.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.15. Slopes from statistically significant long-term and recent regressions of the water quality data against year are given in Table 5.16.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.124-5.126. Statistically significant ($P<0.05$) declines in salinity values were detected at the surface and at 10- and 30-m depths (Tables 5.15 and 5.16). At 30-m depth, the long-term decline appears to have been driven by the recent decline. Although changes in station location and data sources could have influenced the data, it appears that these declines in salinity were real phenomena. Changes in station location would have introduced an apparent decline in salinity into the data. The station sampled recently (Ecology's Station HCB003) is closer to the Skokomish River than are the stations sampled earlier (University of Washington's Stations HCB543, HCB544, HCB545) (see Table 5.13 and Figure 5.107). However, salinity profiles generally are flat in the Mid-Hood Canal region (Collias et al. 1974). Moreover, salinity values at the three University of Washington stations did not differ significantly, although the University of Washington stations were farther from each other than the Ecology station was from University of Washington's Station HCB545. Station HCB545 was the University of Washington station located closest to the Skokomish River. Thus, changes in station location do not seem to have introduced the apparent salinity declines into the data. Data compatibility checks (discussed in Chapter 4 and Appendix D) did not indicate that salinity determinations by the University of Washington and Ecology differed systematically from each other. Therefore, the interpretation that salinity values in the Mid-Hood Canal study area have declined since the early 1950s appears credible.

As was noted for the Dabob Bay study area, water temperature values at 10- and 30-m depths have increased since the early 1950s (Tables 5.15 and 5.16). These changes generally coincided with the changes in the air temperature data from Seattle-Tacoma International Airport, which indicated that a cool period existed during much of the 1950s. Because horizontal temperature profiles in the study area do not vary systematically with location along the central axis of Hood Canal (Collias et al. 1974), artifacts caused by changes in station location do not appear to have introduced the apparent temperature increases into the data. As discussed above for Dabob Bay, differences in analytical techniques between the University of Washington and Ecology could have influenced the apparent

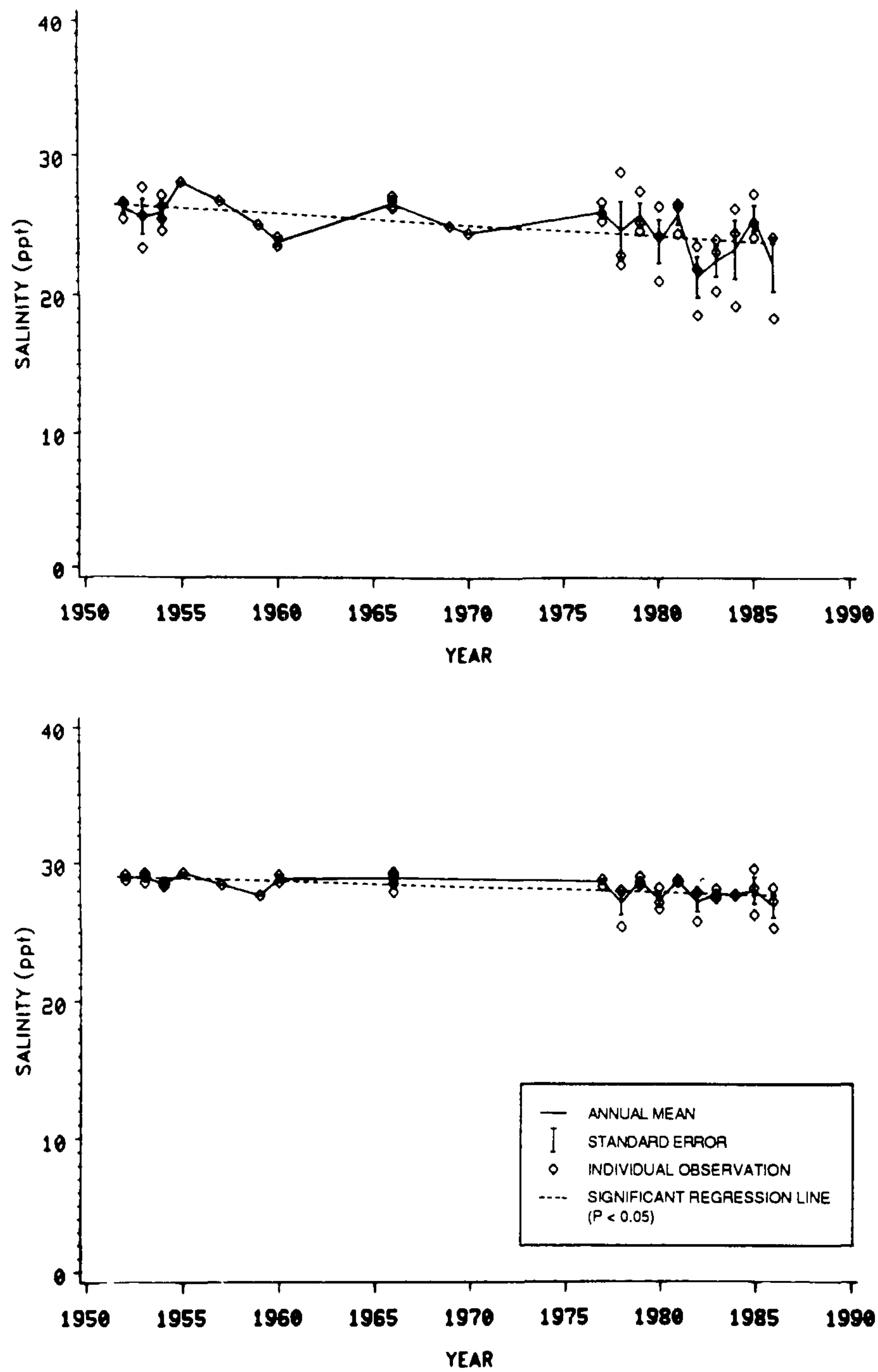


Figure 5.124. Salinity values at the surface and at 10-m depth in the Mid-Hood Canal study area during the algal bloom season.

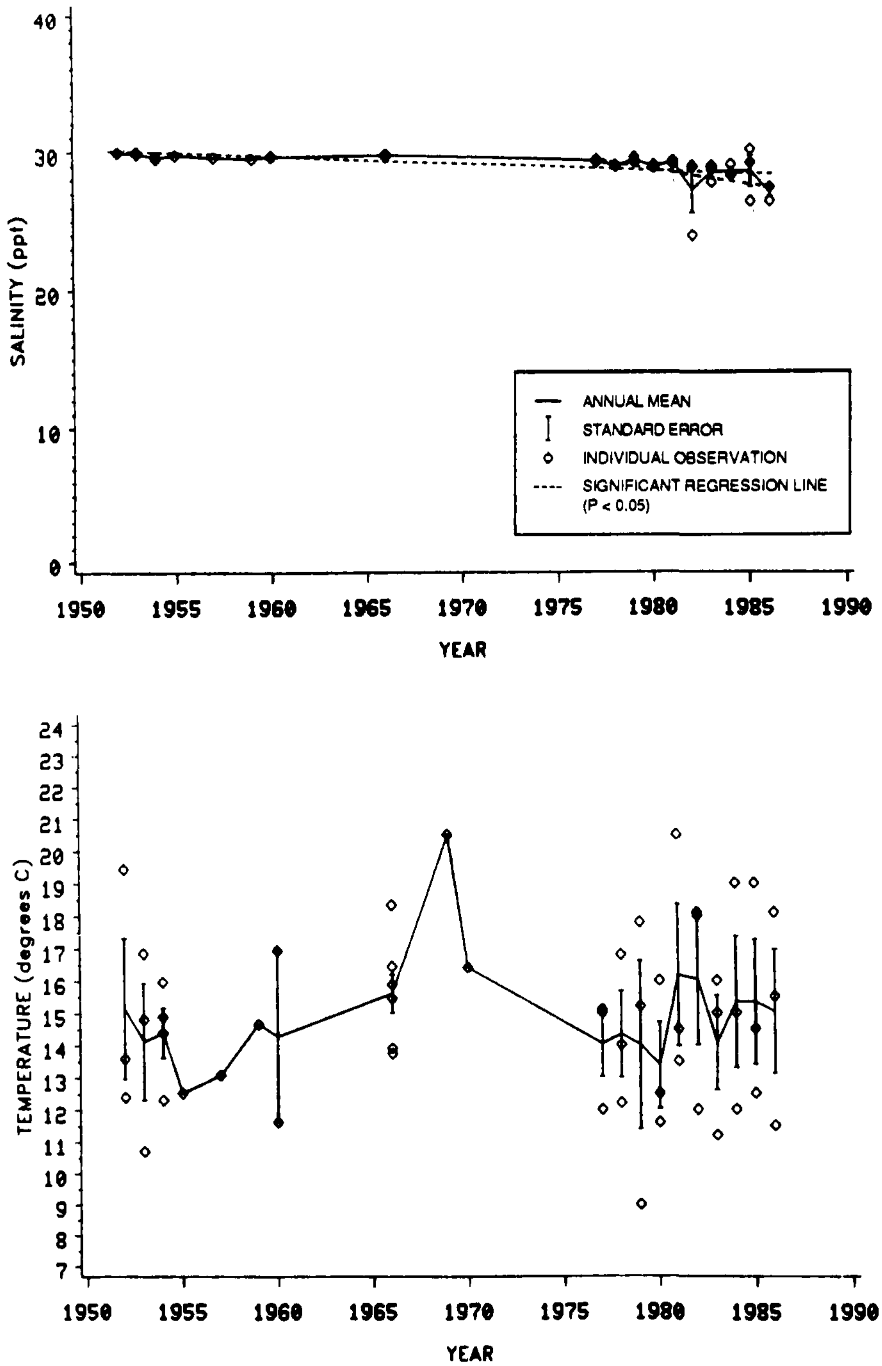


Figure 5.125. Salinity values at 30-m depth and water temperatures at the surface in the Mid-Hood Canal study area during the algal bloom season.

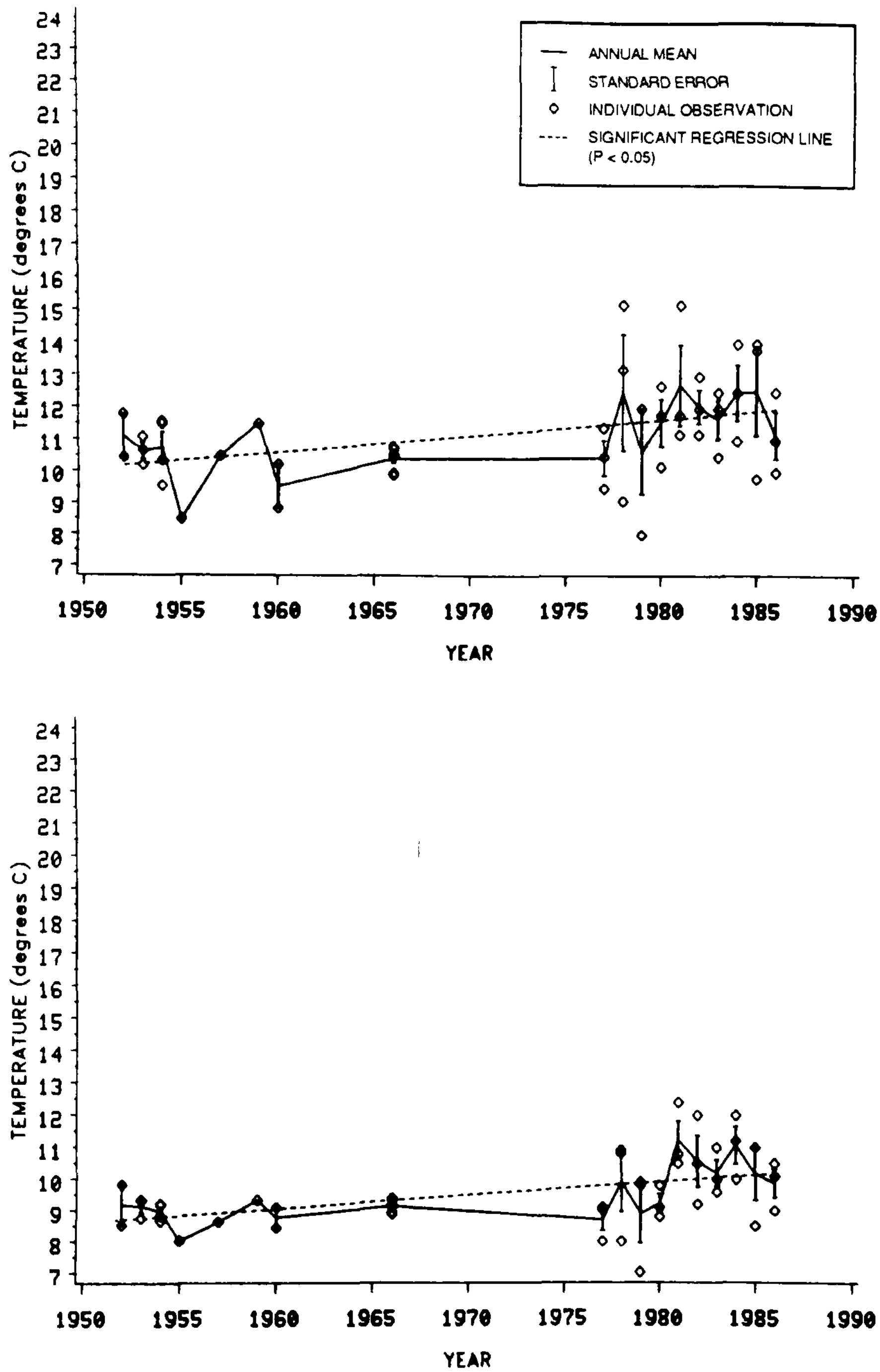


Figure 5.126. Water temperatures at 10- and 30-m depths in the Mid-Hood Canal study area during the algal bloom season.

increases in the water temperature data. However, the most likely interpretation is that the apparent increases in water temperature at 10- and 30-m depths were real phenomena.

Dissolved Oxygen--Plots of dissolved oxygen concentrations by year are shown in Figures 5.127 and 5.128. The Class AA water quality standard (see Table 4.2) was violated once in surface waters and sporadically at 10-m depth. Concentrations at 30-m depth were usually below the standard. The mean dissolved oxygen concentration at this depth was 0.2 mg/L below the standard. As was observed in the Dabob Bay study area, dissolved oxygen concentrations at 10- and 30-m depths appear to have increased (Tables 5.15 and 5.16). At 10-m depth, the recent trend appears to have driven the long-term trend. The likely influence of the changes in station locations over time would have been to artificially decrease dissolved oxygen concentrations at depth. This increase would have resulted because a tongue of water with low concentrations of dissolved oxygen often extends northward from Lynch Cove into the southern portion of the Mid-Hood Canal study area (Collias et al. 1974), and because the recent data were collected at the southern-most station included in the data set. Because the observed increases in dissolved oxygen concentrations were contrary to the decreases that might have been introduced into the data by the changes in station location, station changes probably did not introduce artificial changes in dissolved oxygen concentration into the data.

Nutrients--Plots of nitrate concentrations by year are shown in Figures 5.128 and 5.129. Because data are only available since 1977, comparisons of data collected before and after 1973, and long-term regressions by year could not be performed. The recent regressions of nitrate concentrations by year were not statistically significant ($P>0.05$) (Table 5.16). However, negative slopes were found at all three depths, and the slopes were nearly significant for data collected at 10-m depth (slope=-0.76 ug-at/L/yr, $P=0.10$) and 30-m depth (slope=-0.83 ug-at/L/yr, $P=0.054$). These apparent declines in nitrate concentration do not appear to have been artifacts of changes in station location or analytical technique because all the nitrate data came from the same station and agency.

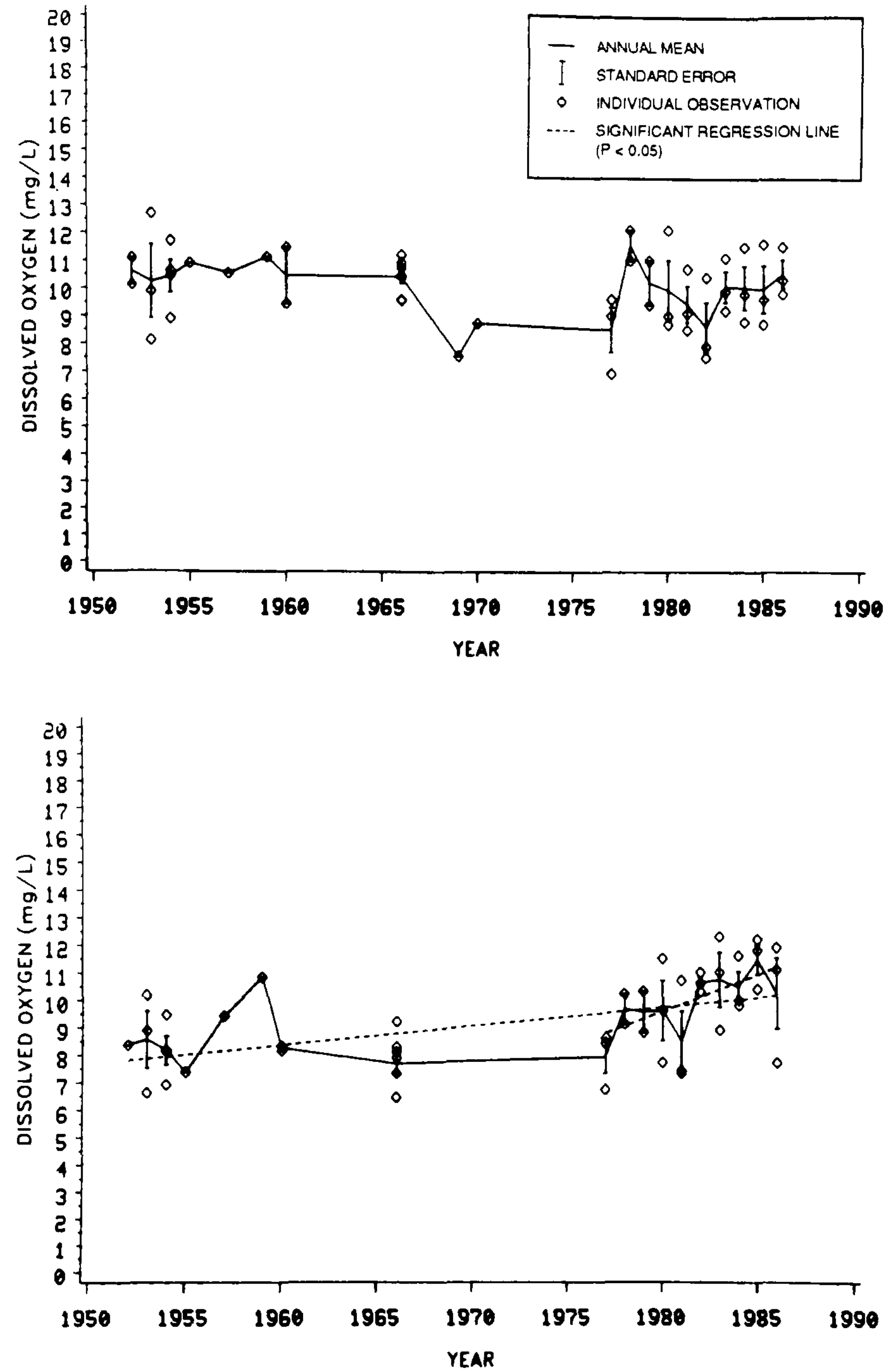


Figure 5.127. Concentrations of dissolved oxygen at the surface and at 10-m depth in the Mid-Hood Canal study area during the algal bloom season.

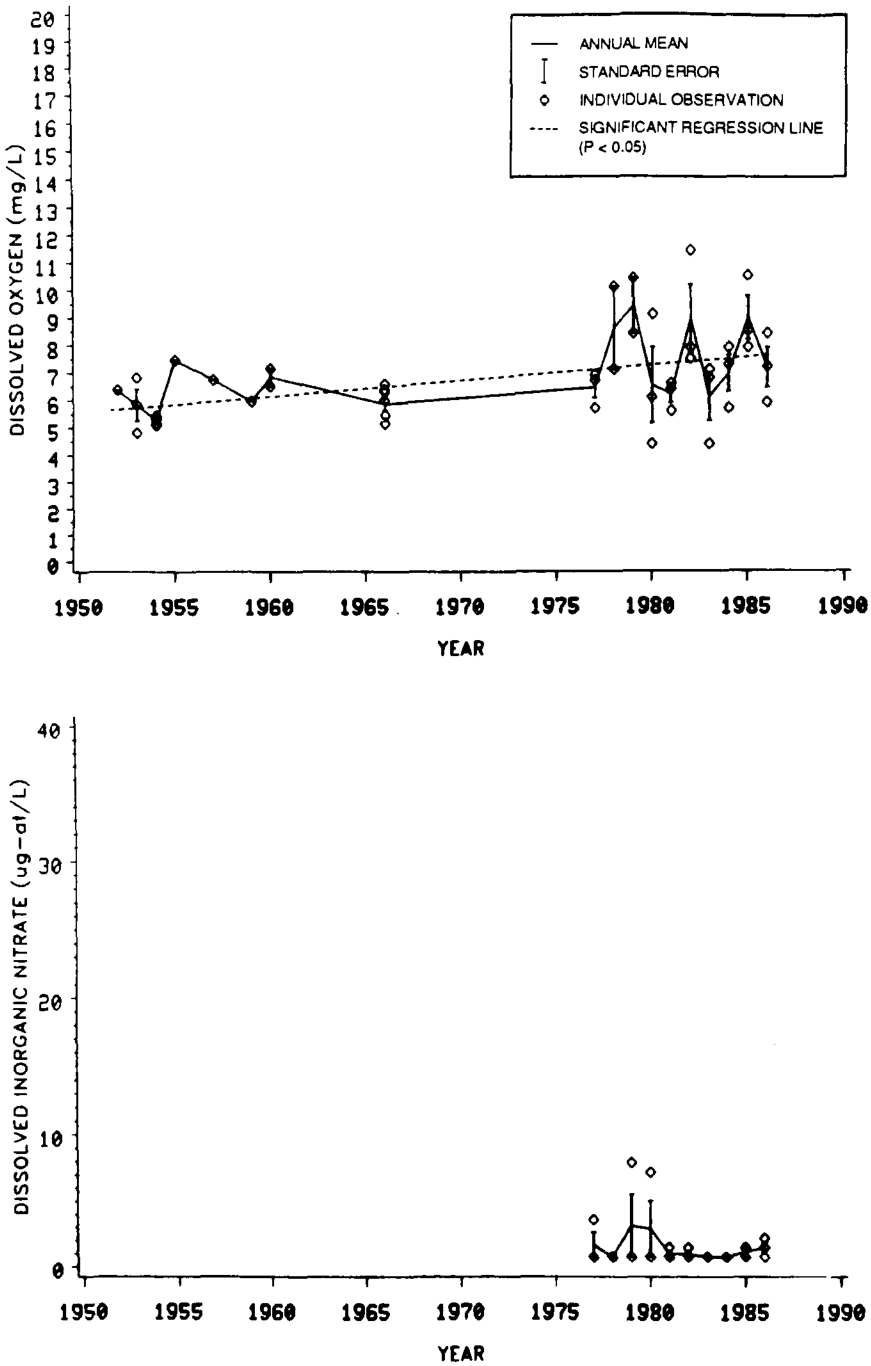


Figure 5.128. Concentrations of dissolved oxygen at 30-m depth and dissolved inorganic nitrate at the surface in the Mid-Hood Canal study area during the algal bloom season.

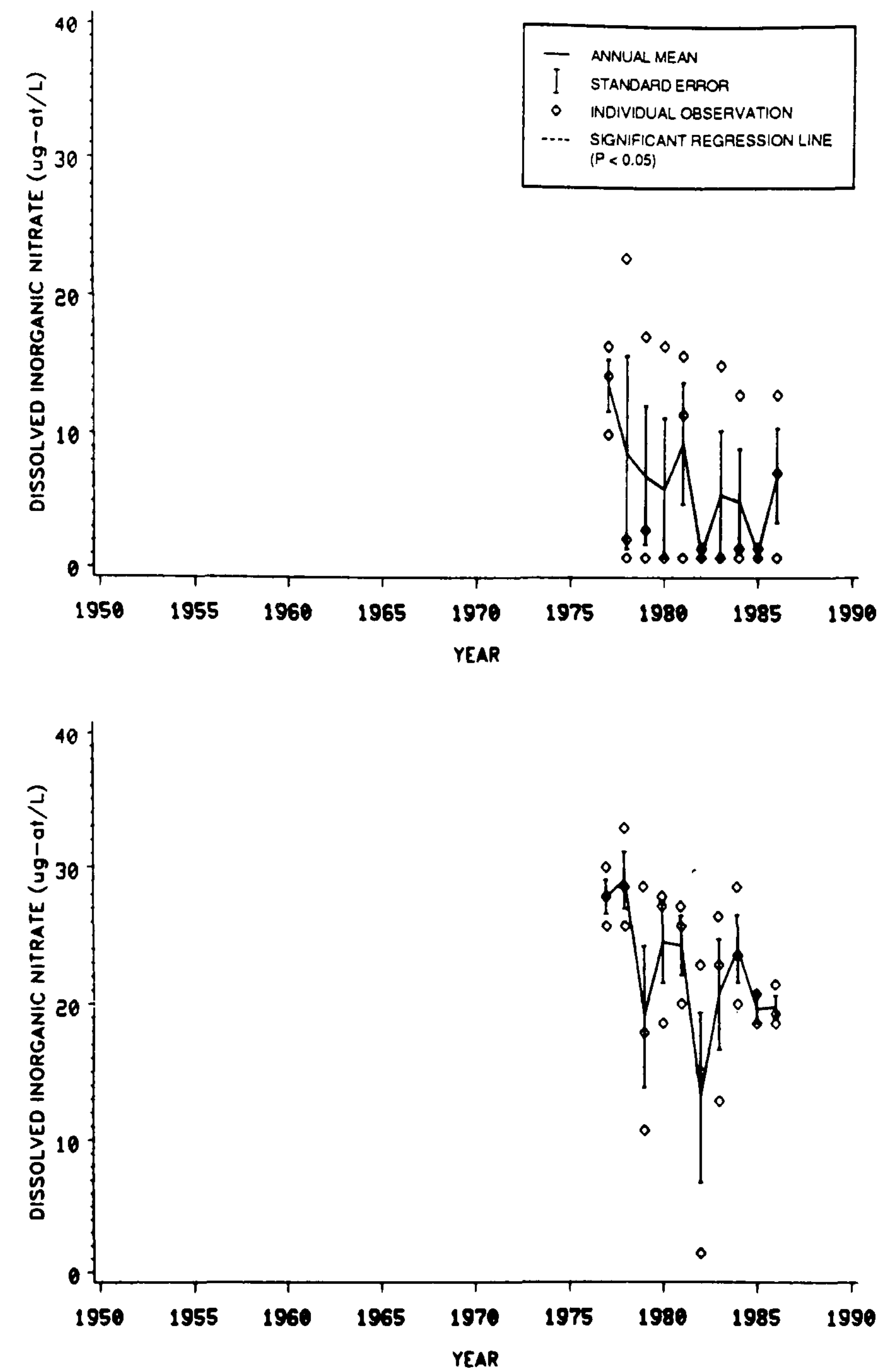


Figure 5.129. Concentrations of dissolved inorganic nitrate at 10- and 30-m depths in the Mid-Hood Canal study area during the algal bloom season.

Plots of phosphate concentrations by year are shown in Figures 5.130 and 5.131. Comparisons with the nonparametric ANOVA of mean phosphate concentrations recorded before and after 1973 indicated that the recent concentrations were significantly ($P<0.05$) lower at both depths (Table 5.15). The regressions of phosphate concentration by year had negative slopes at both depths, although neither slope was significant ($P=0.1$) (Table 5.16). Phosphate concentrations did not change significantly ($P>0.6$) at the surface. As was discussed previously, changes in station location and data sources do not appear to have introduced apparent changes into the phosphate data. As was discussed for Dabob Bay, increase in nutrient consumption by phytoplankton or decreases in oceanic inputs may have contributed to the decreases in phosphate concentrations.

Indicators of Phytoplankton Growth--No statistically significant temporal trends were detected for indicators of phytoplankton growth. However, long-term data were limited to the percent dissolved oxygen saturation at the surface. Oxygen saturation data for the surface are plotted in Figure 5.131. Data on Secchi disk depth date back to 1977 (Figure 5.132). However, the transparency of the water column was high in the Mid-Hood Canal region (mean Secchi disk depth was 6.0 m), and long-term increases in percent dissolved oxygen saturation were found at depth (10-m depth: slope=+0.81 percent/yr, $P=0.0001$; 30-m depth: slope=+0.61, $P=0.0009$). The recent increase (since 1977) in percent dissolved oxygen saturation at 10-m depth (slope=+3.46 percent/yr, $P=0.006$) appears to have driven the long-term trend at this depth, but the recent regression at 30-m depth was not statistically significant ($P>0.6$).

Because nitrate concentrations have declined and oxygen saturation percentages have increased at 10-m depth since 1977, it appears that photosynthetic activity and phytoplankton abundance have increased at this depth. Unfortunately data on chlorophyll *a* concentrations are not available to test this hypothesis. No explanation is available for the long-term increase in percent dissolved oxygen saturation at 30-m depth. However, changes in photosynthetic activity at depth might have influenced the data.

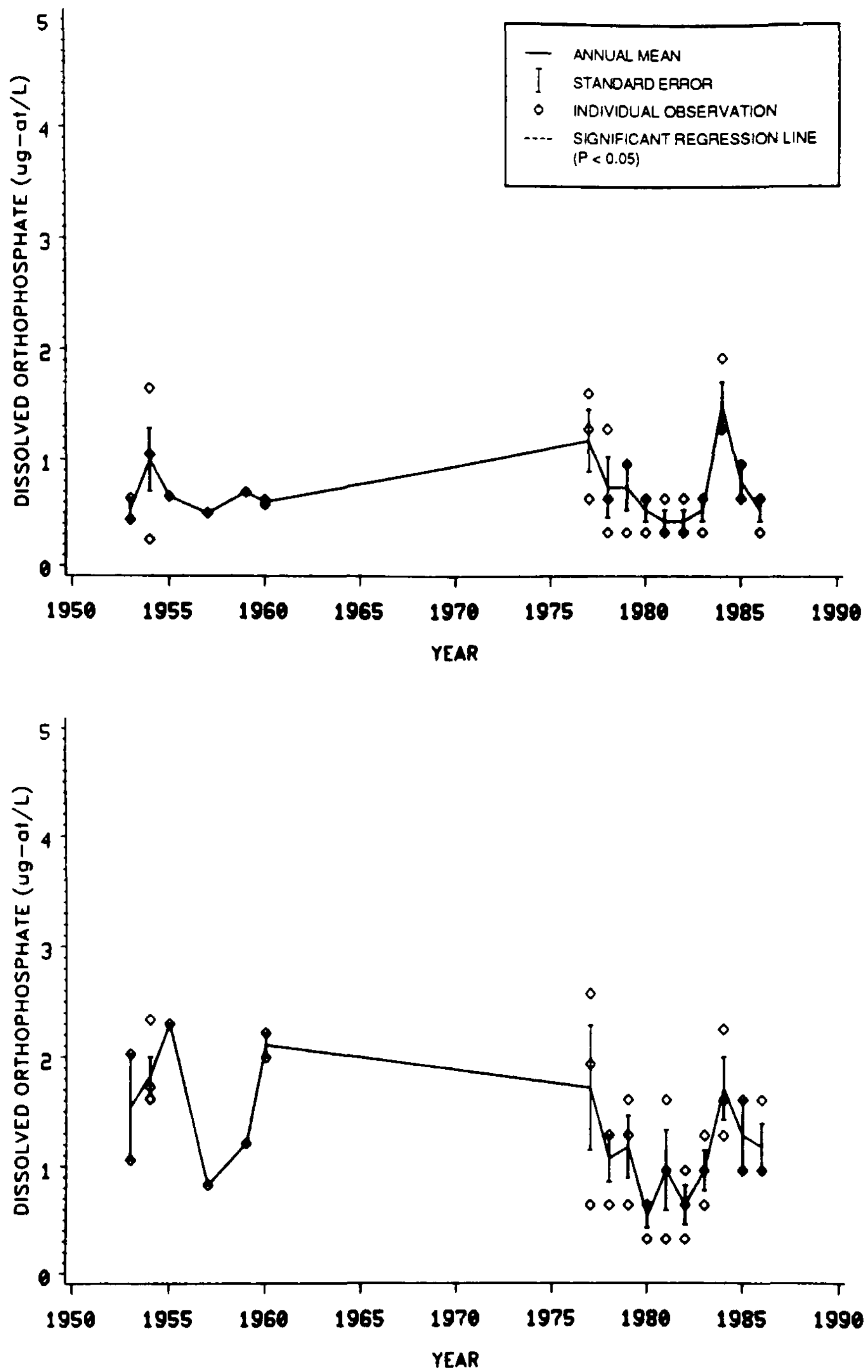


Figure 5.130. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the Mid-Hood Canal study area during the algal bloom season.

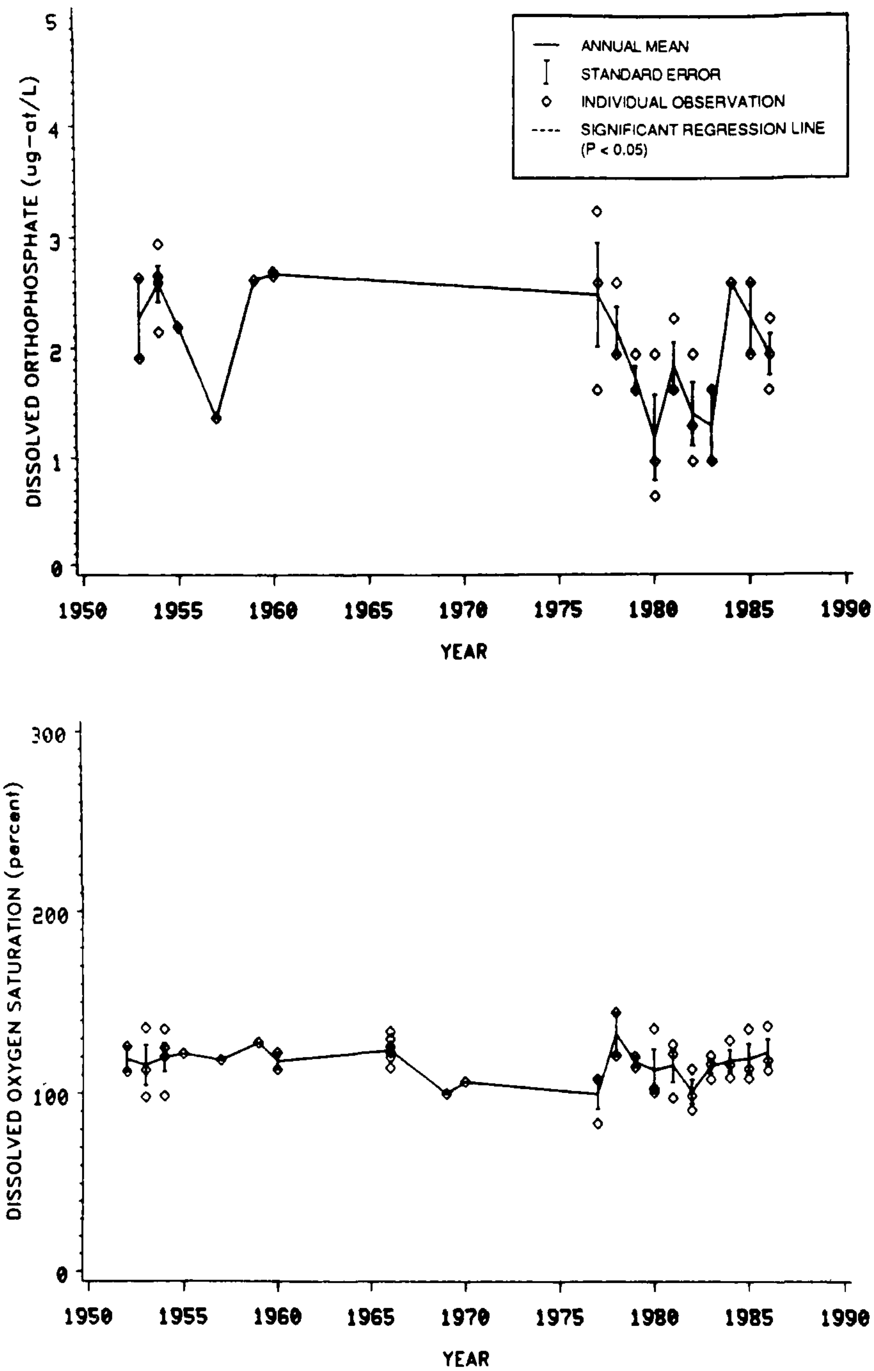


Figure 5.131. Concentrations of dissolved orthophosphate at 30-m depth and percent dissolved oxygen saturation at the surface in the Mid-Hood Canal study area during the algal bloom season.

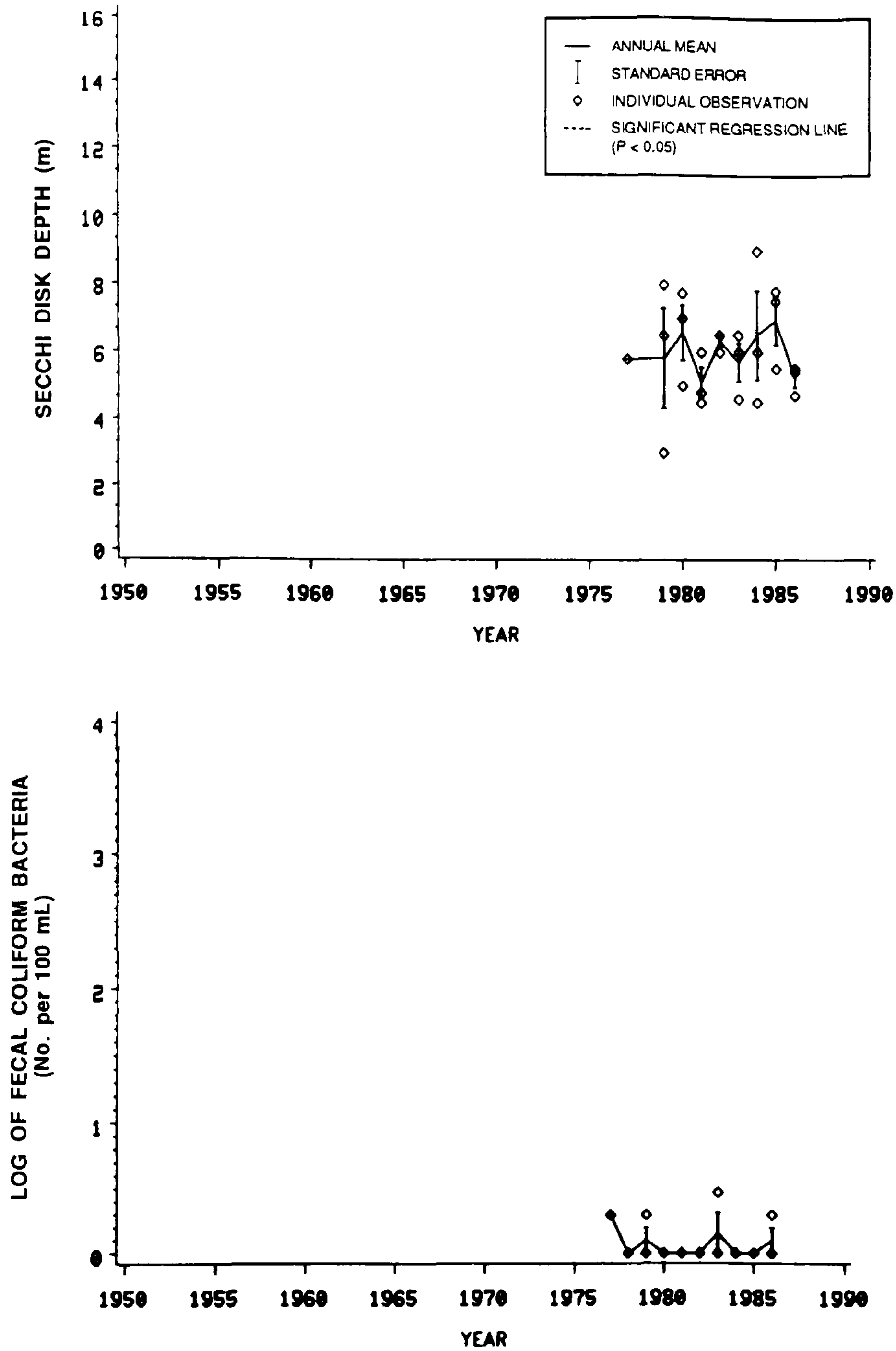


Figure 5.132. Secchi disk depth and log of concentrations of fecal coliform bacteria at the surface in the Mid-Hood Canal study area during the algal bloom season.

Pollutants--The only data available for pollutants included in the characterization study are data on concentrations of fecal coliform bacteria at the surface (Figure 5.132). No significant temporal trend was detected in the fecal coliform data.

South Hood Canal

The study area is located in a rural area near Sisters Point. It is approximately 6.5 km east of The Great Bend in Hood Canal (see Figure 5.107) and 18 km west of Lynch Cove, the head of Hood Canal. It is the study area in Hood Canal most removed from oceanic influences. Class AA water quality standards apply in the region. There are no major population centers near the study area, but there are many summer homes along the shoreline. The study area is roughly 35-40 m deep. Two rivers, the Skokomish and the Tahuya, flow into Hood Canal near Sisters Point. Combined, these rivers contribute approximately 5 percent of the total freshwater flow into Puget Sound (see Table 2.1). Circulation below the surface is sluggish in the study site, and the area is prone to episodes of low dissolved oxygen concentrations in sub-surface water, particularly in late summer. Bottom water usually is replaced only annually in late summer or early autumn (Collias et al. 1974).

Environmental Conditions in the Study Area--

Mean salinity and water temperature values during the algal bloom season are shown in Figure 5.108. Data are available from 1952 through 1986. Depth gradients of these two variables in the South Hood Canal area were the largest of all the Hood Canal sites, with low salinity values and high temperatures having been recorded at the surface. The mean salinity value was 4.8 ppt lower at the surface than at 10-m depth. The mean water temperature value was 3.9° C higher at the surface than at 10-m depth. The South Hood Canal study area can be characterized as having very substantial density stratification and very low rates of vertical mixing and circulation. These physical conditions would be expected to be highly conducive to the development of algal blooms and, as a consequence, low dissolved oxygen concentrations at depth.

Given the physical environment in the South Hood Canal study area, the depth distribution of dissolved oxygen concentrations at this site was distinct from the depth distributions observed at the Dabob Bay and Mid-Hood Canal sites (Figure 5.109). The surface concentrations of dissolved oxygen were similar in the three areas (10.1-10.5 mg/L), but the dissolved oxygen concentrations were much lower at 10-m and 30-m depth in the South Hood Canal area. At the South Hood Canal study area, the mean dissolved oxygen concentration at 10-m depth was only 74 percent of the mean value at 10-m depth at the Dabob Bay study area. At 30-m depth, the mean concentration of dissolved oxygen was only 60 percent of the mean value at this depth in the Dabob Bay site. The lower dissolved oxygen concentrations at 10- and 30-m depths in the South Hood Canal study area were probably influenced by the very low dissolved oxygen concentrations in the deep source water. Other surveys of Hood Canal have also reported very low dissolved oxygen concentrations in the deep waters in this area during spring and summer (e.g., Collias et al. 1974).

Although the vertical distributions of nutrients at the South Hood Canal site were similar to those in the Dabob Bay and Mid-Hood Canal sites, the gradients were more extreme in South Hood Canal (Figures 5.109 and 5.110). Surface concentrations of nitrate and phosphate at the South Hood site were very low, typically below the analytical detection limits. Although low nutrient concentrations frequently could have limited algal growth in the surface water, nutrient concentrations at 10- and 30-m depths in South Hood Canal were the highest of all the Hood Canal sites. Mean nitrate concentrations were 13.0 ug-at/L and 27.0 ug-at/L at 10- and 30-m depths, respectively. Mean phosphate concentrations were 2.1 ug-at/L and 2.9 ug-at/L at 10- and 30-m depths, respectively.

Based on the mean percent dissolved oxygen saturation at the surface (115 percent), the intensity of the algal blooms at the South Hood Canal site was high. However, it was slightly lower than the intensities of the blooms at the Mid-Hood Canal and Dabob Bay sites (Figure 5.111). No chlorophyll a data are available for the South Hood Canal site. The water was more turbid in the South Hood Canal study area than it was in the other two Hood Canal study sites, as the mean value of Secchi disk depth (4.8 m) was lowest in the South Hood Canal study area (Figure 5.111). However, the difference in turbidity may not have been due to phytoplankton densities because indicators of phytoplankton growth did not exhibit higher values at the South Hood site than at the Mid-Hood Canal or Dabob Bay sites. The lack of significant correlations ($P<0.05$, scaled with the Bonferroni inequality) between Secchi disk depth and either surface dissolved oxygen concentration or surface percent dissolved oxygen saturation (Appendix E) suggests that the changes in turbidity were too variable to yield a reliable indication of phytoplankton density.

As discussed for the Dabob Bay and Mid-Hood Canal sites, the lack of correlations between nutrient concentrations and the values of the other variables at the surface probably was due to the lack of analytical sensitivity in the laboratory analyses of nutrient concentrations. Like the other two sites on Hood Canal, nutrient concentrations were higher at depth. As would be expected at a stratified site where algal blooms waxed and waned in intensity, statistically significant ($P<0.05$, scaled with the Bonferroni inequality) negative correlations were found at 10-m depth between nutrient concentrations and both dissolved oxygen concentrations and water temperature values. Thus, as in Dabob Bay, much of the phytoplankton biomass probably occurred well below the surface.

Geometric means of the concentrations of sulfite waste liquor and fecal coliform bacteria were near analytical detection limits in the South Hood Canal area (Figure 5.112), presumably because the area is relatively undeveloped.

Water Quality Trends in the Study Area--

A summary of comparisons between water quality data collected before and after 1973 is given in Table 5.15. Slopes from statistically significant long-term and recent regressions of the water quality data by year are given in Table 5.16.

Physical Conditions--Plots of salinity and water temperature values by year are shown in Figures 5.133-5.135. No statistically significant changes in salinity values were detected for surface water. However, salinity values at 10- and 30-m depths apparently have declined since 1952. Changes in salinity values since 1976 were not statistically significant ($P>0.05$).

It does not appear that the above changes in salinity values were artifacts of changes in station location and data sources. However, this possibility cannot be thoroughly evaluated. Although horizontal salinity gradient was recorded in the area (Collias et al. 1974), the Ecology station sampled since 1968 was located approximately half way between the two University of Washington stations sampled from 1952 through 1966 (Figure 5.107, Table 5.13). Therefore, the horizontal salinity gradient probably did not affect the average data values. As was discussed for Dabob Bay, differences in the analytical methods used to determine salinity by the University of Washington and Ecology do not appear to explain the apparent changes in salinity values (Chapter 4 and Appendix D). In summary, salinity values at 10- and 30-m depths in the South Hood Canal study area appear to have declined. The cause of the salinity declines is not known, but decreased inputs of oceanic water may have been involved.

Water temperature values at 10- and 30-m depths appear to have increased (Tables 5.15 and 5.16). As was discussed for Dabob Bay, these increases may have been caused by the increased air temperatures, as were detected at the Seattle-Tacoma International Airport (see Figure 5.1). Mean annual air temperatures were cool from 1948 through 1955. Although water temperatures in Hood Canal are often higher near the head of Lynch Cove (Collias et al. 1974), changes in station locations over time probably did not introduce these apparent increases into the data. As discussed for Dabob Bay, differences in analytical techniques between the University of Washington and Ecology might have contributed to the apparent increases in water temperatures (see Chapter 4 and Appendix D). Thus, it appears that water temperatures have increased in the South Hood Canal study area, although changes in station location and data sources over time may have contributed to these apparent changes.

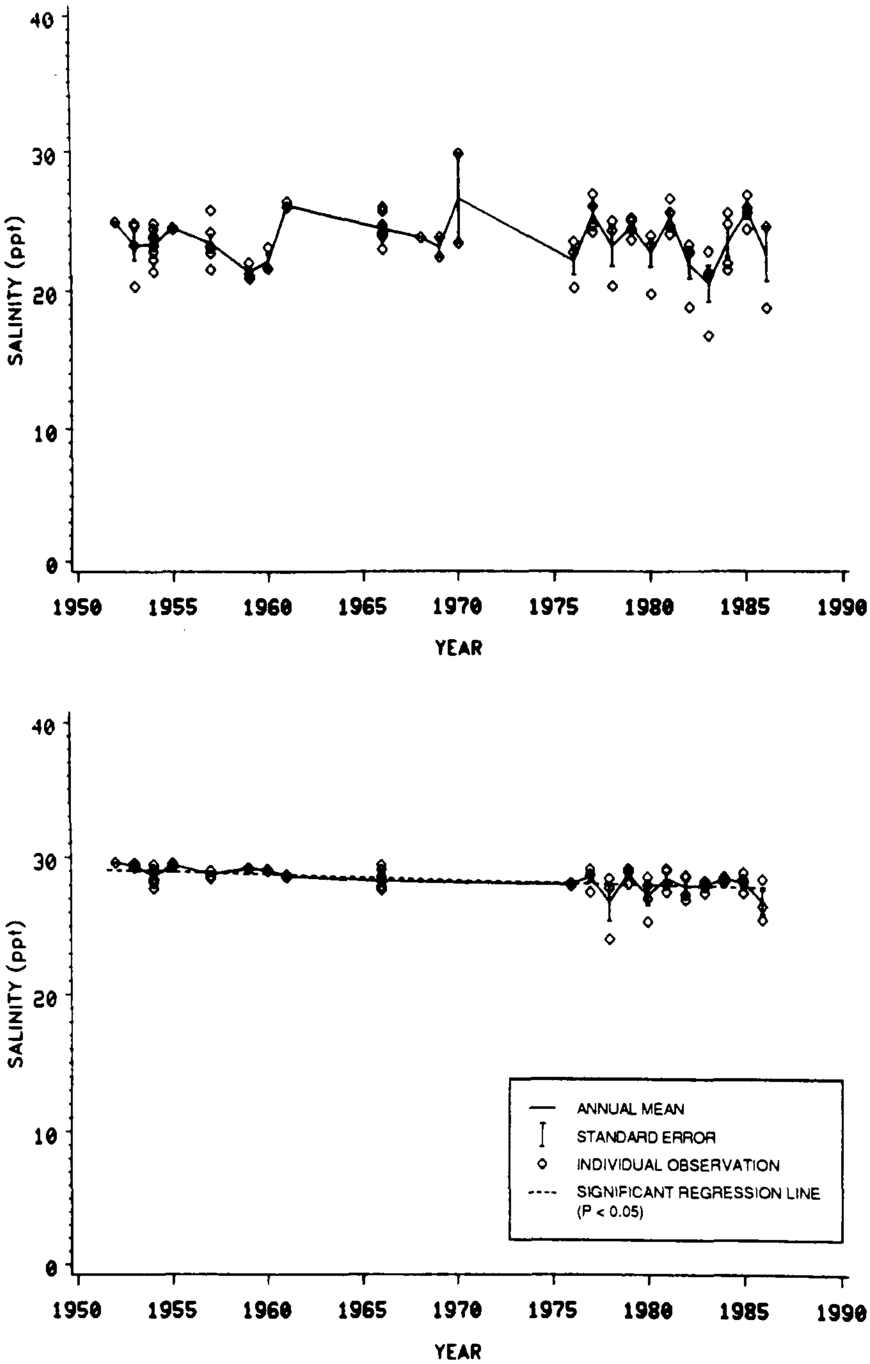
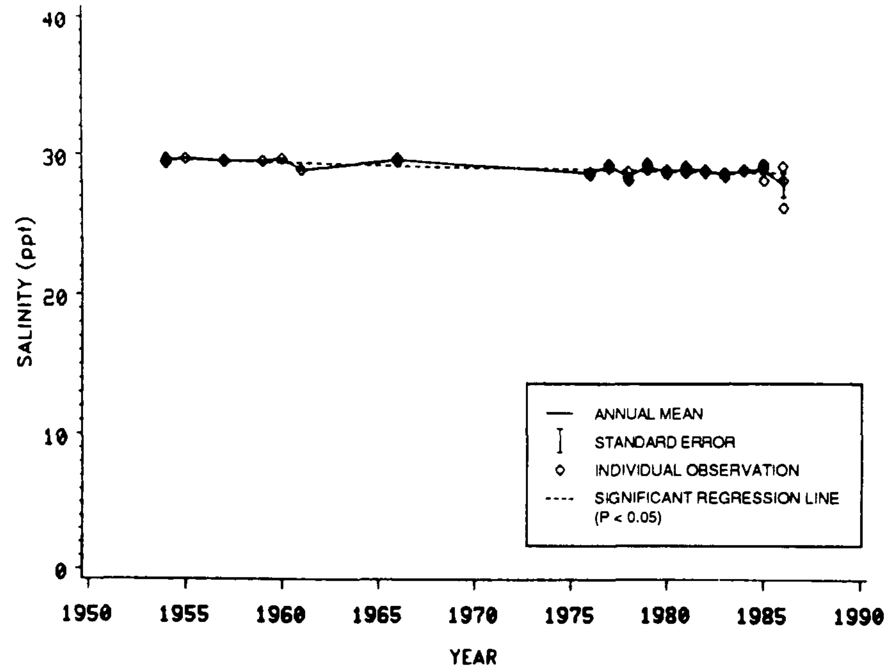


Figure 5.133. Salinity values at the surface and at 10-m depth in the South Hood Canal study area during the algal bloom season.



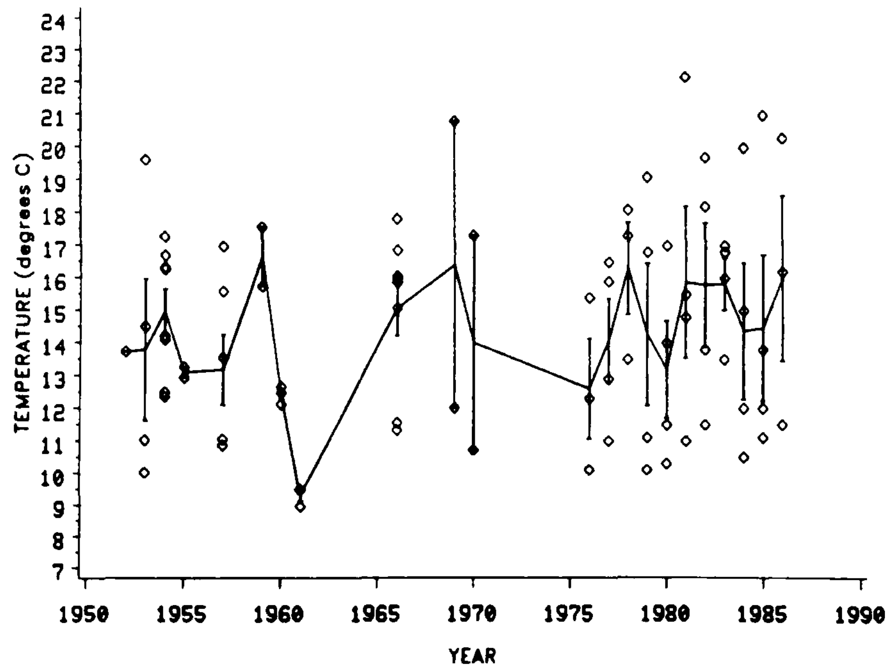


Figure 5.134. Salinity values at 30-m depth and water temperatures at the surface in the South Hood Canal study area during the algal bloom season.

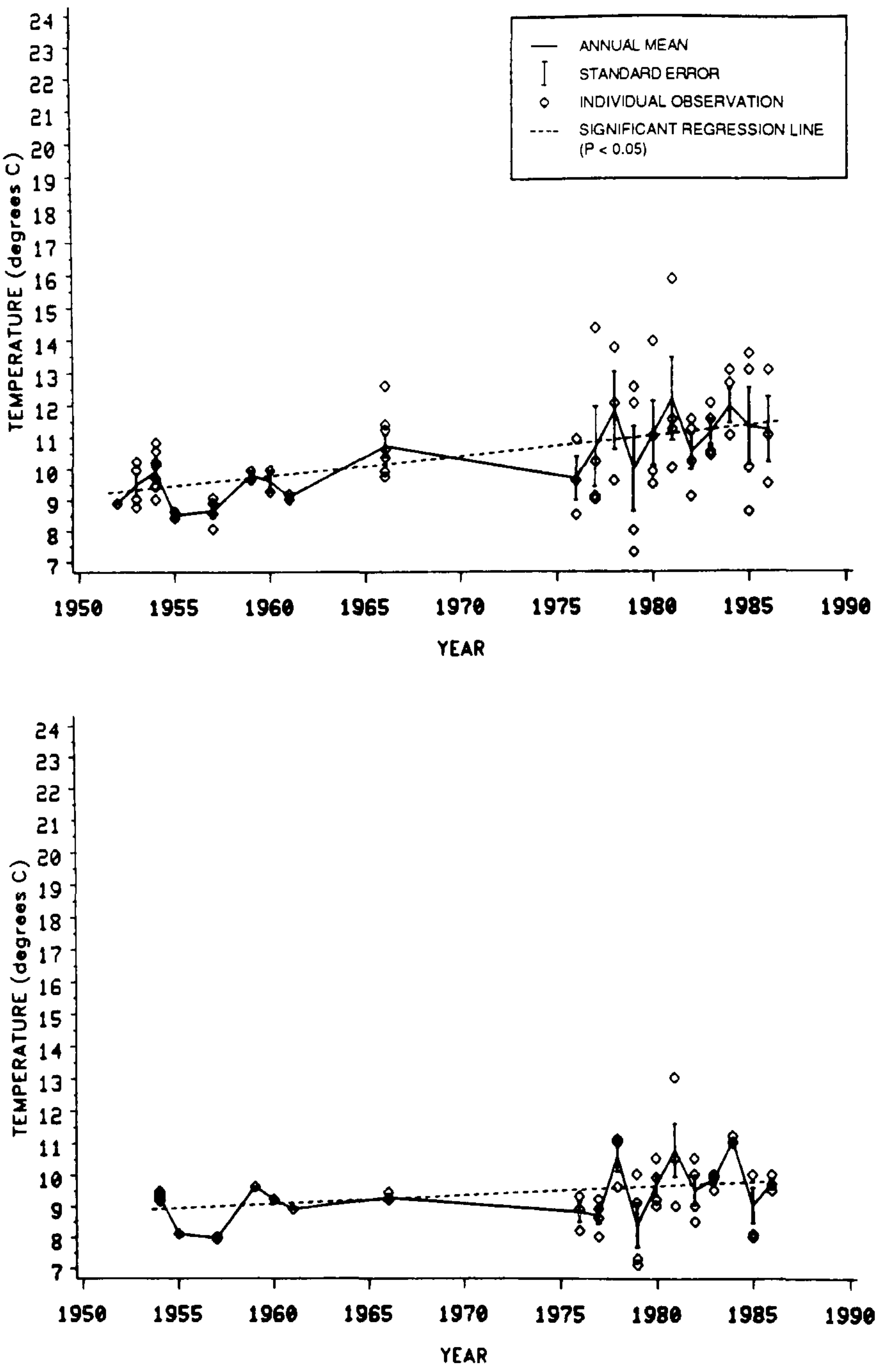
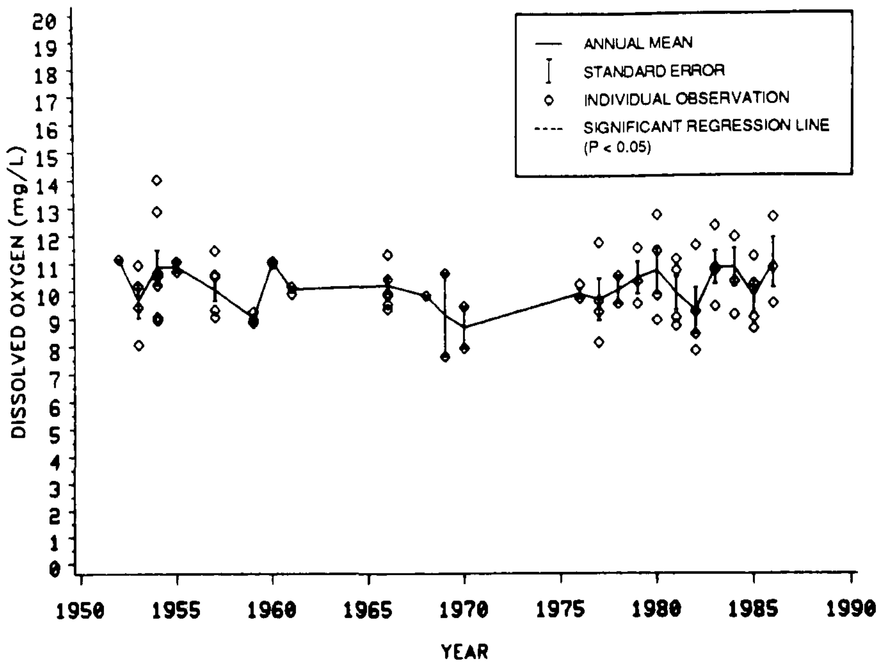


Figure 5.135. Water temperatures at 10- and 30-m depths in the South Hood Canal study area during the algal bloom season.

Dissolved Oxygen--Plots of dissolved oxygen concentrations by year are shown in Figures 5.136 and 5.137. There was no evidence that the Class AA water quality standard (see Table 4.2) was violated in surface waters. Concentrations below the standard occurred occasionally at 10-m depth. The frequency of violation at 10-m depth was higher than at the Mid-Hood Canal study area. Concentrations were usually below the standard at 30-m depth. The mean dissolved oxygen concentration at this depth was 2.7 mg/L below the standard. Statistically significant ($P<0.05$) increases in dissolved oxygen concentrations were found at 10- and 30-m depths. The increase since 1976 was statistically significant only at 10-m depth (Tables 5.15 and 5.16). The long-term increase at 10-m depth appears to have been driven in large part by the recent increase. The recent increase at 10-m was not an artifact because the same sampling station and data source was used since 1976. The long-term increase at 30-m depth was detected statistically. However, much of this trend appears to have been driven by some very low values reported in 1952, the first year from which data were obtained. Thus, the most important change detected for dissolved oxygen concentrations at the South Hood Canal study area was an increase at 10-m depth since 1976.

Nutrients--Plots of nitrate concentrations by year are shown in Figures 5.137 and 5.138. Because data are available only since 1976, comparisons of data collected before and after 1973, and long-term regressions of the data by year could not be performed. No statistically significant ($P<0.05$) changes in nitrate concentrations were detected at the surface, but, as at the Dabob Bay and Mid-Hood Canal sites, the analytical methods probably were not sufficiently sensitive to detect nitrate concentrations reliably at the ambient surface concentrations. A statistically significant ($P<0.05$) decrease in nitrate concentrations was detected at 30-m depth (Table 5.16); at 10-m depth the decline was nearly significant ($P=0.07$). These decreases were not artifacts of changes in station location or data sources because the nitrate data were all collected at the same sampling station by Ecology.

Statistically significant long-term decreases in phosphate concentrations were detected at the surface and at 10- and 30-m depths



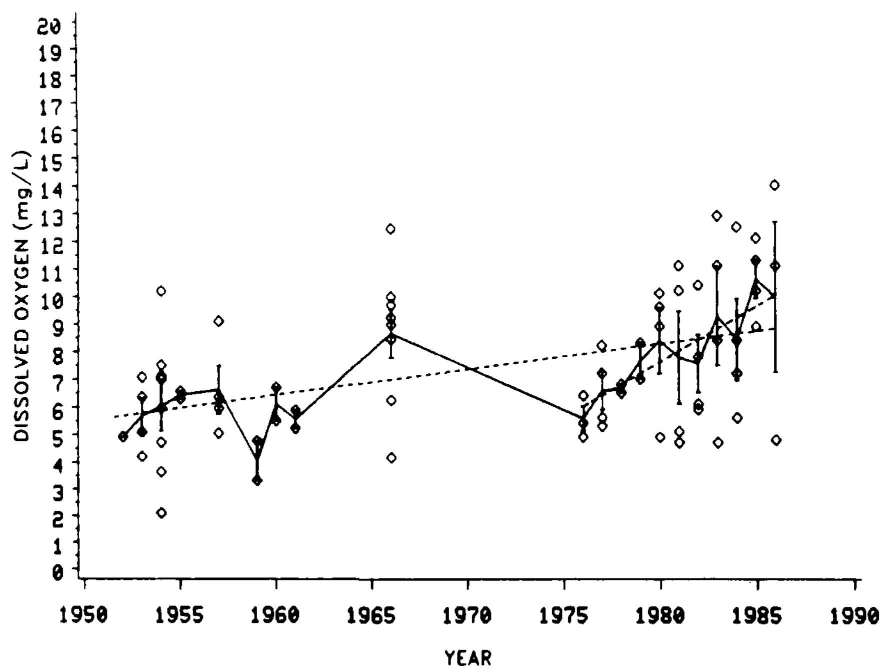


Figure 5.136. Concentrations of dissolved oxygen at the surface and at 10-m depth in the South Hood Canal study area during the algal bloom season.

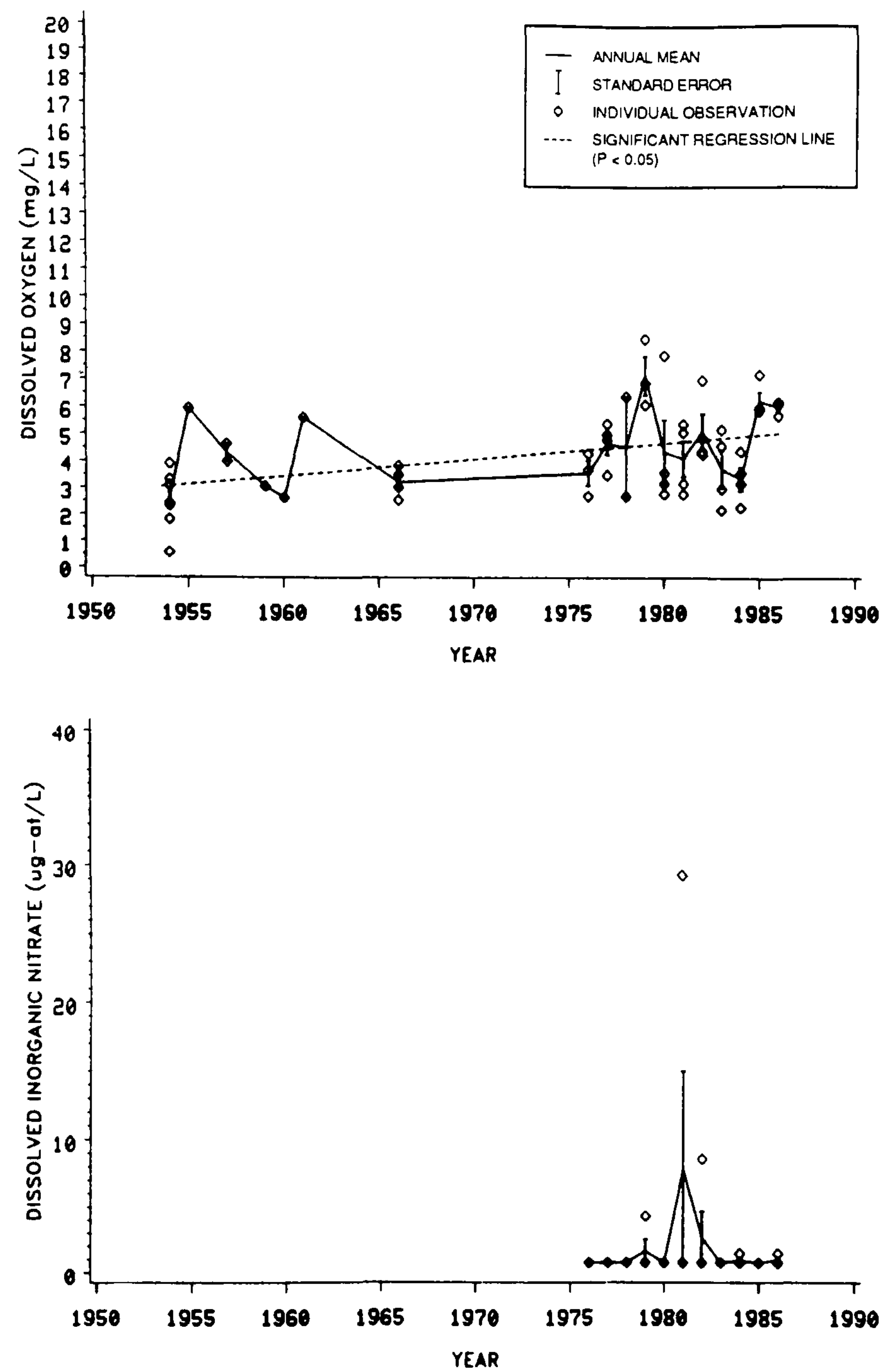


Figure 5.137. Concentrations of dissolved oxygen at 30-m depth and dissolved inorganic nitrate at the surface in the South Hood Canal study area during the algal bloom season.

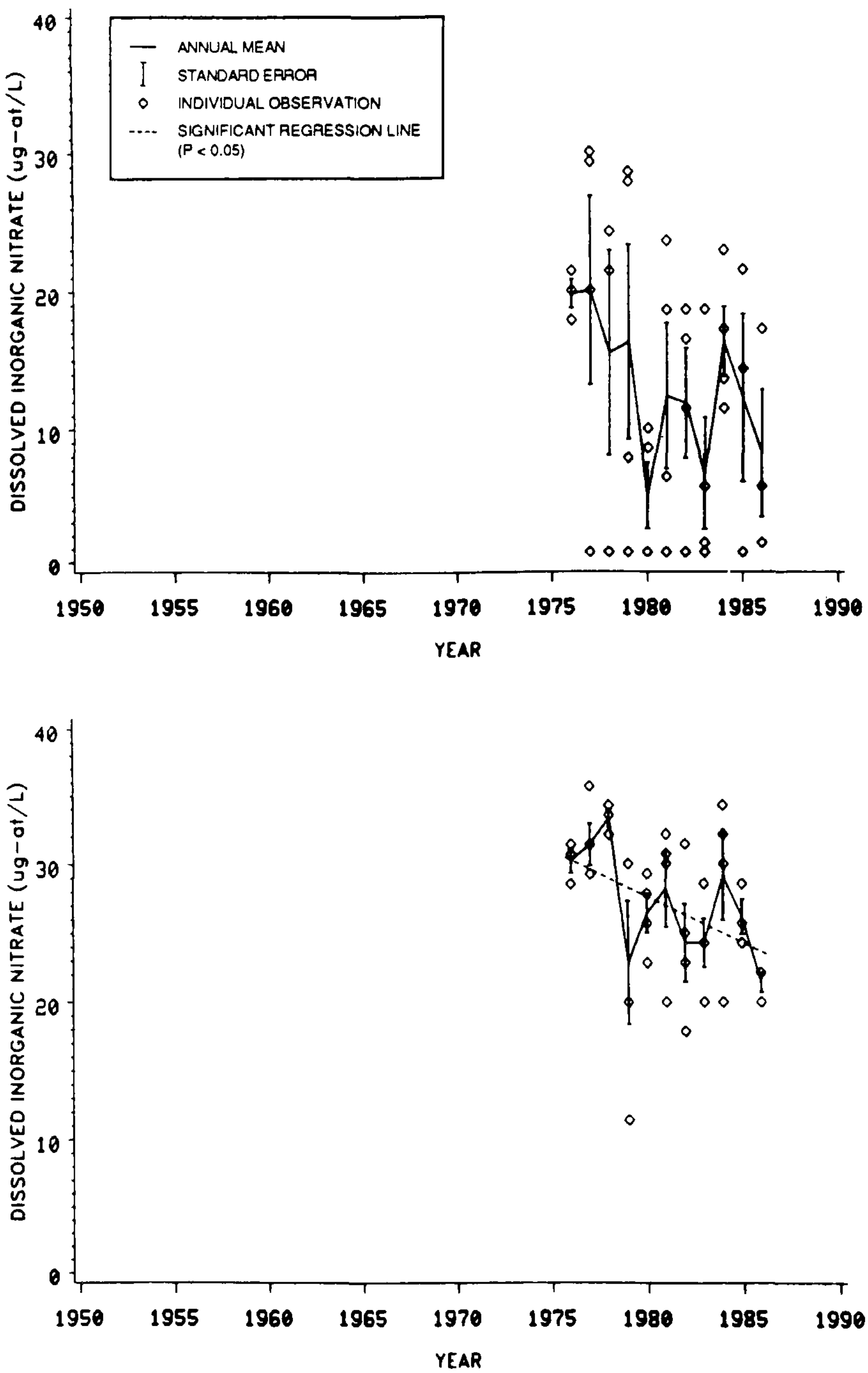


Figure 5.138. Concentrations of dissolved inorganic nitrate at 10- and 30-m depths in the South Hood Canal study area during the algal bloom season.

(Tables 5.15 and 5.16, Figures 5.139 and 5.140). Changes in phosphate concentrations since 1976 were not statistically significant. The values recorded from the early portion of the data set generally were higher than the values recorded from the recent portion of the data set. As discussed above, changes in station locations do not appear to have introduced these decreases into the data, although phosphate concentrations in Hood Canal are often higher close to the head of Lynch Cove (Collias et al. 1974). As discussed for Dabob Bay (see also Chapter 4 and Appendix D), changes in analytical techniques probably had little effect on the phosphate data. The apparent long-term declines in phosphate concentrations in South Hood Canal appear to have been real phenomena. The cause of these phosphate declines may have been increased photosynthesis (see below) or decreased oceanic inputs.

Indicators of Phytoplankton Growth--Data on chlorophyll *a* concentrations are not available. Percent dissolved oxygen saturation at the surface and Secchi disk depth are plotted by year in Figures 5.140 and 5.141. No statistically significant ($P<0.05$) temporal trends were detected for either variable. As was noted for the Dabob Bay and Mid-Hood Canal areas, the percent dissolved oxygen saturation has increased at depth since 1952 (10-m depth: slope=+1.16 percent/yr, $P=0.0001$; 30-m depth: slope=+0.71 percent/yr, $P=0.0003$). Although the long-term increase at 10-m depth appears to have been driven by the recent increase (since 1976) at 10-m depth (slope=+4.81, $P=0.002$), the recent changes in data values at the surface and 30-m depth were not significant. These results suggest that photosynthetic rates and algal abundances near 10-m depth may have increased since 1976.

Pollutants--The data for the concentration of sulfite waste liquor were not analyzed because only a few points were available (Appendix E). Concentrations of fecal coliform bacteria since 1976 are plotted by year in Figure 5.141. No significant temporal trends were evident. Many values were at the detection limit.

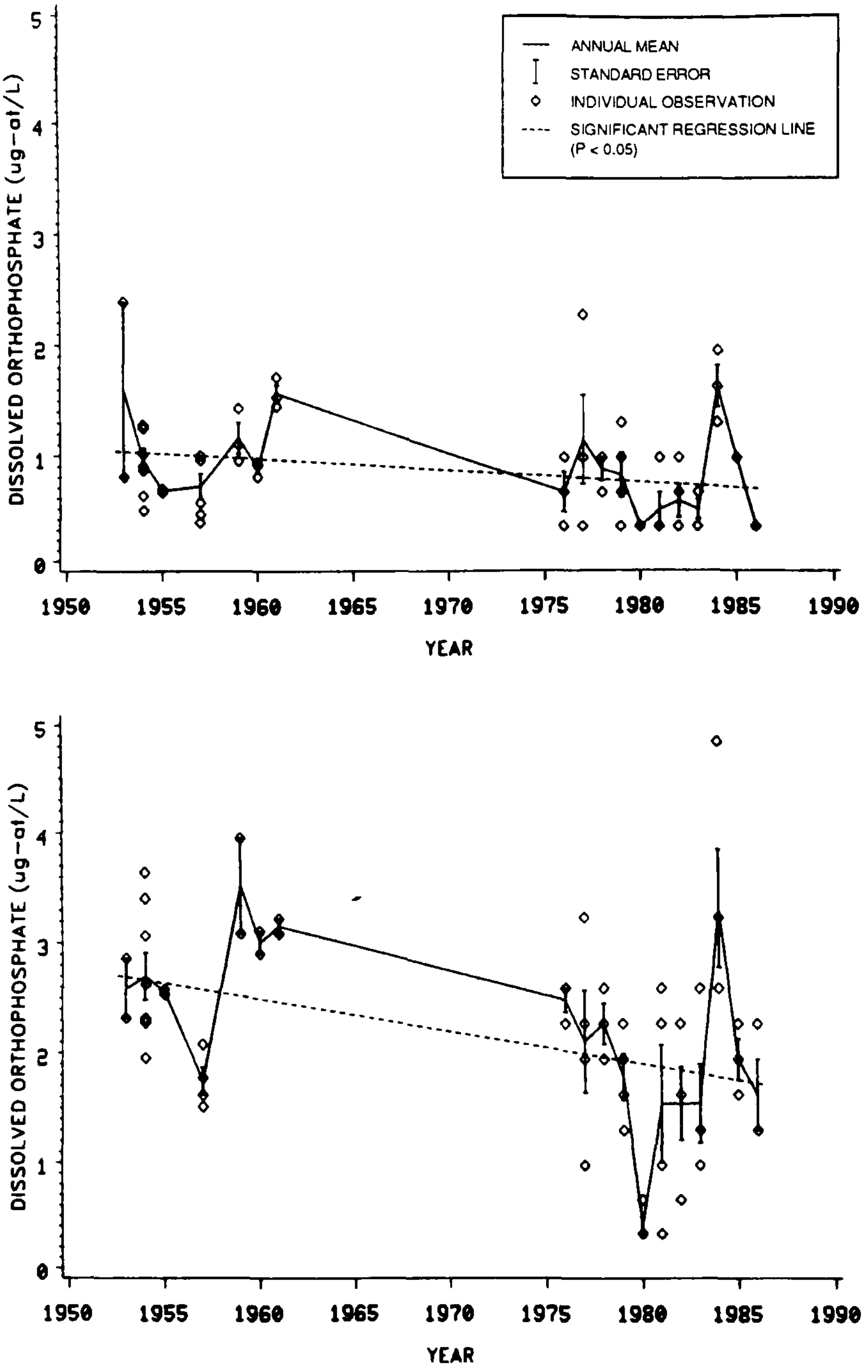


Figure 5.139. Concentrations of dissolved orthophosphate at the surface and at 10-m depth in the South Hood Canal study area during the algal bloom season.

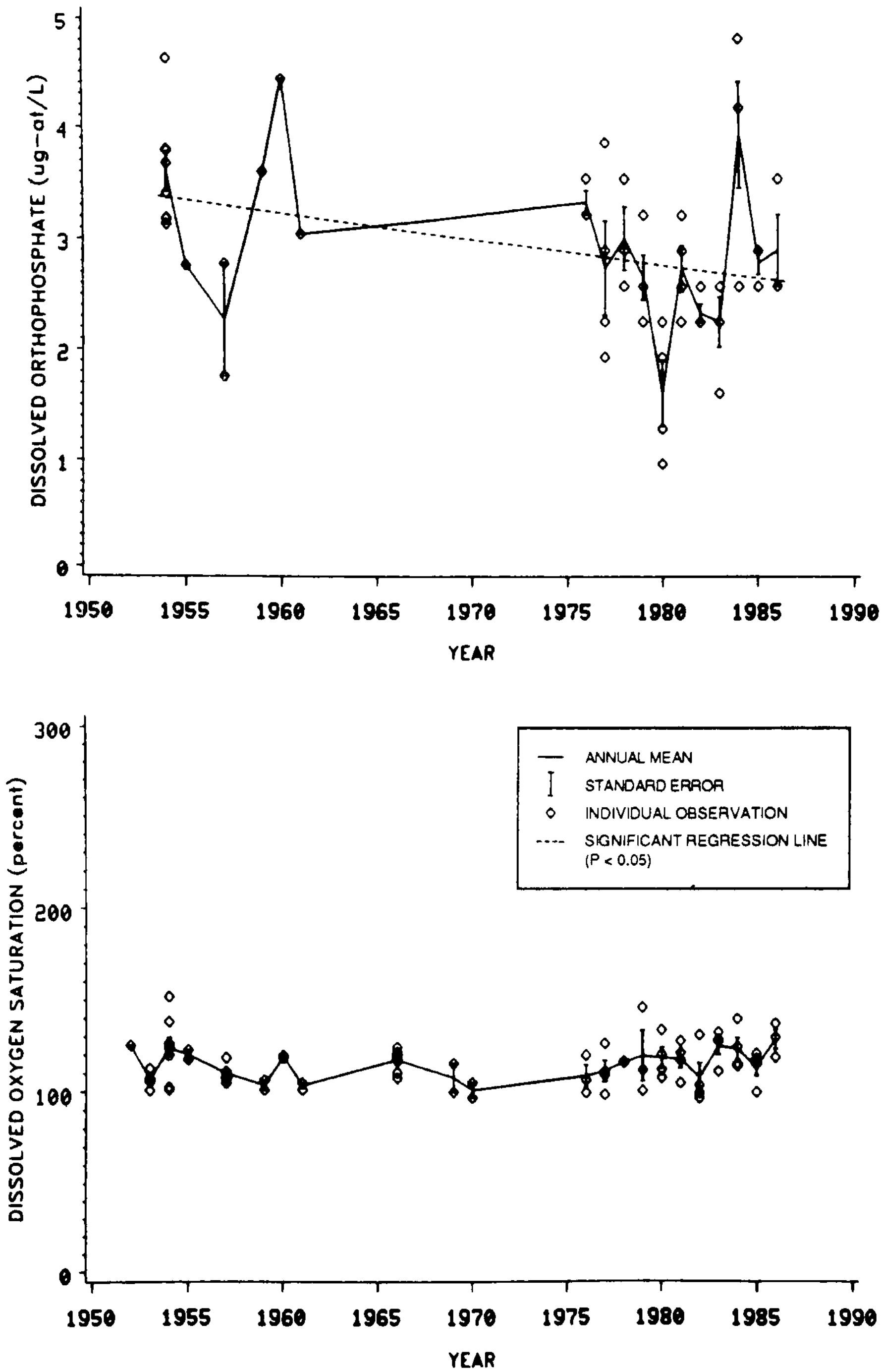


Figure 5.140. Concentrations of dissolved orthophosphate at 30-m depth and percent dissolved oxygen saturation at the surface in the South Hood Canal study area during the algal bloom season.

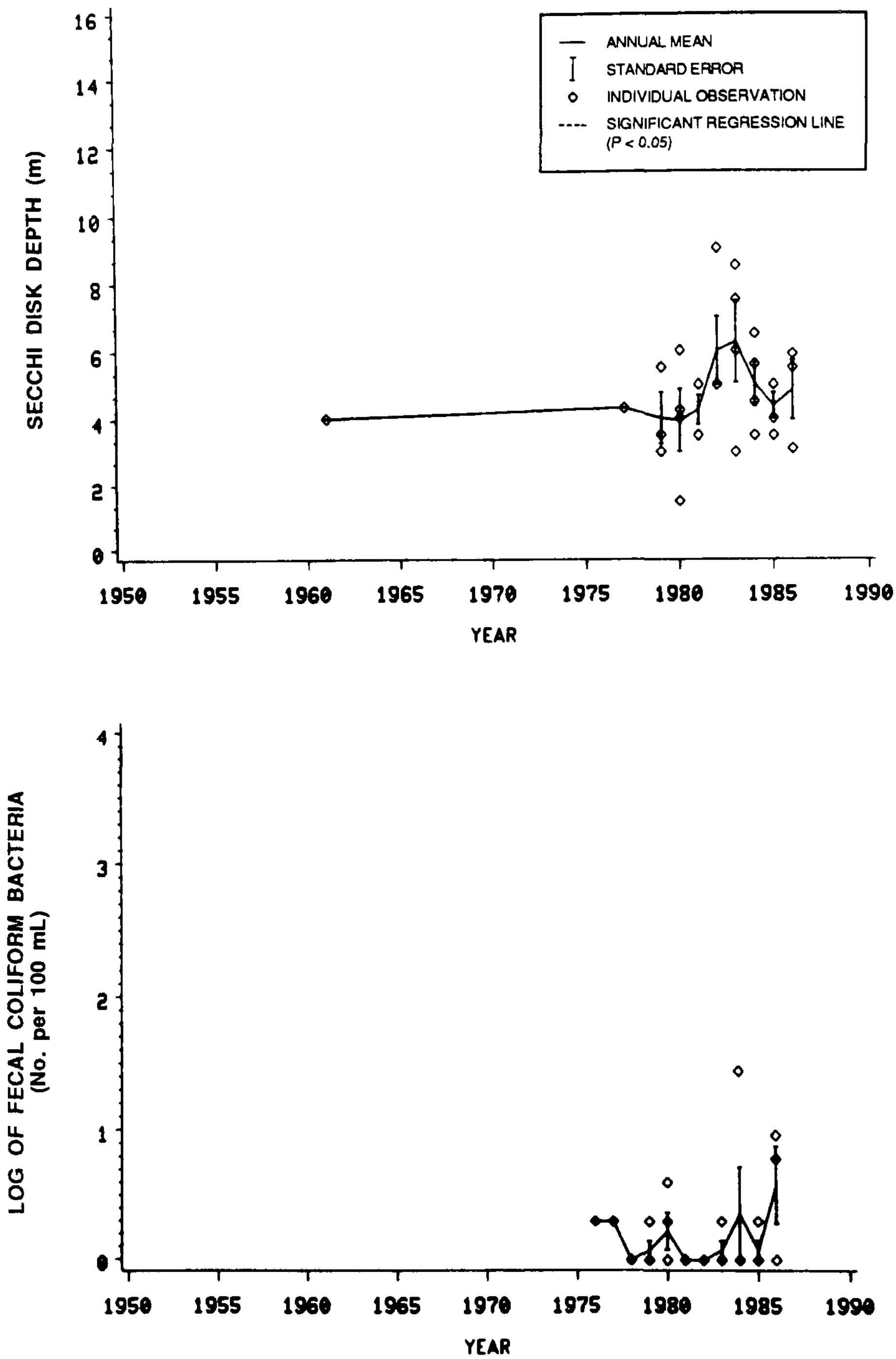


Figure 5.141. Secchi disk depth and log of concentrations of fecal coliform bacteria at the surface in the South Hood Canal study area during the algal bloom season.

Summary of Results for Hood Canal

Major findings for Hood Canal are provided in this section. Environmental conditions in the study areas are summarized and compared. A brief assessment of the sensitivity of the Hood Canal study areas to pollution is provided. Trends in water quality are also summarized.

Environmental Conditions--

Depth gradients of salinity and water temperature values were well developed in all the study areas on Hood Canal. Salinity gradients were steepest in the South Hood Canal study area, the study area closest to substantial sources of fresh water. The mean salinity value was 4.8 ppt lower at the surface than at 10-m depth at this site. Thermal gradients also were steepest in the South Hood Canal study area. The mean water temperature value was 3.9^{o} C higher at the surface than at 10-m depth at this site. These results suggest that the rates of vertical mixing and circulation are low throughout Hood Canal, and are lowest in the South Hood Canal area.

Substantial depth gradients in dissolved oxygen concentrations were well developed in all three Hood Canal study areas. Mean surface dissolved oxygen concentrations (10.1-10.5 mg/L) were similar in all three areas. Dissolved oxygen concentrations at 10-m depth were nearly as high as the concentrations were at the surface in the Dabob Bay and Mid-Hood Canal study areas, suggesting that photosynthetic rates tended to be high at depth in those two areas. Low dissolved oxygen concentrations at depth were most prevalent in the South Hood Canal site. The mean dissolved oxygen concentration at 30-m depth was only 4.3 mg/L (46 percent saturation) at this site.

Depth gradients of nutrient concentrations were highly developed in all three study areas. All three study areas exhibited very low nutrient concentrations at the surface (e.g., mean nitrate concentrations <2 ug at/L). The depth gradients for nitrate concentrations were particularly steep. Mean nitrate concentrations at the surface typically were less than

10 percent of the mean concentrations at 30-m depth. Because vertical mixing rates are low and because the photic zone tends to be deep in Hood Canal, the low nitrate concentrations at the surface suggest that nutrients could limit the production of phytoplankton in near-surface waters. In general, nutrient concentrations were highest at depth in the South Hood Canal site. Lower nutrient concentrations were found at depth in the more northern study sites. For example, the mean nitrate concentration at 30-m depth was 27.0 ug-at/L in the South Hood Canal site, 22.3 ug-at/L in the Mid-Hood Canal site, and 20.5 ug-at/L in the Dabob Bay site.

The intensity of algal blooms (determined by the percent dissolved oxygen saturation at the surface) was high in all three Hood Canal sites. The blooms were most intense in the Dabob Bay area (mean surface dissolved oxygen saturation was 120 percent) and were least intense in the South Hood Canal area (mean surface dissolved oxygen saturation was 115 percent). The data for Secchi disk depth indicate that the clarity of the surface water in the Dabob Bay and Mid-Hood Canal study areas was relatively high (mean Secchi disk depths were 6.0 m), and that the surface water was more turbid in the South Hood study area (mean Secchi disk depth was 4.8 m). The relative contributions of phytoplankton and other suspended particulate material to these turbidity patterns is unknown.

The chlorophyll a data from Dabob Bay indicate that the highest concentration of chlorophyll a occurred well below the surface. By inference, high chlorophyll a concentrations below the surface also may have existed in the Mid-Hood and South Hood areas. The occurrence of low surface concentrations of chlorophyll a in the Dabob Bay study area supports the hypothesis that low nutrient concentrations may limit the growth of phytoplankton in the surface waters of Hood Canal.

The concentrations of sulfite waste liquor and fecal coliform bacteria were near analytical detection limits in all of the Hood Canal study areas. Because the region is relatively rural and undeveloped, major impacts from pollutants would not be expected (Singleton, L., 30 November 1987, personal communication; Tarr, M., 30 November 1987, personal communication).

Sensitivity to Nutrient Enrichment--

Because of limitations in the capacity to export or assimilate pollutants without deleterious ecological effects, all three Hood Canal study sites appear to be sensitive to inputs of excess nutrients. Nitrate concentrations were very low in the surface waters of the sites, which suggests that nitrogen inputs to surface waters would be rapidly used by growing phytoplankton. Because flushing rates in the study areas are low, export rates for pollutants would also be low. The potential for deleterious impacts of pollutants is probably highest in the South Hood Canal site, which is the shallowest and least flushed of the study areas.

Inputs of small amounts of nutrients to deep water in northern or central Hood Canal (i.e., below the photic zone and pycnocline) might not have a substantial impact on phytoplankton growth. Although flushing rates are low, the volume of deep water along much of the length of Hood Canal could dilute pollutant inputs at depth. Vertical mixing rates are low in the system, which suggests that nutrients discharged to deep water might not reach the photic zone during the bloom season. Based on the available information, it would seem likely that nutrients discharged at depth to northern or central Hood Canal would be exported during the autumnal replacement of deep water that occurs in Puget Sound.

Trends in Water Quality--

The three study areas in Hood Canal exhibited similar patterns of change in water quality. Information in the following discussion is based on the material in Tables 5.15 and 5.16. The similarities in the changes detected at the three sites suggest that changes in station location may not have affected the data substantially. However, no definitive analysis of this hypothesis was possible. Because the same data sources were used at all three sites, the influences of changes in the data sources over time probably were the same in all three sites. Thus, the potential impact of changes in data sources cannot be evaluated by comparisons among the study areas.

Physical Conditions--Sub-surface salinity values appear to have declined and sub-surface water temperature values appear to have increased since the early 1950s in all three Hood Canal study areas. Changes in station locations and data sources do not appear to have contributed to the salinity decreases. However, changes in the data sources may have contributed to the apparent temperature increases. The cause(s) of the decreases in salinity values in Hood Canal are unknown, but may involve decreased inputs of oceanic water. The temperature increases generally coincided with the trends in air temperature at the Seattle-Tacoma International Airport, which indicate that the early 1950s was a relatively cool period.

These changes in the physical conditions in Hood Canal suggest that hydrographic factors have evolved in the area since the 1950s. The absence of changes in salinity and water temperature values at the surface suggests that the physical factors affecting the surface water were distinct from the physical factors affecting the water at depth. The extreme density stratification in Hood Canal may allow changes at depth to occur independently of changes at the surface.

Dissolved Oxygen--There was no evidence for substantial changes in dissolved oxygen concentrations in the surface waters, nor was there a substantial number of violations of the Class AA water quality standard (see Table 4.2) for dissolved oxygen. The frequency of violations increased with depth at all study areas as well as with distance from the mouth of Hood Canal. However, dissolved oxygen concentrations have increased steadily at 10- and 30-m depths in all three Hood Canal study areas. There have been no major changes in discharges to Hood Canal during the study period that could explain these increases (Singleton, L., 30 November 1987, personal communication; Tarr, M., 30 November 1987, personal communication). As with the physical conditions discussed above, the absence of changes in dissolved oxygen concentrations at the surface may indicate that the surface waters were responding to different environmental factors than were the waters at depth.

Nutrients--Nutrient concentrations in all three Hood Canal study areas appear to have declined at 10- and 30-m depths. Nitrate data are only available back to the late 1970s. Most of the statistical tests for detecting changes in nitrate concentrations were not significant (P>0.05). However, substantial negative slopes of nitrate concentrations by year were detected at 10- and 30-m depths at all three sites [e.g., the smallest slope was -0.65 ug-at/L/yr (P=0.12) at 30-m depth]. At all three sites, phosphate concentrations at 10- and 30-m depths declined significantly (P<0.05) since the early 1950s. However, phosphate concentrations have not changed significantly in the three sites since the late 1970s. These declines in nutrient concentrations may be attributed to increased photosynthesis (see below). The long-term declines in phosphate concentrations may also have been influenced by decreased oceanic inputs.

<u>Indicators of Phytoplankton Growth</u>--Statistically significant changes in the indicators of phytoplankton growth were not found at any of the Hood Canal sites. The variables used as these indicators either were not suitable for detecting trends at depth, or they contained limited data. Secchi disk depth and percent dissolved oxygen saturation at the surface do not provide information about productivity at depth.

Increases in the percent dissolved oxygen saturation and decreases in nutrient concentrations at 10- and 30-m depths suggest that photosynthetic rates and algal abundances have increased at depth. The geographic gradient in the percent dissolved oxygen saturation at 10-m depth suggests that the greatest changes were detected in South Hood Canal and that the smallest changes were detected in Dabob Bay. Hence, the physical factor(s) causing the apparent changes in photosynthetic activity were most influential in South Hood Canal.

<u>Pollutants</u>--The only statistically significant change in the concentrations of sulfite waste liquor or fecal coliform bacteria was a decline in fecal coliform bacteria in the surface waters of the Dabob Bay study area. However, fecal coliform concentrations always were low in the study areas, and never approached the Class AA water quality standard. Thus, the three

Hood Canal study areas were not substantially impacted by either sulfite waste liquor or fecal coliform bacteria.

CHAPTER 6. SUMMARY AND RECOMMENDATIONS

The trend analyses for the 13 study areas and a brief assessment of the sensitivity of the study areas to nutrient enrichment are summarized in this chapter. Recommendations are also given regarding the implementation of environmental monitoring programs.

SUMMARY OF WATER QUALITY TRENDS IN PUGET SOUND

Although problems caused by changes in station locations and data sources limited data interpretation in some areas (e.g., Port Gardner, Budd Inlet, Oakland Bay), numerous trends in the water quality of Puget Sound were observed. Results of the study are summarized in Table 6.1. The information in Table 6.1 was derived from the interpretations provided in Chapter 5. Some statistically significant results that appeared to have been artifacts of changes in station locations or data sources are omitted from Table 6.1.

Several limitations in the data sets used in this study may have adversely affected the sensitivity of the analyses. Most of the sampling stations were located offshore, removed from the influences of local onshore pollutant sources. Data typically consisted of only monthly samples without replication. Several sources of variation that could have strongly influenced the data, (e.g., time of day and stage of tide during which samples were collected) were not controlled during the sampling. In addition, because long-term data from below 30-m depth were only available at the Point Jefferson study area, changes in dissolved oxygen concentrations at depth could not be assessed for the other study areas. Readers are cautioned that trends observed in each study area only apply to the immediate vicinity of the sampling stations (i.e., conditions nearby may have been different).

TABLE 6.1. SUMMARY OF WATER QUALITY TRENDS IN PUGET SOUND[a]

Study Area	Depth (m)	Salin.[b] L R	Water Temp. L R	Diss. Oxygen L R	Diss. Nitrate L R	Diss. Phos. L R	Chl. a L R	Diss. Oxy. Satur. L R	Secchi Depth L R	SWL[c] L R	Fecal col. Bacteria L R
North Sound											
Bellingham Bay	0	0[d]	- +	0 0	. 0	0 0	. .	0 0	0 0		.
	10	0	0 0	0 0	. 0	0 +	. .	. .	. .	. 0	. .
	30	. 0	. +	. 0	. 0	. 0	. .	. .	. .	0 0	. .
Central Sound											
Port Gardner	0	. .	. .	0 0	. 0	- 0	. .	0 0	. 0	- 0	. +
	10	. .	. .	0 0	.	- +	. .	. .	. .	- -	. .
Point Jefferson	0	0 +	0 -	0 -	. .	. .	0 .	- -	0 +	. .	. .
	10	- 0	+ 0	0 0	. .	. .	0 .	. .	. .	. .	. .
	30	0	+ 0	0 0	. .	. .	. .	. .	. .	. .	. .
	100	0 -	0 0	0 0	. .	. .	. .	. .	. .	. .	. .
	150		0 0	0 0	. .	. .	. .	. .	. .	. .	. .
	200	0 .	0 .	. .	. .	. .	. .	. .	. .	. .	. .
Sinclair Inlet	0	0 0	0 0	0 0	. 0	. 0	. .	0 0	. 0	0 .	. 0
	10	. 0	. 0	. 0	. 0	. +	. .	. .	. .	. .	. .
City Waterway	0	0 0	0 0	0 0	. 0	. +	. 0	0 0	. 0		. 0
	10	. 0	. 0	. 0	. +	. +	. 0	. .	. .		. .
South Sound											
Carr Inlet	0		+ 0	0 +	.	0 0	. .	0 +	0	. .	.
	10	0	+ 0	0 +	. 0	0	. .	. .	. .	. .	. .
	30	0	+ 0	+ +	. 0	- 0	. .	. .	. .	. .	. .
Nisqually Reach	0	- 0	+ 0	0 +	. 0	0 0	. .	0 +	. 0	. .	.
	10	- 0	+ 0	+ 0	. 0	0 0	. .	. .	. .	. .	. .
Budd Inlet	0	0 .	0 0	. .	. 0	. 0	. .	. .	. .	0 0	. .
	10	0 .	0 0	. .	. 0	. +	. .	. .	. .	. .	. .
Totten Inlet	0	0	0 0	0 0	. 0	0	. .	0 0	0 0	0 .	. 0
	10	0 0	0 0	0 +	. 0	0	. .	. .	. .	. .	. .
Oakland Bay	0	. 0	0 0	+ 0	0 0	- +	0 .	+ 0	0 +	- .	. 0
	10	. 0	. 0	. 0	. 0	. +	. .	. .	. .	. .	. .
Hood Canal											
Dabob Bay	0	0 0	0 0	0 0	. 0	0 0	. 0	0 0	. 0	. .	.
	10	- 0	+ 0	+ 0	. 0	- 0	. 0	+ 0	. .	. .	. .
	30	0	+ 0	+ 0	. 0	- 0	. 0	+ 0	. .	. .	. .
Mid-Hood Canal	0	0	0 0	0 0	. 0	0 0	. .	0 0	. 0	. .	. 0
	10	0	+ 0	+ +	.	0	. .	+ +	. .	. .	. .
	30	- -	+ 0	+ 0	.	0	. .	+ 0	. .	. .	. .
South Hood Canal	0	0 0	0 0	0 0	. 0	- 0	. .	0 0	0 0	. .	0 0
	10	0	+ 0	+ +	.	- 0	. .	+ +	. .	. .	. .
	30	- 0	+ 0	+ 0	.	0	. .	+ 0	. .	. .	. .

[a] The trends depicted in this table were derived from interpretations in the text and not directly from statistical tables. Some results that were statistically significant (P<0.05) were omitted from this table because they appeared to be artifacts of changes in data sources. Also, the recent trends in phosphate concentrations at 10-m depth in the Budd Inlet site and the recent trends in nitrate concentrations at 10- and 30-m depths in the Mid-Hood Canal site and at 10-m depth at the South Hood Canal site were not quite statistically significant ($P \leq 0.10$). However, because those trends were judged to be credible, they were included in the table.

TABLE 6.1 (Continued)

[b] L Long-term trend based on all the data available from a given study area.
R Recent trend based on all the data available from a given study area from 1973 to 1986.

[c] SWL = Sulfite waste liquor.

[d] 0 = No trend.
= Declining trend.
\+ Increasing trend.
. Trend cannot be determined because of ambiguity in the results or a lack of data.

Physical Conditions

Except for a slight increase in salinity values detected since 1973 at the surface in the Point Jefferson study area, salinity values either declined or did not change significantly in the study areas. Decreased salinity values recorded for the Bellingham Bay, Carr Inlet, Totten Inlet, Dabob Bay, Mid-Hood Canal, and South Hood Canal study areas occurred gradually, having begun with relatively high salinity values in the early 1950s. The gradual salinity declines in the Nisqually Reach and Point Jefferson study areas date back to the early 1930s. Changes in salinity values were not detected in the Sinclair Inlet and City Waterway study areas. However, data collection at these two sites did not begin until the late 1960s, resulting in a shorter data record for detection of a gradual trend.

Factors underlying the declines in salinity values are not known. One explanation involves decreasing inputs of high salinity water at depth from the Strait of Juan de Fuca. Declines in salinity values were detected at 100- and 150-m depths at the Point Jefferson study area, the only study area for which data collected at depths greater than 30-m were available. Point Jefferson is close to Admiralty Inlet, through which the deep water from the Strait of Juan de Fuca must pass to reach most of Puget Sound. Moreover, most of the other declines in salinity values that were detected in the study occurred at 10- and 30-m depths, not at the surface. The salinity of deeper water may have a greater influence over the salinities at 10- and 30-m depths than over the salinity at the surface. (It must be emphasized that the foregoing discussion merely presents a plausible hypothesis for the salinity declines, and that information to test the hypothesis was not available to this project.)

The available information on rainfall and runoff does not appear to explain the observed declines in salinity values. Rainfall data recorded at the Seattle-Tacoma International Airport showed that a wet period occurred during the early 1950s. However, no statistically significant changes in total runoff to Puget Sound were detected between 1930 and 1978 (see Figure 5.2). The effect of changes in rainfall would have been to increase salinity values since the 1950s, which is contrary to the observed decreases. Of possible importance is that the salinity declines typically were not detected at the surface, the portion of the water column most directly influenced by rainfall and runoff.

Changes in water temperature values generally coincided with climatic changes. Water temperatures in the study areas either increased or did not change significantly, except for declines in surface water temperature values in the Bellingham Bay and Point Jefferson study areas. The Carr Inlet, Dabob Bay, Mid-Hood Canal, and South Hood Canal data sets began in the early 1950s, which was a cool period in Seattle (see Figure 5.2). Similarly, long-term increases in water temperature values were detected in the Point Jefferson and Nisqually Reach study areas. The data sets analyzed for these two areas began in the early 1930s, which also was a relatively cool period (NOAA 1985). The Bellingham Bay study area was unusual in that a long-term decline in water temperature values was detected. However, the first year of data collection for this site was 1958, which happened to be an unusually warm year (see Figure 5.2).

Water temperatures in most of the study areas where significant changes were not detected (Sinclair Inlet, City Waterway, Budd Inlet, Totten Inlet, and Oakland Bay) also may have been influenced by climate. Data collection did not begin in these sites when climatic conditions were markedly different from recent conditions. Therefore, the absence of changes in water temperature values in these areas does not preclude a climatic influence over water temperature.

Dissolved Oxygen

Dissolved oxygen concentrations in the study areas generally have increased or have not changed significantly during the study period. Very low dissolved oxygen concentrations were rarely observed. Except for the Point Jefferson study area, which is unlikely to have low dissolved oxygen concentrations at depth because of high rates of circulation, dissolved oxygen data were collected only from the top 10 or 30 m of the water column. Low dissolved oxygen concentrations in near-bottom waters could have occurred in all the study areas except Point Jefferson without being detected in this study.

Increased dissolved oxygen concentrations were observed in the southern sound study areas. Dissolved oxygen data in these study areas were strongly influenced by very high values observed in 1986, the last year from which data were obtained. The most recent points in these data sets had the highest values, inducing a positive slope to the regressions of dissolved oxygen concentrations by year. Although limitations of the available data preclude definitive interpretations, these high dissolved oxygen concentrations of 1986 appear to have been caused by intense algal blooms.

In the Hood Canal study areas, increased dissolved oxygen concentrations appear to have occurred more gradually than did the increased concentrations recorded in the southern sound sites. Unlike the southern sound sites, unusually high dissolved oxygen concentrations were not observed in 1986 in the Hood Canal sites.

With the exception of surface waters in the Point Jefferson study area, none of the study areas in the northern sound and central sound study areas exhibited significant temporal changes in dissolved oxygen concentrations. Unusually high dissolved oxygen concentrations were not observed in these regions during 1986.

Discharges of oxygen-demanding wastes from pulp mills only influenced dissolved oxygen concentrations significantly in the Oakland Bay study area. The high dissolved oxygen concentrations recorded in 1986 contributed to the increase detected in dissolved oxygen concentrations at this site. However, a few very low values also were detected early in the data set. Because these early low values coincided with high concentrations of sulfite waste liquor, pulp mill discharges probably were the causal agent. The pulp mill in the Oakland Bay area closed in 1957. Extremely low dissolved oxygen concentrations have not been found since that time.

Dissolved oxygen concentrations in the Bellingham Bay and City Waterway study areas were not markedly influenced by changes in the discharges of nearby pulp mills. These study areas are less exposed to the local pulp mill discharge plumes than was the Oakland Bay study area. Also, dilution of the effluent in these areas probably is more effective than in Oakland Bay, which is shallow and poorly flushed. However, changes in dissolved oxygen concentrations close to the discharge points of the pulp mills in Bellingham Bay and City Waterway could have occurred without having been detected at the study sites.

The influence of pulp mill discharges on dissolved oxygen concentrations in the Port Gardner study area could not be determined because the proximity of the sampling stations to the discharge points of the local pulp mills varied greatly over time.

Nutrients

With the exception of the study areas in Port Gardner, Carr Inlet, and Hood Canal, changes in nitrate concentrations do not appear to have resulted from well-developed temporal trends. The recent increase in nitrate concentrations detected statistically at 10-m depth in the City Waterway study area appears to be attributable to erratic fluctuations. Data for this site include a few low values near the beginning of the data set and a few high values near the end of the data set.

Data on nitrate concentrations in the Port Gardner, Carr Inlet, and Hood Canal study areas are only available since the mid-1970s. The decline in the Carr Inlet study area may have been caused by increased nutrient uptake by algae (see below). Substantial decreases in nitrate concentrations were detected in the South Hood Canal study area. Decreases also were detected in the Mid-Hood Canal and Dabob Bay study areas, although the declines were not well developed in the Dabob Bay site. The factor affecting the nitrate concentrations in Hood Canal [apparently algal blooms (see below)] was probably most influential in southern Hood Canal. No explanation is available for the decline in nitrate concentrations in the Port Gardner study area.

Temporal changes in phosphate concentrations were apparent in 11 of the 12 study areas from which phosphate data were available. Statistically significant ($P<0.05$) long-term decreases (since the 1950s) were detected in seven of the nine study areas from which long-term data are available. However, no long-term increases or recent decreases were detected. Recent increases (since the mid-1970s) were detected at the surface and/or at 10-m depth at six study areas. Five of the six recent increases were statistically significant at $P<0.05$. The significance level at the sixth site (Budd Inlet) was $P=0.08$. Both long-term decreases and recent increases were detected in the Port Gardner and Oakland Bay study areas.

The cause(s) of the widespread decreases in phosphate concentrations since the 1950s are unknown. Because declines occurred in both urban and rural study areas, anthropogenic influences do not explain these results. One explanation involves decreased inputs of phosphate in oceanic water from the Strait of Juan de Fuca, but this hypothesis could not be tested in this study. Although it was not possible to calibrate the analytical techniques used in the 1950s with those used more recently, the older techniques generally were accurate (Appendix A).

The recent increases in phosphate concentrations all occurred in urban study areas. No evidence of recent changes in phosphate concentrations was found in any rural study area (Figure 6.1). The absence of detectable changes in phosphate concentrations in rural study areas suggests that local anthropogenic factors may have influenced phosphate concentrations in the urban study areas.

Although changes in numerous factors (e.g., sewage discharges, urban runoff) may have influenced the phosphate data in the urban study areas, three of the urban increases may be attributable at least in part to known anthropogenic factors. Because sulfite waste liquor removes dissolved orthophosphate from seawater solution (Westley and Tarr 1978), reductions in the discharges of sulfite waste liquor by the local pulp mills during the 1970s may have contributed to the increased phosphate concentrations in these two areas. In another case, phosphoric acid has been added to the effluent discharged by the kraft pulp mill near the City Waterway study area

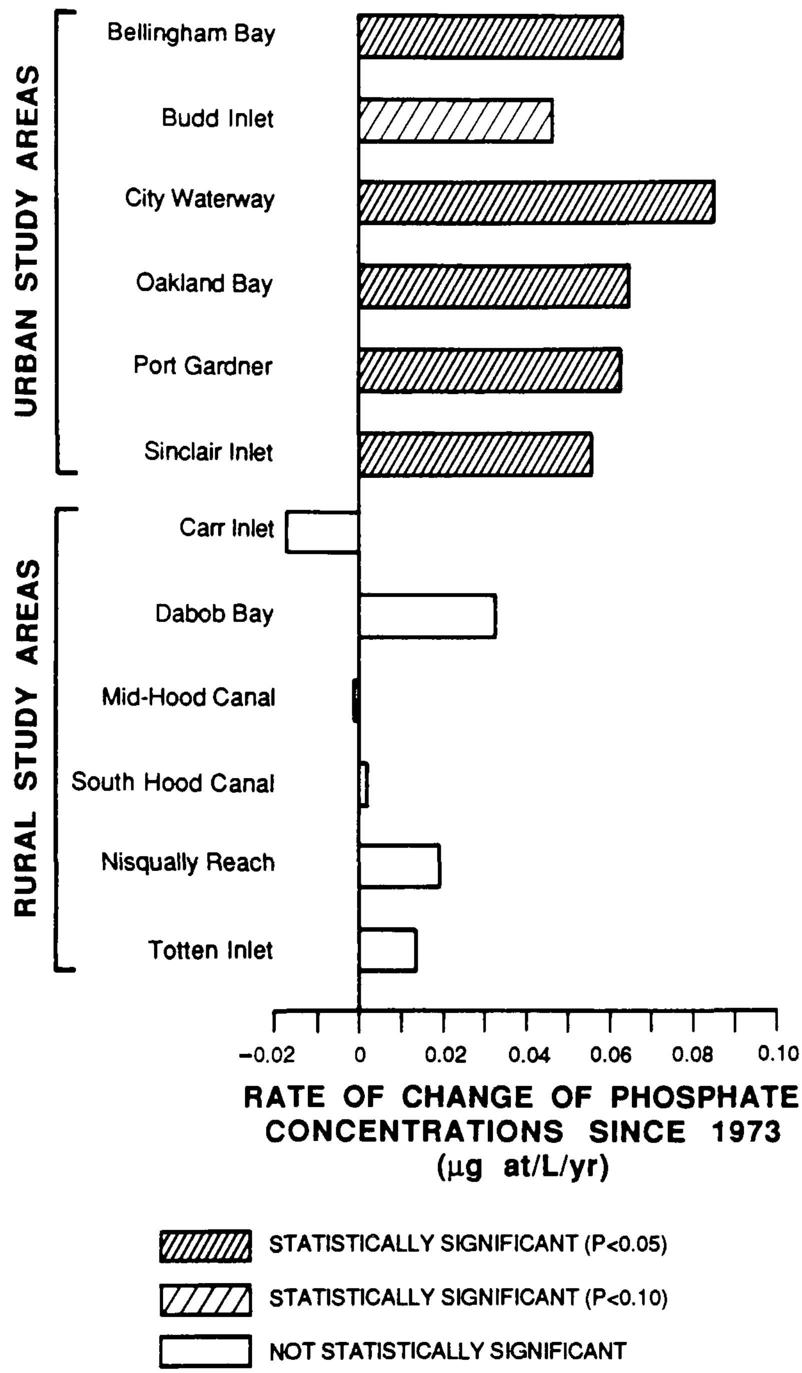


Figure 6.1. Rates of change of phosphate concentrations during the algal bloom seasons in urban and rural study areas since 1973.

since 1977. This addition may have resulted in increased phosphate concentrations in City Waterway (Henry, C., 17 November 1987, personal communication). The recent increases in phosphate concentrations that were detected in the remaining urban areas (Sinclair Inlet, Budd Inlet, Oakland Bay) do not appear to be attributable to known anthropogenic factors.

Indicators of Phytoplankton Growth

Few systematic changes were evident in the values of the variables used in this study to indicate phytoplankton growth. No changes were detected in chlorophyll a concentrations, although relatively few data are available. This general lack of detected change can be attributed in part to inadequate sampling frequency. The typical duration of an algal bloom in Puget Sound is on the order of days. The monthly samplings used in most of the data sources included in this study do not provide sufficient temporal resolution to assess algal bloom dynamics effectively.

Some changes in algal abundance apparently were detected. In the Carr Inlet study area, a decline in Secchi disk depth and an increase in percent dissolved oxygen saturation at the surface suggest that algal densities may have increased in this area. In the Point Jefferson study area, increased Secchi disk depths and decreased values of surface percent dissolved oxygen saturation suggest that phytoplankton concentrations have declined. However, this decline appears to have been due to erratic fluctuations in phytoplankton abundance, rather than to a systematic trend.

With the exception of the study areas located on Hood Canal and the Carr Inlet and Point Jefferson study areas (discussed above), the changes in surface percent dissolved oxygen saturation and Secchi disk depth that were detected do not suggest that substantial changes in phytoplankton abundance have occurred. Increased percentages of dissolved oxygen saturation at the surface were detected at the Nisqually Reach and Oakland Bay study areas, and increased Secchi disk depths were detected at the Oakland Bay study area. The increase in surface percent dissolved oxygen saturation at the Nisqually Reach study area occurred since 1977, and may be attributable statistically to the high dissolved oxygen concentrations observed throughout the southern sound in 1986. The increase in percent dissolved oxygen saturation at the surface at the Oakland Bay study area occurred since 1956, and may be attributable to both the low dissolved oxygen concentrations caused by sulfite waste liquor in 1956-57 and the high dissolved oxygen concentrations observed in the southern sound in 1986. The increased Secchi disk depths at the Oakland Bay study area appear to have been the result of erratic fluctuations, rather than a systematic trend.

In the Hood Canal study areas, statistically significant changes were not detected in the values of the standard indicators of phytoplankton growth (chlorophyll a concentration, percent dissolved oxygen saturation at the surface, Secchi disk depth). However, these indicators do not provide sufficient information to characterize phytoplankton abundance in Hood Canal. Average chlorophyll a and nutrient concentrations were higher at 10-m depth (well below mean Secchi disk depth) than at the surface. Although the chlorophyll a data set from the Dabob Bay study area included data from depths of 10 and 30 m, data collection only began in 1979, while the apparent changes in phytoplankton abundance that were detected in Hood Canal (see below) occurred earlier. Therefore, the only standard indicator variables with data from the period during which increases in phytoplankton abundance apparently occurred were percent dissolved oxygen saturation at the surface and Secchi disk depth. Unfortunately, these variables provide information only about conditions near the surface. Maximum phytoplankton abundances in Hood Canal are probably well below the surface.

Changes in the values of additional variables that may respond to phytoplankton abundances in the Hood Canal study areas suggest that increases in phytoplankton abundance may have occurred below the surface. At 10- and 30-m depths, values of percent dissolved oxygen saturation have increased, while concentrations of phosphate (long-term) and nitrate (recently) have declined. These chemical changes suggest that photosynthetic activity has increased at depth. The data discussed previously on water clarity and depth distributions of nutrients and chlorophyll a concentrations demonstrate that substantial rates of photosynthesis probably occur well below the surface. Unfortunately, data to confirm the possible increase in phytoplankton abundance at depth in Hood Canal (e.g., uninterrupted data on chlorophyll _a_ concentrations since the 1950s) are not available.

Pollutants

Concentrations of sulfite waste liquor and fecal coliform bacteria either declined or did not change greatly in the various study areas. Concentrations of sulfite waste liquor declined in all four study areas located near pulp mills (Bellingham Bay, Port Gardner, City Waterway, and Oakland Bay). The sulfite waste liquor decline in Oakland Bay coincided with the closure of the local pulp mill. The declines in the other sites generally coincided with upgrades in the effluent treatment procedures used by nearby pulp mills.

Several changes in the concentrations of fecal coliform bacteria may be attributable to changes in point or nonpoint sources. The decline in the concentration of fecal coliform bacteria in the Bellingham Bay study area coincided with improvements in the sewage treatment facilities and with closures of combined sewer overflows in the area. The increase in the concentrations of fecal coliform bacteria in the Port Gardner study area probably was due to an increase in the abundance of the bacterium, _Klebsiella_, which is discharged in large amounts from the secondary treatment facilities of sulfite pulp mills.

The decline in the concentrations of fecal coliform bacteria in the Nisqually Reach study area probably was due to one high value that was detected in 1978, at the beginning of the data set for this variable. Low concentrations of fecal coliform bacteria were detected in the Nisqually Reach site after 1978, so a declining trend was found. Because the high 1978 value came from a sample collected near the end of a heavy rainstorm, the bacteria probably are attributable to runoff into the Nisqually River drainage basin.

No explanations are apparent for the remaining changes detected in the concentrations of fecal coliform bacteria. Declines in the relatively rural Carr Inlet and Dabob Bay study areas may have resulted from the slightly higher concentrations that were observed near the beginnings of the data sets in those two areas. These early, slightly higher concentrations were followed primarily by values at the detection limit. The elevated concentrations were not associated with storm events or changes in point source discharges. It is uncertain whether these statistical declines in the Carr Inlet and Dabob Bay study areas were real phenomena.

SENSITIVITY TO NUTRIENT ENRICHMENT

Sensitivity of an estuary to nutrient enrichment depends on nutrient inputs and physical factors. Urban study areas probably have the highest potential for receiving large inputs of nutrients because of the presence of large human populations. The urban study areas in this project are Bellingham Bay, Port Gardner, Sinclair Inlet, City Waterway, Budd Inlet, and Oakland Bay. (Elliott Bay, which was not included in this study, also is adjacent to a large population.) Strong density stratification and low flushing rates tend to promote algal blooms and limit export rates of excess nutrients. These factors affect several of the study areas, including Sinclair Inlet, Budd Inlet, Totten Inlet, Oakland Bay, Dabob Bay, Mid-Hood Canal, and South Hood Canal.

The following study areas appear to be most sensitive to nutrient enrichment, due to both proximity to urban populations and to physical factors:

- Sinclair Inlet
- Budd Inlet
- Oakland Bay
- South Hood Canal.

The Sinclair Inlet, Budd Inlet, and Oakland Bay study areas are adjacent to cities. Increases in phosphate concentrations since 1973 were detected in all three of these areas. The available evidence does not indicate that algal blooms have increased in intensity in response to these increases in phosphate concentrations. However, as discussed previously, sampling frequency was insufficient to assess algal bloom dynamics effectively. South Hood Canal is also highly vulnerable to nutrient enrichment because of physical factors. It may have significant inputs of nutrients during the summer, due to the presence of numerous summer homes.

RECOMMENDATIONS FOR ENVIRONMENTAL MONITORING IN PUGET SOUND

The water quality characterization study involved analysis of data originally collected for a variety of purposes by several independent groups of researchers. A retrospective study of existing data provides a unique opportunity to assess the historical and existing studies from the perspective of a trends analysis. The following institutional and technical recommendations are based on the results of this water quality characterization study and the comments of the characterization work group and other peer reviewers.

Institutional Recommendations

1. One organization should oversee all water quality monitoring in Puget Sound to maximize the compatibility of field techniques, laboratory techniques, and database formats, and to coordinate geographic coverage. Use of the protocols recommended by PSEP (U.S. EPA 1986a) would standardize the field and laboratory techniques of monitoring programs used in Puget Sound.

2. Changes in field and laboratory techniques should be fully documented. New techniques should be calibrated with old techniques. These steps will facilitate future trend analyses as technology evolves.

Technical Recommendations

Monitoring Program Design--

1. The goals of the monitoring program should be stated quantitatively before the study design is developed (e.g., how much change in dissolved oxygen concentrations should be detectable over a given time period?).

2. The allocation of sampling effort should be assessed statistically, using existing data, as an initial step in developing the sampling design. The following points should be considered during development of the sampling design.

- Assess the influences of known sources of variation (e.g., time of day, stage of tide) on the water quality variables of interest in particular types of locations (e.g., open main channel, enclosed embayment).

- Design monitoring programs to reduce the impact of sources of variation that are not of interest. For example, dissolved oxygen concentrations are strongly influenced by predictable diel, tidal, and fortnightly variation. Fortnightly sampling of the water during a particular window of time would minimize the impact of these factors (e.g., collecting samples near the noon high tide) because sampling would always occur at the same time of day, stage of tide, and phase of the semi-lunar tidal cycle.

- Use statistical power analysis to compare the ability of alternative study designs to detect a given amount of environmental change.

3. The influence of physical factors on water quality should be addressed to improve understanding of ecosystem function and to permit comparisons of the influences of natural and anthropogenic factors on water quality. Data acquisition should reflect the temporal scale of variation

for each variable of interest. Potentially important physical variables are listed below:

- Oceanographic data (e.g., sampling through the entire water column to estimate extrinsic oceanic inputs into a locality)

- Climatic data (e.g., air temperature, wind velocity, input rates for runoff). These data may be available from NOAA and USGS.

4. The monitoring program should include embayments with limited flushing and mixing (e.g., Budd Inlet, Sinclair Inlet) as high priority areas because water quality is most sensitive to anthropogenic degradation in such areas. Water quality changes in areas with high flushing rates and rapid currents (e.g., West Point, Point Jefferson, Nisqually Reach) are more difficult to detect because contaminants do not accumulate in such areas.

5. Sampling stations should be located close enough to large local contaminant sources to be able to detect a likely change (e.g., effect of improvements in sewage treatment on ambient nutrient concentrations).

6. Monitoring for low dissolved oxygen concentrations at depth should focus on sites, depths, and periods where and when low dissolved oxygen is likely to occur (i.e., in near-bottom waters of poorly flushed areas in late summer).

7. Intensities of algal blooms should be monitored frequently during periods when blooms are likely to occur in each particular locality. Because algal blooms wax and wane over a period of only a few days, the time between consecutive samplings should be less than a few days (e.g., daily). Blooms are prominent during spring and summer, but the seasonal occurrence of algal blooms differs among sites.

8. Changes in phytoplankton communities should be monitored by measurement of chlorophyll *a* concentrations and species identification. Changes in species composition of the phytoplankton community may have

ecological consequences (e.g., changes in the quality of the phytoplankton as a food source for filter-feeding organisms) even if the concentration of chlorophyll a does not change.

9. Sampling for contaminants discharged episodically (e.g., discharges from combined sewer overflows and pulp mills) should coincide with discharge events. Infrequent sampling scheduled at random with respect to discharge events will detect only very large changes.

10. In poorly flushed embayments where nutrients may limit algal growth during algal blooms, the detection of changes in nutrient concentrations requires frequent sampling and analytical detection limits that are lower than those generally used in the existing monitoring programs for Puget Sound. Lower analytical detection limits might be achieved simply by collecting larger sample volumes.

11. A microbiological test is needed to distinguish between bacterial contamination from sewage or agricultural runoff, which represents a risk of possible exposure to human pathogens, and bacterial contamination from Klebsiella. Although this organism is detected in standard tests for fecal coliform bacteria, its principal source is the effluent from secondary treatment ponds of sulfite pulp mills. Therefore, violations of water quality standards (and the subsequent closure of shellfish beds) attributed to contamination by sewage may actually be caused by exposure to secondary pulp mill effluent. Although not well studied in Puget Sound, the health risk caused by environmental contamination from Klebsiella appears to be low. Possible applicable microbiological tests include screening for Escherichia coli or enterococci (Singleton, L., 24 September 1987, personal communication).

12. Future monitoring programs should include some sampling stations where a long-term historical record of water quality already exists. This strategy would allow that changes in water quality over time would be documented with a record that extends as far back in time as possible. Many such stations were used in this study.

Specific Technical Issues--

1. Water quality should be monitored closely in Budd Inlet to determine whether nitrogen removal by the LOTT sewage treatment plant is successful in reducing the intensity of algal blooms.

2. The Secchi disk should to be replaced with, or be supplemented by, more quantitative measures of specific water column variables (e.g., suspended particulate matter, concentration of chlorophyll a, depth of the photic zone). Secchi disk depth data cannot distinguish between turbidity caused by suspended particulate material and turbidity caused by phytoplankton. The Secchi disk can only provide measurements of turbidity in the upper-most portion of the water column, while maximum phytoplankton densities may occur below the Secchi disk depth.

3. Monitoring of variables affected by a pycnocline (e.g., salinity, temperature, concentrations of dissolved oxygen, chlorophyll a, and nutrients) should include determination of the depth of the pycnocline. Sampling would then be done above and below the pycnocline, as well as at the depths normally sampled. This procedure would reduce the variability in the water quality data caused by sampling only at a given depth when the depth of the pycnocline fluctuates.

4. Some variables must be sampled near the surface (e.g., photosynthesis rate), but because many variables change rapidly very close to the surface (e.g., temperature, salinity, dissolved oxygen, nutrient concentrations), sampling at 1-m depth, rather than right at the surface, may provide more representative data. Also, sampling at 1-m depth may reduce scatter in the data and avoid possible artifacts caused by surface contaminants.

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APPENDIX A

HISTORY OF ANALYTICAL TECHNIQUES USED IN WATER QUALITY STUDIES IN PUGET SOUND

HISTORY OF ANALYTICAL TECHNIQUES USED IN WATER QUALITY STUDIES IN PUGET SOUND

VALIDITY OF HISTORICAL TECHNIQUES

The analytical techniques historically used in the Puget Sound water quality studies that were selected as data sources for this characterization project are summarized below. The validity of the techniques is also assessed. A time line of the major changes in techniques for these water quality studies is also presented.

Salinity

Early salinity determinations in Puget Sound were made using the Knudsen method. This method involves precipitation of halides with silver nitrate. Potassium chromate is used as a titration endpoint indicator. The quality of data produced with this method is excellent; reported accuracy can be as high as 0.01 ppt.

More recently, salinity determinations have been made using various methods involving measurements of conductivity or refraction. Conductivity-based methods typically are highly reliable [e.g., Riley (1975) cites a precision of 0.003 percent]. Refraction-based measurements, made with a salinometer, are probably less reliable than conductivity-based measurements. However, agencies using salinometers typically calibrate their instruments with titration- or conductivity-based measurements of salinity standards. Thus, data produced from salinometers were deemed of sufficient quality for this project.

Water Temperature

Historically, reversing thermometers or laboratory thermometers in water bottles have been used for water quality investigations of Puget Sound. The former method is probably superior because the data are obtained in situ. However, either method is adequate for this investigation. More recent work has generally involved various types of in situ electronic thermometers, which probably yield higher quality data.

Dissolved Oxygen

Most of the determinations of dissolved oxygen in Puget Sound monitoring programs have either been based on the Winkler method or have been calibrated to it. This method uses a series of chemical reactions that ultimately liberate an amount of iodine from reagents added to a water sample that is equal to the amount of dissolved oxygen in that water sample. The amount of iodine is then measured by titration. This method is quite reliable for unpolluted water. Strickland and Parsons (1972) estimate the precision of ship-board Winkler determinations as +/- 0.1 mg/L for a single determination over a wide range of concentrations.

The presence of certain pollutants in Puget Sound may cause errors in Winkler determinations of dissolved oxygen. Barnes (1959) states that chlorinated effluents and sulfite-containing wastes from pulp mills can cause analytical errors in Winkler titrations by interfering with iodine production. Moreover, sulfites are oxidized by the oxygen dissolved in the receiving water, which lowers ambient dissolved oxygen concentrations. Barnes (1959) suggests a modification of the Winkler method for water containing such pollutants. This modification involves pre-treatment of the samples with hypochlorite to oxidize the pollutants. Apparently, such a modification has not been included in any of the routine monitoring programs conducted in Puget Sound (Cunningham, R., 22 May 1987, personal communication; Duxbury, A., 22 May 1987, personal communication; Tarr, M., 22 May 1987, personal communication). According to Cunningham (22 May 1987, personal communication), analytical errors caused by sulfite waste liquor in some areas of Puget Sound can reduce the apparent dissolved oxygen concentration by about 0.7 mg/L. This problem reduces the reliability of dissolved oxygen determinations in areas heavily contaminated by wastes from sulfite pulp mills. Study areas investigated in the characterization project potentially affected by sulfite wastes include Bellingham Bay, Port Gardner, and Oakland Bay. The greatest impact of this problem is on data from the 1950s, when discharges of sulfite wastes were the highest.

More recently, electronic oxygen probes have been used in water quality studies of Puget Sound. Such methods are less accurate than Winkler titrations, but are more efficient. In most cases, the oxygen probes are calibrated against Winkler titrations. Although electronic methods are less susceptible to interference by pollutants (Riley 1975), proper equilibration of the oxygen probe is needed when recording depth profiles. Generally, competent use of oxygen probes can provide data of sufficient quality for use in this project.

<u>Nitrate</u>

Colorimetry was one of the earliest methods for measuring nitrate in seawater. It involved the use of reduced strychnine. Color instability was a substantial problem. Also, because the colors were measured visually in Nessler Tubes, differences in the visual capacities of the investigators may have affected the data (Riley 1975). Since the mid-1960s, methods of measuring nitrate in seawater have depended on the reduction of nitrate to nitrite. In the presence of sulphanilamide, the nitrite is converted to a highly colored dye (Morris and Riley 1963). A correction for the amount of nitrite originally in the water sample is made by subtracting the original amount from the total after the conversion of the nitrate to nitrite. By the mid-1970s, auto-analyzers were reliably used. Because no nitrate data from before the mid-1960s were available for the areas studied in the characterization project, all the available nitrate data were deemed acceptable.

Phosphate

Concentrations of dissolved orthophosphate are measured in seawater using a filtration technique that removes particulates and produces of a phosphomolybdenum blue complex in the filtered water. Prior to 1953, dissolved phosphate was measured visually with Nessler Tubes in studies of Puget Sound. The early assays also suffered from problems with color instability and salt errors. Since 1953, various spectrophotometers and auto-analyzers have been used. In the mid-1960s, modifications developed by Murphy and Riley (1962) to improve color stability were widely adopted. Phosphate data from the mid-1960s and beyond are the most reliable, and phosphate data from before 1953 are the least reliable. However, because the measurement of phosphate in seawater has a long history in Puget Sound, the limited amount of early phosphate data were retained, at least for the sake of comparison.

Chlorophyll a

Reliable measurements of chlorophyll in seawater date from the work of Richards and Thompson (1952). The Richards and Thompson (1952) method involves the extraction of phytoplankton pigments and measurement of light extinction by the extracted pigments at three wavelengths. Because studies through the mid-1960s did not include a correction for phaeophytins (chlorophyll degradation products), chlorophyll data from before the mid-1960s probably overestimate chlorophyll concentrations by about 25 percent (Heinle et al. 1980). It is not possible to calculate a correction factor retrospectively without actual data on phaeophytin concentrations. Therefore, none of the small amount of chlorophyll data that exist for Puget Sound from before this period were used in the water quality characterization project.

Since the mid-1970s, fluorometric methods sometimes have been used for chlorophyll determinations in Puget Sound. Such data are somewhat less reliable than absorbance-based data, but are of adequate quality for this project.

Secchi Disk Depth

Secchi disk depth is a measurement of water transparency. It provides an estimate of the amount of particulate matter in the water, as well as an estimate of the depth of the photic zone. The Secchi disk is a white disk, usually 30 cm in diameter. However, Ecology uses a 20-cm diameter Secchi disk (Singleton, L., 22 September 1987, personal communication). The Secchi disk is lowered into the water until it disappears from view. Readings are affected by the visual acuity of the observer and several factors that affect the light field in the water. These factors include the height of the sun above the horizon, refraction caused by surface waves, and ship shadows. The diameter of the Secchi disk only affects Secchi depth slightly [e.g., increasing the diameter of a Secchi disk from 43 to 60 cm increases the Secchi depth approximately 1 percent (Preisendorfer 1986, p. 923)]. The effects of these and related factors are relatively small. Use of Secchi depths is well-accepted, as long as the data are interpreted only as a simple index of water clarity (Preisendorfer 1986).

Fecal Coliform Bacteria

Historically, the concentration of fecal coliform bacteria in Puget Sound was measured by the most probable number (MPN) method (Greenberg et al. 1985). The MPN method involves a 48-h incubation of a series of dilutions of a water sample in a culture medium. Fecal coliform bacteria are detected by the presence of gas bubbles that are produced by bacterial metabolism. The precision of the MPN method is low, and, especially at low concentrations of bacteria, this method tends to yield overestimates of the actual bacterial concentration.

By the mid-1970s, the membrane filtration method for measuring the concentration of fecal coliform bacteria was widely adopted by the agencies working in Puget Sound. The membrane filtration method involves filtration of a water sample through a membrane filter (pore size=0.45 um). The filtered material is incubated for 24 h in a culture medium, after which fecal coliform colonies are counted under a dissecting microscope.

The membrane filtration method is both more accurate and more precise than the MPN method (Greenberg et al. 1985). Moreover, the two methods do not yield compatible results. Only fecal coliform data produced by the membrane filtration method were used in the water quality characterization project.

Sulfite Waste Liquor

Measurement of sulfite waste liquor in Puget Sound has been based on the Pearl Benson Index, which dates back to 1940. This method detects the lignin sulfonates in sulfite waste liquor through the formation of highly colored quinone oxime derivatives (Barnes et al. 1963; Felicetta and McCarthy 1963). Lignin sulfonates are chemically stable waste products of the pulping process. The intensity of the color in a treated sample is proportional to the amount of lignin sulfonates present in the original sample. Other lignins and tannins are also detected by the Pearl Benson Index, which could cause problems with erroneously high values in some samples. However, the errors caused by this problem probably are too small to be a substantial concern for samples heavily contaminated by pulp mill discharges.

Prior to 1953, values of the Pearl Benson Index were determined by visual comparisons of treated samples to treated standards, probably using Nessler tubes. After 1953, various spectrophotometers were used. The earlier data are less reliable and were not analyzed in the characterization project.

TIME COURSE OF ANALYTICAL TECHNIQUES

A time line of the changes in analytical techniques in the monitoring programs used as data sources for this project is given in Table A-1. This information was obtained from reading reports produced during the original studies and from interviews with the participating scientists.

TABLE A-1. TIME LINE OF ANALYTICAL TECHNIQUES USED IN THE ANALYSIS OF WATER QUALITY IN PUGET SOUND

Organization	Years Used	Analytical Method Used
Temperature		
UW	1932-1987	Deep sea reversing thermometers
	1975-1985	In situ CTD and STD
WDF	1956-1987	Lab thermometer in (WDF) water bottle
Ecology	1965-1970	Lab thermometer (?)
Ecology	1970-1972	No data
	1973-1987	Electric thermometer on D.O. probe
Metro	1965-1967	Lab thermometer in bottle
	1967-1982	Deep sea reversing thermometer
	1982-1987	In situ CTD
Salinity		
UW	1932-1960	Knudsen titration
	1960-1984	Precision salinity bridge
	1975-1985	In situ CTD and STD
	1984-1987	Auto-Analyzer
WDF	1956-1987	Knudsen titration
Ecology	1965-1970	Salinometer calibrated by Knudsen titration
	1970-1972	No data
	1973-1985	Salinometer calibrated in laboratory by an STD

TABLE A-1. (Continued)

Organization	Years Used	Analytical Method Used
Ecology (Continued)	1986	Knudsen titration
	1987	Hydrometer and titration
Metro	1965-1968	Knudsen titration
	1968-1971	Laboratory salinometer
	1971-1972	In situ CTD
	1972-1982	Laboratory salinometer
	1982-1987	In situ CTD
Dissolved Oxygen		
UW	1932-1975	Winkler titration
	1975-1986	Carpenter modification of Winkler titration
WDF	1956-1986	Winkler titration
Ecology	1965-1970	Winkler titration
	1970-1972	No data
	1973-1987	In situ D.O. probe calibrated against Winkler titration
Metro	1965-1982	Winkler titration
	1982-1983	In situ D.O. probe
	1983-1987	Winkler titration
Dissolved Orthophosphate		
UW	1932-1953	Thompson and Robinson Nessler Tubes
	1953-1962	Thompson and Robinson Spectrophotometer
	1962-1970	Murphy and Riley Spectrophotometer

TABLE A-1. (Continued)

Organization	Years Used	Analytical Method Used
UW (Continued)	1970-1987	Hager, Gordon and Park Auto-Analyzer
WDF	1956-1962	Thompson and Robinson Spectrophotometer
	1962-1973	Murphy and Riley Spectrophotometer
	1973-1987	Murphy and Riley Photometer
Ecology	1965-1970	Standard Methods for Water and Wastewater Manual, American Waterworks Assoc.
	1970-1972	No data
	1973-1987	U.S. EPA Manual 365.1 Auto-Analyzer techniques
Metro	1966-1971	Strickland and Parsons
	1972-1987	No marine data
<u>Nitrate</u>		
UW	1932-1953	Thompson and Robinson Nessler Tubes
	1953-1963	Thompson and Robinson Spectrophotometer
	1963-1970	Morris and Riley Spectrophotometer
	1970-1987	Armstrong, Stearns and Strickland Auto-Analyzer
WDF	1956-1966	Thompson and Robinson Spectrophotometer
	1966-1973	Morris and Riley Spectrophotometer
	1973-1987	Morris and Riley Photometer

TABLE A-1. (Continued)

Organization	Years Used	Analytical Method Used
Ecology	1965-1970	Standard Methods for Water and Wastewater Manual, American Waterworks Assoc.
	1970-1972	No data
	1973-1987	U.S. EPA Manual NO. 365.1 Auto-Analyzer
Metro	1965-1969	Strickland and Parsons buffered hydrazine
	1969-1971	Non-buffered hydrazine FWPCA Manual
	1971-1975	Strickland and Parsons Cadmium reduction
<u>Chlorophyll a</u>		
UW	1952-1970	Richards and Thompson Spectrophotometer
	1970-1987	Strickland and Parsons Fluorometer Auto-Analyzer
WDF	1956-1970	Richards and Thompson Spectro-photometer
	1970-1973	Strickland and Parsons Spectrophotometer
	1973-1987	Strickland and Parsons Photometer
Ecology	1965-1970	Strickland and Parsons Spectrophotometer
	1973-1987	Strickland and Parsons Fluorometer Auto-Analyzer
Metro	1966-1968	Creitz and Richards

TABLE A-1. (Continued)

Organization	Years Used	Analytical Method Used
Metro (Continued)	1968-1987	Strickland and Parsons
<u>Fecal Coliform Bacteria</u>		
Ecology	1973-1987	Standard Methods for Water and Wastewater Membrane Filtration
Metro	1967-1976	Standard Methods for Water and Wastewater Most Probable Number
	1977-1987	Standard Methods for Water and Wastewater Membrane Filtration
<u>Sulfite Waste Liquor</u>		
UW	1940-1953	Pearl Benson Index Nessler Tubes (?)
	1953-1967	Pearl Benson Index Spectrophotometer
WDF	?-1953	Pearl Benson Index Nessler Tubes (?)
	1953-1971	Pearl Benson Index Spectrophotometer
Ecology	1967-1984	Pearl Benson Index Spectrophotometer

PHOSPHATE

American Public Health Association. 1971. Standard methods for the examination of water and wastewater (13th Edition).

Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 12:162-176.

Redfield, A.C., H.P. Smith, and B.H. Ketchum. 1937. The cycle of organic phosphorus in the Gulf of Maine. Biol. Bull. Woods Hole 73:421-423.

Robinson, R.J., and T.G. Thompson. 1948. The determination of phosphorus in seawater. J. Mar. Res. 7:33-39.

Whiteledge, T., S.C. Malloy, C.J. Patton, and C.D. Wirick. 1981. Automated nutrient analysis in seawater. Report BNL-51398. Brookhaven National Laboratory, Upton, N.Y.

NITRATE

Chon, D.T.-W., and R.J. Robinson. 1953. Polarographic determination of nitrate in seawater. J. Mar. Res. 12:1-12.

FWPCA. 1969. Manual of analytical techniques for the National Eutrophication Research Program.

Morris and J.P. Riley. 1963. Anal. Chim. Acta 29:272.

Mullin, J.B., and J.P. Riley. 1955. The spectorphotometric determination of nitrate in natural waters with particular reference to seawater. Anal. Chim. Acta 12:464-480.

Zwicker, B.M.G., and R.J. Robinson. 1944. The photometric determination of nitrate in seawater with a strichnidine reagent. J. Mar. Res. 5:214-232.

CHLOROPHYLL a

Creitz, G.I., and F.A. Richards. 1955. The estimation and characterization of plankton populations by pigment analysis. III. A note on the use of "millipore" membrane filters in the estimation of plankton pigments. J. Mar. Res. 14(3):211-216.

Parsons, T.R., Y. Maita, and C.M. Lalli. 1984. A manual of chemical and biological methods for seawater analysis. Pergamon Press.

Richards, F.A., and T.G. Thompson. 1952. The estimation and characterization of plankton populations by pigment analysis. II. A spectrographic method for the estimation of plankton pigments. J. Mar. Res. 2:156-172.

Strickland, J.D.H., and T.R. Parsons. 1968. A practical handbook of seawater analysis. Fish. Res. Board of Canada. Bull. 167 Section IV. 3. Ottawa, Canada.

FECAL COLIFORM BACTERIA

Greenberg, A.E., R.R. Trussell, and L.S. Clesceri, (eds). 1985. Standard methods for the examination of water and wastewater (sixteenth edition). American Public Health Association, Washington, DC. 1268 pp.

SULFITE WASTE LIQUOR

Barnes, C.A., E.E. Collias, V.F. Felicetta, O. Goldschmid, B.F. Hrutfiord, A. Livingston, J.L. McCarthy, G.L. Toombs, M. Waldichuk, and R. Westley. 1963. A standardized Pearl Benson, or nitroso, method recommended for the estimation of spent sulfite liquor or sulfite waste liquor concentration in waters. Tech. Assoc. Pulp and Paper Industry 46(6):337-346.

Felicetta, V.F., and J.L. McCarthy. 1963. Spent sulfite liquor: X. The Pearl Benson, or nitroso, method for the estimation of spent sulfite liquor concentration in waters. Tech. Assoc. Pulp and Paper Industry 46(6):347-350.

APPENDIX B

SUMMARY OF DATA SET QUALITY ASSURANCE REVIEWS

INTRODUCTION

Results of the quality assurance reviews for the data sets included in the characterization study are summarized below. The corrections described herein were made <u>only</u> in the data file analyzed in the characterization study and <u>not</u> in the original files belonging to the agencies that provided the data. Therefore, these errors may still exist in their files.

UNIVERSITY OF WASHINGTON

Several major problems were encountered during the quality assurance review of the University of Washington's data set. Although much of the data were in STORET prior to the initiation of the characterization project, some data had never been entered into STORET and had to be read into a computer file. The data were read from existing keypunched cards made available by E.E. Collias. When a hard copy of the new data entered from these cards was examined, the letters "B" or "V" sometimes occurred as part of the depth value. These letters apparently were an artifact of the obsolete STORET format that was used at the time the data were originally punched on cards. The letters appeared only in data from continuation cards for particular records. The space in the data field occupied by these letters was dropped from the characterization database.

Other problems included errors in data coding and units of measurement. Data coding errors included the occasional addition of 8 h to the time of sample collection and reporting nitr<u>i</u>te concentrations in the nitr<u>a</u>te data field. Because the time of day was not analyzed in the characterization study, except to check that Secchi disk depth readings were taken only during daylight hours, the additional 8 h did not affect the project. The erroneous nitrate data were dropped from the characterization database. The units of measurement reported in the University of Washington documentation (Collias 1970) differed from the units encoded in the STORET file for sample depth, phosphate concentration, and dissolved oxygen concentration. Corrections for sample depth required multiplying values measured in feet by 0.305 to obtain values measured in meters. Corrections for dissolved oxygen concentration required changing values measured in mg-at/L to values measured in mg/L. Phosphate concentrations were reported to be encoded in mg/L, but were actually encoded in tenths of mg/L. Correction required multiplying the original values by 10.

WASHINGTON DEPARTMENT OF ECOLOGY

Some problems were encountered during the quality assurance review of Ecology's data set. The units for sample depth were given as meters in the documentation, but the depths were in feet in the STORET file. These values were simply converted by multiplication by the necessary scaling factor, 0.305. Extremely high phosphate concentrations were reported from some sites in August 1985. These concentrations were caused by an apparent laboratory error (Krafft, W., 23 July 1987, personal communication); these phosphate data were dropped. Data below detection limits were reported as the detection limit, accompanied in a separate data field by a STORET code that identified such points as having concentrations below the detection limit. However, a few points with undetected values for concentrations of nitrate and fecal coliform bacteria in the mid-1970s were reported as zeroes. These values were changed to the appropriate detection limit values.

WASHINGTON DEPARTMENT OF FISHERIES

No problems were encountered during the quality assurance review of these data sets.

METRO

The quality assurance review of Metro's data set uncovered two significant problems. Some Secchi disk depth values were unreasonably high. Metro field personnel indicated that Secchi disk depths of 10 m are common in the region included in this study (i.e., Point Jefferson), but that substantially higher readings are not credible (Waddell, D., 20 May 1987, personal communication). However, approximately 6 percent of the Secchi disk depth values were above 15 m, with values running as high as 72 m. In a table of the frequency distribution of the Secchi depth values for this region, the values above 15 m inexplicably jumped from one figure to the right of the decimal to two figures to the right of the decimal. Because this shift suggested an error in data coding, all Secchi depths greater than 15 m were discarded.

The other problem encountered in Metro's data set involved an analytical anomaly. An oxygen probe was used to measure dissolved oxygen concentrations in the water column, starting in September 1982. However, the probe was not properly equilibrated at each depth for measurements taken between September 1982 and January 1983 (Lehman, K., 20 May 1987, personal communication). Various corrections in the field procedures were instituted from February 1983 to September 1983, except that no corrections were used during April 1983. Starting in October 1983, Metro's database contains only Winkler dissolved oxygen determinations. Therefore, the dissolved oxygen data for the periods September 1982 to January 1983 and April 1983 were discarded.

CLIMATIC DATA

The quality of the climatic data is high. The locations of the monitoring stations have not changed greatly over the periods of the observations. The weather data are validated by the National Climatic Data Center staff before the reports are published. The runoff estimates, which are based on gaging data from seven stations, were compared with more detailed runoff estimates based on data from 22 gaging stations for the period of 1970-1975 (NOAA 1984a). The mean difference in the two estimates was only 3.3 percent, suggesting that the seven gaging stations used for the 1930-1978 runoff estimates provided reasonably good data.

The quality of the computer file containing the climatic data is also high. Both the weather and the runoff data were entered manually into a file for the characterization project. A hard copy of the data was validated by comparison with the original data reports.

APPENDIX C

SOURCES OF PUGET SOUND WATER QUALITY DATA

INSTITUTION: U.S. Navy - Bangor

CONTACT: Mr. Rick Spencer, U.S. Naval Submarine Base - Bangor, Bldg. 1101, Code 8622, Bremerton, WA 98315; Phone (206) 396-4192.

DATA DESCRIPTION: Monitoring program to evaluate the impact of naval activities on the water quality of Hood Canal. Water samples taken for trace metals (chromium, copper, iron, lead, mercury, silver, zinc, nickel), nutrients (ammonia, nitrates, nitrites, Kjeldahl nitrogen, orthophosphate), total organic carbon, pH, salinity, temperature, and dissolved oxygen. Secchi disk readings taken concurrently with water sampling.

LOCATION: Twenty sites in Hood Canal and Dabob Bay ranging from 47° 43' 46"N to 47° 46' 29" N and 122° 42' 10" W to 122° 46' 77" W.

PERIOD/FREQUENCY: 1974 to present and ongoing. All 20 sites sampled twice per year in summer and winter.

DATA FORMAT: Raw data files. All data sent to Naval Energy and Environmental Support Activities, Port Heuneme, CA.

PRIORITY: Low because of frequency of observation and not in the area chosen for analyses.

DATA EVALUATION: Unique because of area covered and scope of sample types. Nominal or low importance to trends study unless Ecology data are bad. These data are not in chosen area.

INSTITUTION: Washington Department of Natural Resources

CONTACT: Mr. Tom Mumford, Research and Development Center, Washington Department of Natural Resources, Olympia, WA 98504; Phone (206) 753-3703.

DATA DESCRIPTION: Hydrographic and chemical data from surface waters (temperature, salinity, phosphorus, nitrates, nitrites, and ammonia).

LOCATION: See below.

PERIOD/FREQUENCY:

Budd Inlet - 1979-1980. Daily monitoring.

Squaxin Island - Fall 1982 to Spring 1983. Daily monitoring.

Harstene Island - Fall 1982 to Spring 1983. Daily monitoring.

McNeil Island - Fall of 1982 to present and ongoing. Temperature and salinity daily, nutrients weekly.

DATA FORMAT: Raw data files with portions also available on magnetic tape.

PRIORITY: Medium for project, especially Budd Inlet.

DATA EVALUATION: Unique to sample areas - quality control good.

INSTITUTION: Washington Department of Fisheries

CONTACT: Mr. Stan Hammer, Fox Island Net Pens, 335 Island Blvd., Fox Island, WA 98333; Phone (206) 857-4324.

DATA DESCRIPTION: Temperature and dissolved oxygen measurements taken to protect salmon rearing operations.

LOCATION: Fox Island.

PERIOD/FREQUENCY: Mid-1970s to present and ongoing. Temperature measurements taken daily. Dissolved oxygen samples taken daily during critical periods, generally June and July.

DATA FORMAT: Raw data files.

PRIORITY: Low for project.

DATA EVALUATION: Probably inconsistent quality control; low importance to areas being used for analysis.

INSTITUTION: Padilla Bay National Estuarine Sanctuary.

CONTACT: Mr. Terry Stevens, Padilla Bay National Estuarine Sanctuary, 1043 Bay View-Edison Rd., Mount Vernon, WA; Phone (206) 428-1558.

COMMENTS: Padilla Bay Estuarine Sanctuary does not fund research nor perform any environmental data gathering activities independent of other institutions or government agencies. However, they provide facilities for research conducted under the auspices of other agencies. A summary of past research conducted in the Padilla Bay area is given below.

Type of Sampling	Agency(s)	Date	Investigator
Sulfite Waste 1946 (Water Quality)	Fish & Wildlife Ser., WDF	1946	Saxton-Young
Pulp Mill Pollution & Oyster Culture	WA Water Pollution Commission	1950	G. Orlob - A. Neale

Sulfite Waste Liquor Pollution Fidalgo & Padilla Bays	WA Water Pollution Commission	1948	W. Saxton
Industrial Waste (Water Quality)	Pollution Control Commission	1957	A. Neale
Oyster (Water Quality)	Pollution Control Commission	1952	A. Neale
Oyster (Water Quality)	WDF	1950	Orlob-Neale-Lindsay
Eelgrass	WDG/Funded by Fish & Wildlife Serv.	1971-75	B. Jeffrey
Benthic Forams of Samish & Padilla Bays	WWU M.S. Thesis	1973	D. Scott
Prelim. Inventory of Biota of Padilla Bay	WA Dept. of Game	1976	R. Jeffrey
Swinomish Channel Maint. Dredging	U.S. Army Corps of Engineers EIS	1976	---
Effects on Biota of Fidalgo Bay due to Navigation Channel	U.S. Army Corps of Engineers	1977	---
Swinomish Channel Dredged Material Reuse Study	Skagit Co. Planning Dept.	1980	---
Investigation of Tidal Soils of Padilla Bay	WSU	1980	D. Turner
Subtidal Benthic Communities and Density of Petroleum-Degrading Bacteria in Padilla Bay	WWU M.S. Thesis	1982	J. Barreca
Southwest Padilla Bay Tidelands Environ. Impact Assessment	WWU	1983	Huxley College
Physical, Chemical, & Biological characteristics of Padilla Bay	U of W	1984	R. Wissman
Trace Metals in Ecosystem of Padilla Bay	WWU M.S. Thesis	1985	L. Antrim

Padilla Bay Dungeness Crab Habitat Study	U of W	1986	P. Dinnel R. McMillan D. Armstrong
Definitions of Origins & Fates of Organic Nitrogen in Padilla Bay Food Webs	U of W	1986	R. Wissman
Padilla Bay Base-Water Quality Record	WWU	1986	P. Cassidyline G. McKeen
Intertidal Benthos	WWU Huxley College Funded by Ecology	1974-75, 1979	Webber-Smith
Subtidal-Eelgrass Benthos	WWU Huxley College Funded by Ecology	1976	Webber-Smith
Beach Seine (fish)	WWU Huxley College Funded by Ecology	1974-75	Webber-Smith
Marine Birds	WDG + funded by U.S.F.W.S	1965-79	Webber-Smith
Marine Birds	John Graham Co. Funded by ACOE	1977-78	Peters-Richter
Marine Birds	U.W. funded by EPA through NOAA (MESA)	1978-79	Manuwal-Wahl
Marine Mammals	NMFS funded by NOAA (MESA)	1977-79	R. Everitt
Land Use/Land Cover	WDG funded by OCZM through WDOE	1978	R. Albright
Drift Sectors	John Norman Assoc. funded through WDOE	1977	J. Norman
Inventory of Compilation of Biota (Data)	WWU Huxley College WDF, WDG	1976	B. Jeffrey
Inventory of Compilation of Biota (Data)	WDG	1977	Sweeney

LOCATION: University of Washington

CONTACT: Dr. Carl Lorenzen, University of Washington, Dept. of Oceanography Seattle, WA 98195; unavailable.

DATA DESCRIPTION: Research directed toward understanding phytoplankton dynamics and seasonal variability. Measurements made of phytoplankton pigment concentrations and primary productivity throughout a vertical profile to a depth of 100 m.

LOCATION: Dabob Bay.

PERIOD/FREQUENCY: 1975-1985. A single site occupied at monthly intervals.

DATA FORMAT: Raw data files.

PRIORITY: Medium for chlorophyll a data in Dabob Bay.

DATA EVALUATION: Data hard to access. Advice of Dr. Lorenzen unavailable.

INSTITUTION: University of Washington

CONTACT: Dr. Jerry Stober, Fisheries Research Institute, College of Fisheries, University of Washington, Seattle, WA 98195; Phone (206) 543-9041.

COMMENTS: In an effort to evaluate the potential ecological impacts of a nuclear power plant, a multidisciplinary study of the fisheries and marine ecology of northern Skagit Bay in the vicinity of Kiket Island was undertaken by the Fisheries Research Institute. Because of the diverse data collected, each component of the research is considered individually in the following summaries. All of the reports cited in these sections can be found in:

> Stober, Q.J., and E.O. Salo. 1973. Ecological studies of the proposed Kiket Island nuclear power site. University of Washington College of Fisheries, Fisheries Research Institute, FRI-UW-7304. Final Report. Submitted to Snohomish County P.U.D. and Seattle City Light.

PRIORITY: Low.

DATA EVALUATION: Unique for Skagit Flats area and high density data for 1 yr; not applicable for present trends study because of location.

LOCATION: University of Washington

CONTACT: Dr. Jerry Stober, Fisheries Research Institute, College of Fisheries, University of Washington, Seattle, WA 98195; Phone (206) 543-9041.

DATA DESCRIPTION: Hydrographic data (temperature, salinity, turbidity, dissolved oxygen) from surface and bottom waters.

LOCATION: Similk Bay, North Skagit Bay, Swinomish Channel.

PERIOD/FREQUENCY: 1970-1972. Continuous record of temperature at surface, 3 m, and bottom. Grid sampling of surface waters, March-July 1970; March-May 1971; and March-August 1972.

DATA FORMAT: Stober, Q.J., S.J. Walden, and D.T. Griggs. Seasonal water quality in North Skagit Bay. In: Stober et al. (1973). Chap. 4, pp. 7-34.

PRIORITY: Low.

DATA EVALUATIONS: See previous comments.

INSTITUTION: University of Washington.

CONTACT: Dr. Jerry Stober, Fisheries Research Institute, College of Fisheries, University of Washington, Seattle WA 98195; Phone (206) 543-9041.

DATA DESCRIPTION: Investigation of temporal and spatial distribution and abundance of ichthyoplankton. Two replicate vertical plankton hauls taken from both bottom to surface and 5 m to surface. Nansen casts for temperature and salinity taken at each station prior to zooplankton sampling.

LOCATION: Northern Skagit Bay.

PERIOD/FREQUENCY: January 1971 through April 1972 with sampling intervals spaced 1 wk to 1 mo apart. Some stations repeated as frequently as twice per cruise.

DATA FORMAT: Blackburn, J.E. Pelagic eggs and larval fish of Skagit Bay. In: Stober et al. (1973). Chap. 6, pp. 71-118.

PRIORITY: Low.

DATA EVALUATION: See previous comments.

INSTITUTION: University of Puget Sound.

CONTACT: Dr. Eric Lindgren, University of Puget Sound, 1500 N. Warner, Tacoma, WA 98416; Phone (206) 765-3121.

DATA DESCRIPTION: Hydrographic data on surface waters (temperature, salinity, dissolved oxygen, turbidity, pH).

LOCATION: Tacoma Narrows.

PERDIO/FREQUENCY: 1973 to present and ongoing. Samples taken annually every fall and occasionally in spring.

DATA FORMAT: Student reports.

COMMENT: Data collected by students as part of an introductory oceanography class. Inexperience of students makes the data highly suspect.

PRIORITY: Low.

DATA EVALUATION: Infrequent sampling but long time span. Data hard to access and may have quality control problems.

INSTITUTION: Shoreline Community College.

CONTACT: Mr. Jack Serwold and Mr. Bob Harman, Shoreline Community College, 16101 Greenwood Avenue N., Seattle, WA 98133; Phone (206) 546-4101.

DATA DESCRIPTION: Species composition and abundances of benthic diatoms, foraminifera, and macroinvertebrates collected using 0.1 m^2 Van Veen grab sampler. Concurrent Secchi disk readings and temperature and salinity measurements at 1 and 3 m. Sampling has recently included a plankton sample at 3-m depth.

LOCATION: Approximately 2,000 sites throughout Puget Sound, primarily in the Nisqually Delta, central basin, and northern sound. Samples generally taken at 1, 5, 10, 20 fathoms and in the deep areas of each region.

PERIOD/FREQUENCY: Nearly all work to date has been done as single surveys with only occasional resampling of specific sites. Sampling periods are as follows:

Central basin: 1974-1978
Central basin north of Edmonds: 1981
Commencement Bay: 1980-1981
Everett-Port Susan: 1978-1979
Nisqually Delta: 1982
Northern Saratoga Passage-Skagit Bay: 1984

DATA FORMAT: Raw data files.

COMMENTS: The level of analysis of the benthic samples is dependent on taxonomic groups. Molluscs have been identified to species; polychaetes and other groups have generally been identified only to higher taxa.

PRIORITY: Low.

DATA EVALUATION: Sample locations not repeated through time. Data difficult to access.

INSTITUTION: Olympic Community College

CONTACT: Dr. Don Seavy, Olympic Community College, 16th and Chester, Bremerton, WA 98310; Phone (206) 478-4557.

DATA DESCRIPTION: Measurements of surface water temperature, salinity, pH, and dissolved oxygen along with concurrent zooplankton samples.

LOCATION: Several stations within Sinclair Inlet.

PERIOD/FREQUENCY: 1977 to present and ongoing. Monthly samples but lacking the summer months.

DATA FORMAT: Raw data files.

COMMENTS: Zooplankton samples only partially worked up but available for further analysis. Much of the hydrological data has been forwarded to Alan Mearns, NOAA.

PRIORITY: Low.

DATA EVALUATION: Geographically limited; time span good for area covered; data difficult to access.

LOCATION: Highline School District.

CONTACT: Mr. Lauren Rice, Marine Technology Dept., 18010 8th Avenue S.,Seattle, WA 98148, Phone (206) 433-2524.

DATA DESCRIPTION: Vertical profiles of temperature, salinity, and dissolved oxygen.

LOCATION: Shilshole.

PERIOD/FREQUENCY: 1975 to present and ongoing, annually each May.

DATA FORMA: Raw data files.

PRIORITY: Low; infrequently sampled.

DATA EVALUATION: This group no doubt has nearshore data near Pully Point in the south main basin study area. Data difficult to access and may have problems in quality control; limited time coverage.

LOCATION: Battelle Northwest

CONTACT: Dr. Jack Anderson, Battelle Pacific Northwest Division, Marine Research Laboratory, Route 5, Box 1000, Sequim, WA 98382; Phone (206) 683-4151.

COMMENTS: During 1972-1974 Battelle Northwest was involved in an extensive baseline study involving both chemical and biological surveys, prior to operation of the ARCO refinery at Cherry Point. This study represents a potentially valuable database for any future monitoring efforts in the Strait of Georgia, but is still considered proprietary data by ARCO.

PRIORITY: Low.

DATA EVALUATION: Outside of Bellingham Bay study region; data difficult to access.

INSTITUTION: Seattle Aquarium

CONTACT: Mr. Bill Bruin, Seattle Aquarium, Pier 59, Seattle, WA 98101; Phone (206) 625-4358.

DATA DESCRIPTION: Hydrographic and water quality measurements of aquarium intake water (temperature, salinity, pH, turbidity, total coliform, dissolved oxygen). Intake located 80 ft below surface.

LOCATION: Elliott Bay.

PERIOD/FREQUENCY: 1977 to present and ongoing. Data collected intermittently in 1977. Since 1978, temperature, salinity, pH, and turbidity have been collected daily, total coliform and dissolved oxygen on a weekly basis.

DATA FORMAT: Raw data files.

PRIORITY: Low.

DATA EVALUATION: Data have good time span but are not within a study region of the sound included in the characterization study.

INSTITUTION: Point Defiance Zoo and Aquarium.

CONTACT: Mr. John Rupp, Pt. Defiance Zoo and Aquarium, N 54th Street and N Pearl, Tacoma, WA 98407; Phone (206) 592-5223.

DATA DESCRIPTION: Hydrographic measurements on aquarium intake water (temperature, salinity, dissolved oxygen, pH). Intake located 15-20 ft below surface.

LOCATION: Point Defiance.

PERIOD/FREQUENCY: 1982 to present and ongoing. Sampling at irregular intervals but approximately on a monthly basis. Greatest sampling frequency in winter and spring.

DATA FORMAT: Raw data files.

PRIORITY: Low.

DATA EVALUATION: Sampling location is outside of study areas.

INSTITUTION: Domsea Farms, Inc.

CONTACT: Mr. Mike Gardner, Domsea Farms, Inc., 4398 West Old Belfair Highway, Bremerton, WA 98312; Phone (206) 479-9941.

DATA DESCRIPTION: Dissolved oxygen measurement of surface waters to protect salmon rearing operations.

LOCATION: Fort Ward (Bainbridge Island) and Orchard Point.

PERIOD/FREQUENCY: 1975 to 1978. Monitoring on an irregular basis only when there is cause for concern. Most samples taken during fall months.

DATA FORMAT: Raw data files.

PRIORITY: Low.

DATA EVALUATION: Outside of study and not continuous in time or over the annual cycle.

INSTITUTION: Sundquist Laboratory.

CONTACT: Mr. Paul Cassidy, Sundquist Laboratory, 1900 Shannon Point Avenue, Anacortes, WA 98221; Phone (206) 293-6800.

DATA DESCRIPTION: Hydrographic data of surface waters (temperature, pH, turbidity, dissolved oxygen, total alkalinity, carbonate alkalinity, dissolved CO_2, and salinity).

LOCATION: Shannon Point, Anacortes.

PERIOD/FREQUENCY: 1974 - present and ongoing (temperature, pH, dissolved oxygen, turbidity). 1977 to present and ongoing (total and carbonate alkalinity, CO_2, salinity). Sampling was daily but currently approximately three times per week. Special study of Padilla Bay in 1985 for 1-yr period. Samples taken several times per month.

DATA FORMAT: Raw data files.

PRIORITY: Low for Shannon Pt., high for Padilla Bay locations, if used.

DATA EVALUATION: Monthly data. Data presentation poor but analytical methods probably good. Can be accessed on 5.25-in floppy disk.

INSTITUTION: Tulalip Tribes.

CONTACT: Mr. Dave Somers, Tulalip Tribe, 7600 Totem Beach Road, Marysville, WA 98370; Phone (206) 653-4588.

DATA DESCRIPTION: Parametrix, Inc. was contracted to conduct a baseline survey of the water quality and fisheries resources of Tulalip Bay in preparation for expansion of a salmonid hatchery operation. A wide variety of parameters were measured in the surface waters of the bay, including general physical and chemical properties, nutrients, coliforms, trace metals, and synthetic organics.

LOCATION: Tulalip Bay, four stations.

PERIOD/FREQUENCY: General physical/chemical properties, nutrients, and microbial analyses: April 13 to June 27, 1979; weekly sampling frequency. Metals and synthetic organics: April 18 to June 27, 1979; sampling every third week.

DATA FORMAT: Campbell, R.F., and D.E. Weitkamp. 1979. Water quality and nearshore fish investigations in Tulalip Bay, Washington, 1979. Prepared by Parametrix, Inc. for the Tulalip Tribes, Marysville, WA.

PRIORITY: Low.

DATA EVALUATION: Surface values, good mix of variables, but not in study areas; limited time span.

INSTITUTION: Post Point Sewage Treatment Plant, Bellingham, WA.

CONTACT: Operator on Duty; (206) 676-6977; or Gary Hess, same number.

DATA DESCRIPTION: Not well known, but must be water quality data including conventionals; data results from study by CH2M HILL in Bellingham's effort to secure secondary treatment waiver (1982-1983).

LOCATION: Bellingham and Sammish Bays.

PRIORITY: Medium for Bellingham Bay.

DATA EVALUATION: Data unevaluated.

INSTITUTION: Evans-Hamilton

CONTACT: Jeff Cox, Evans-Hamilton, 6302 21st Northeast, Seattle, WA 98105; Phone (206) 525-5268.

DATA DESCRIPTION: Full suite water parameter data, Metro Seahurst Study, 1982-83.

LOCATION: Main Basin (south).

PRIORITY: Medium for south half of Main Basin; time covered too short.

DATA EVALUATION: This may be the only source of water quality data from Metro Seahurst Study; Metro claims their data tapes are unreadable; Evans-Hamilton's data tapes are edited and would cost money to access.

INSTITUTION: University of Washington.

CONTACT: Jim Postel, School of Oceanography, WB-10, University of Washington.

DATA DESCRIPTION: Chlorophyll a and water property data; Metro Seahurst Study, 1983-1983.

LOCATION: Main Basin (south).

PRIORITY: Medium for south half of Main Basin; time covered too short.

DATA EVALUATION: Published report by A. Copping, J. Postel, and J. Anderson; data should be good but may be hard to access by computer; must check with Postel for confirmation.

INSTITUTION: University of Washington.

CONTACT: Jan Downs, School of Oceanography, WB-10, University of Washington; Phone (206) 543-9658.

DATA DESCRIPTION: Chlorophyll a and water property data; monthly collected by Carl Lorenzen.

LOCATION: Dabob Bay region.

DATA FORMAT: Data logs and notebooks; a little published; some compiled by J. Downs.

PRIORITY: Medium for Dabob Bay area; sampling not done in characterization study areas.

DATA EVALUATION: Good data but study sites far from Ecology station; 1979-early 1980's; data hard to access by computer; Lorenzen not capable of assistance.

INSTITUTION: University of Washington.

CONTACT: Bruce Frost, School of Oceanography, WB-10, University of Washington.

DATA DESCRIPTION: Chlorophyll a and water property data; weekly 1979-1980, monthly 1982, 1984, 1985; includes nutrients.

LOCATION: Dabob Bay region.

DATA FORMAT: Data logs and some published.

PRIORITY: Medium for Dabob Bay region; sampling not done in characterization study areas.

DATA EVALUATION: Good data coverage through time; hard to access by computer.

INSTITUTION: University of Washington.

CONTACT: George Anderson, retired, School of Oceanography, WB-10, University of Washington; or Jim Postel, same address, (206) 543-6141.

DATA DESCRIPTION: Chlorophyll a data, Main Basin of Puget Sound, and productivity data 1964-67.

LOCATION: Main Basin of Puget Sound.

DATA FORMAT: Printed and published data; nine-track tape available through J. Postel.

PRIORITY: Medium for Main Basin area; major source of chlorophyll a data for this area; time covered too short.

DATA EVALUATION: Unique source but data may be hard to access.

INSTITUTION: University of Washington.

CONTACT: Willis K. Peterson, School of Oceanography, WB-10, University of Washington; Phone (206) 543-6141.

DATA DESCRIPTION: Chlorophyll *a* data, Main Basin of Puget Sound, and productivity in 1975.

LOCATION: Main Basin of Puget Sound.

DATA FORMAT: Published report: Phytoplankton Production and Standing Stick in the Main Basin of Puget Sound. Puget Sound Interim Studies, 1977.

PRIORITY: Medium for Main Basin area; significant source of Chlorophyll *a* data; time covered too short.

DATA EVALUATION: Unique study but data may be hard to access.

INSTITUTION: Municipality of Metropolitan Seattle.

CONTACT: Rich Tomlinson or Ray Dalseg, Metro Water Quality Lab; Phone (206) 684-2313.

DATA DESCRIPTION: Salinity, temperature, dissolved oxygen, some nutrients, chlorophyll *a*, special purpose surveys in Main Basin of Puget Sound; 1966 - present; some monthly.

LOCATION: Main Basin Puget Sound.

DATA FORMAT: Computerized data in STORET.

PRIORITY: High for Main Basin. Required to extend time line for Point Jefferson Station.

DATA EVALUATION: Unique source but doubtful quality control in dissolved oxygen due to field techniques and continual change in equipment and technologies.

INSTITUTION: University of Washington.

CONTACT: Eugene E. Collias, 4318 First Avenue NE, Seattle, WA 98105; phone (206) 633-5570.

DATA DESCRIPTION: Salinity, temperature, dissolved oxygen, nutrients, Secchi disk; Puget Sound Interim Studies, Metro's Nutrient Budget of Puget Sound (1976).

LOCATION: Main Basin Puget Sound.

DATA FORMAT: Computer card storage and tape.

PRIORITY: High for location, types of parameters, and the project.

DATA EVALUATION: Good, University of Washington data to extend time series at Point Jefferson.

INSTITUTION: Washington Department of Ecology.

CONTACT: Merley McCall, Chief Chemist, Manchester Lab, (206) 442-0370.

DATA DESCRIPTION: Salinity, temperature, dissolved oxygen, nutrients, chlorophyll a, and others; routine surveys 1967 to present, widely spaced Puget Sound stations about once each month (except winter); 0, 10, 30-m depths only.

LOCATION: Stations throughout Puget Sound.

DATA FORMAT: Computerized data in STORET.

PRIORITY: High throughout Puget Sound; required to extend time series from earlier work.

DATA EVALUATION: Lack of continuity and changing lab practices may affect data.

LOCATION: Marine Science Center.

CONTACT: Mr. James Kolb, Marine Science Center, 17771 Fjord Drive NE, Poulsbo, WA 98370; Phone (206) 779-5549.

DATA DESCRIPTION: Salinity, temperature, dissolved oxygen, pH, weather.

LOCATION: Liberty Bay, fall-winter 1971-72, twice monthly spring 1973.

DATA FORMAT: Report log sheets by P. Maloney and M. J. Delk.

PRIORITY: High for location, low for project.

DATA EVALUATION: Unique because area involved; low importance to study; directed study by high school students.

INSTITUTION: Washington State Department of Fisheries.

CONTACT: Marvin Tarr, Point Whitney Lab, Brinnon, WA; (206) 796-4601.

DATA DESCRIPTION: Salinity, temperature, dissolved oxygen, nutrients, chlorophyll a; 1950s and 1970s data from shellfish producing areas.

LOCATION: Much in small embayments of southern sound and in Bellingham and Dabob Bays.

DATA FORMAT: Log sheets and printed reports.

PRIORITY: High for location, types of parameters, and the project.

DATA EVALUATION: Good data through time in areas of sound but subject to changes in chemical techniques.

INSTITUTION: University of Washington.

CONTACT: Fish-Ocean Library, School of Oceanography.

DATA DESCRIPTION: M.S. and Ph.D. theses containing chlorophyll a and water property data.

LOCATION: Main Basin and Dabob Bay regions.

DATA FORMAT: Variable, some data appendices.

PRIORITY: Medium for project.

DATA EVALUATION: See list of selected theses given below. These will be very difficult to extract data from because most of these are interpretations of the data.

CHLOROPHYLL a SOURCES

John P. Bavlon, Spring Changes in Phytoplankton Abundance in a Deep Estuary, Hood Canal, Washington, Journal of Marine Research, Vol. 17, 1958, p. 53-67. (Chlorophyll a and productivity estimates for four periods in 1953. Data are in the publication.)

Robert Theodore Cooney, PhD Dissertation, Zooplankton and Micronekton Associated with a Diffuse Sound-Scattering Layer in Puget Sound, Washington, 1971. Fish Ocean Library GC/7/Th 19248 (see Figure 8 for plotted values, 3 stations).

Jed Hirota, MS Thesis, Use of Free-Floating Polyethylene Cylinders on Studies of Puget Sound Phytoplankton Ecology, 1967. (Some chlorophyll and productivity estimates) Fish Ocean Library, GC/7/TH16457.

Hans Julian Hartmann, MS Thesis, Release and Assimilation of Dissolved Organic Carbon by Natural Marine Phytoplankton Populations, 1974. (Some Chlorophyll a and C14 productivity values).

Jerry David Larrance, MS Thesis, A Method for Determining Volume of Phytoplankton in a Study of Detrital Chlorophyll a, 1964. Fish-Ocean Library 551.46, Th 13399.

Willis K. Peterson, Serena Campbell, Phytoplankton Production and Standing Stock in the Main Basin of Puget Sound, 1977. Metro Interim Studies. Fish-Ocean Library, QK 192 C34 1977.

Robert Munson, The Horizontal Distribution of Phytoplankton in a Bloom in Puget Sound, May 1969, Non-Thesis MS degree report, 1970. (available from Karl Bause, University of Washington; has data for 1967, salinity, temperature, dissolved oxygen, phosphate, nitrate, Secchi depth, Chlorophyll a).

Mark David Ohman, PhD Dissertation, 1983. The Effects of Predation and Resource Limitation on the Copepod Pseudocalnus sp. in Dabob Bay, a Temperate Fjord. Fish Ocean Library, GS/7/Th 31369.

Jeffrey Albert Runge, PhD Dissertation, 1981. Egg Production of Calanus pacificus Brodsky and its Relationship to Seasonal Changes in Phytoplankton Availability. Fish Ocean Library, GC/7/Th 29440.

Frank Randolph Shuman, PhD Dissertation, 1978, The Fate of Phytoplankton Chlorophyll in the Euphotic Zone, Washington Coastal Waters. Fish Ocean Library, GS/7/Th 26441. (C_{14} and Chlorophyll a values, Dabob Bay, 1975-1976).

Andrea Copping, PhD Dissertation, 1982, The Distribution and Passage of Organic Matter in the Marine Food Web, Using Nitrogen as a Tracer. Fish Ocean Library, GC/7/Th 30233.

Nicholas A. Welschmeyer, PhD Dissertation, 1982. The Dynamics of Phytoplankton Pigments: Implications for Zooplankton Grazing and Phytoplankton Growth, Dabob Bay. Fish Ocean Library, GC/7/Th 29691.

Jeffrey Reinge, 1985. Relationship of Egg Production of Calanus pacificus to Seasonal Changes in Phytoplankton Availability in Puget Sound, Washington. Limnology and Oceanography, 30(2), pp. 382-396.

APPENDIX D

COMPARABILITY OF DATA FROM DIFFERENT SOURCES AT STATIONS WITH OVERLAPPING SAMPLING PERIODS

TABLE D-1. DATA COMPARISONS BETWEEN WASHINGTON DEPARTMENT OF FISHERIES AND WASHINGTON DEPARTMENT OF ECOLOGY

Variable	Agency	Season	Number of Observations	Mean	Standard Error	p
Dissolved Oxygen	WDF[a]	Spring	22	9.06	0.16	--[c]
	Ecology[b]		3	9.70	0.23	
	WDF	Summer	29	7.37	0.19	--
	Ecolgy		3	6.17	0.48	
	WDF	Autumn	20	7.18	0.18	--
	Ecolgy		1	6.50	----	
	WDF	Winter	10	9.64	0.08	--
	Ecology		3	8.83	1.45	
Salinity	WDF	Spring	22	23.41	0.53	--
	Ecology		3	23.67	1.92	
	WDF	Summer	29	27.02	0.19	--
	Ecology		3	26.37	1.66	
	WDF	Autumn	20	25.53	0.52	--
	Ecology		1	25.80	----	
	WDF	Winter	10	18.81	0.88	--
	Ecology		3	21.73	1.75	
Water Temperature	WDF	Spring	20	12.76	0.69	--
	Ecology		2	11.10	0.50	
	WDF	Summer	31	18.05	0.27	--
	Ecology		3	19.60	1.19	
	WDF	Autumn	20	11.38	0.49	--
	Ecology		1	13.70	----	
	WDF	Winter	8	6.83	0.45	--
	Ecology		3	5.70	2.07	

[a] Washington Department of Fisheries, Station 23, Oakland Bay.

[b] Washington Department of Ecology, Station OAK004, Oakland Bay.

[c] -- = Not statistically significant (P>0.05).

TABLE D-2. DATA COMPARISONS BETWEEN METRO AND UNIVERSITY OF WASHINGTON

Variable	Agency	Season	Number of Observations	Mean	Standard Error	p
Dissolved Oxygen	Metro[a]	Spring	97	11.18	0.18	--[c]
	UW[b]		26	11.00	0.31	
	Metro	Summer	100	9.65	0.17	--
	UW		14	8.81	0.55	
	Metro	Autumn	15	7.09	0.11	--
	UW		11	6.99	0.16	
	Metro	Winter	6	9.37	0.14	--
	UW		10	9.05	0.18	
Salinity	Metro	Spring	97	26.50	0.21	*[d]
	UW		34	27.42	0.18	
	Metro	Summer	98	27.80	0.22	*
	UW		15	28.75	0.48	
	Metro	Autumn	15	29.35	0.34	*
	UW		11	30.14	0.11	
	Metro	Winter	6	27.19	0.76	--
	UW		10	27.09	0.65	
Water Temperature	Metro	Spring	112	10.05	0.17	**[e]
	UW		33	10.80	0.21	
	Metro	Summer	108	13.48	0.13	--
	UW		15	13.61	0.32	
	Metro	Autumn	19	11.96	0.16	--
	UW		12	11.17	0.30	
	Metro	Winter	6	7.35	0.16	--
	UW		10	7.60	0.25	

[a] Metro, Station KSBP01, Point Jefferson.

[b] University of Washington, Station PSB305, Point Jefferson.

[c] -- = Not statistically significant (P>0.05).

[d] * = Statistically significant (P<0.05).

[e] ** = Statistically significant (P<0.01).

TABLE D-3. DATA COMPARISONS BETWEEN UNIVERSITY OF WASHINGTON AND WASHINGTON DEPARTMENT OF ECOLOGY

Variable	Agency	Season	Number of Observations	Mean	Standard Error	p
Dissolved Oxygen	UW[a]	Spring	7	9.32	0.38	**[c]
	Ecology[b]		3	11.10	0.12	
	UW	Summer	4	8.43	0.57	--[d]
	Ecology		2	8.50	0.90	
	UW	Autumn	5	6.98	0.18	*[e]
	Ecology		2	5.75	0.05	
	UW	Winter	3	8.78	0.52	--
	Ecology		3	8.50	0.45	
Salinity	UW	Spring	7	28.62	0.39	*
	Ecology		3	26.57	0.47	
	UW	Summer	4	29.80	0.19	*
	Ecology		2	27.30	1.20	
	UW	Autumn	5	30.48	0.09	--
	Ecology		2	31.80	4.20	
	UW	Winter	3	28.99	0.53	--
	Ecology		2	30.70	1.40	
Water Temperature	UW	Spring	7	9.66	0.37	--
	Ecology		3	10.63	0.37	
	UW	Summer	4	13.04	0.32	--
	Ecology		2	13.15	0.15	
	UW	Autumn	5	11.01	0.57	--
	Ecology		2	11.55	0.65	
	UW	Winter	3	8.33	0.15	--
	Ecology		3	8.53	0.78	

[a] University of Washington, Station PSB318, Alki Point.

[b] Washington Department of Ecology, Station PSB002, Alki Point.

[c] ** = Statistically significant ($P<0.01$).

[d] -- = Not statistically significant ($P>0.05$).

[e] * = Statistically significant ($P<0.05$).

APPENDIX E

DESCRIPTIVE STATISTICS FOR WATER QUALITY VARIABLES

TABLE E-1. BELLINGHAM BAY STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	103	24.24	0.42	17.7
		10	52	28.44	0.21	5.5
		30	33	28.50	0.41	8.3
Water Temperature	°C	0	102	14.52	0.25	17.2
		10	52	11.08	0.23	14.7
		30	32	9.65	0.22	12.6
Dissolved Oxygen	mg/L	0	99	10.14	0.17	16.5
		10	48	8.95	0.23	17.6
		30	28	7.56	0.26	18.0
Dissolved Oxygen Saturation	Percent	0	98	116.11	1.94	16.5
		10	46	97.96	2.71	18.8
		30	26	80.47	2.69	17.0
Nitrate[a]	ug-at/L	0	35	3.88	0.94	144.2
		10	35	10.08	1.19	69.8
		30	35	14.91	1.12	44.6
Phosphate[a]	ug-at/L	0	42	0.67	0.08	74.8
		10	35	1.11	0.09	49.0
		30	35	1.47	0.11	46.3
Chlorophyll *a*	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	24	3.10	0.31	49.8
Sulfite Waste Liquor	Pearl Benson Index	0	100	22.09[b]	1.16	11.7
		10	51	4.40[b]	1.17	38.2
		30	33	2.86[b]	1.25	69.6
Fecal[a] Coliform Bacteria	No./100 mL	0	35	2.44[b]	1.25	88.4
		10	8	1.30[b]	1.13	81.3
		30	8	1.73[b]	1.44	92.3

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-2. PORT GARDNER STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	85	19.77	0.54	25.4
		10	47	28.00	0.12	3.0
		30	22	29.13	0.07	1.2
Water Temperature	°C	0	85	11.93	0.26	20.2
		10	47	9.64	0.20	14.2
		30	22	8.64	0.15	8.2
Dissolved Oxygen	mg/L	0	85	10.07	0.18	16.4
		10	47	8.87	0.17	12.9
		30	22	7.46	0.14	8.9
Dissolved Oxygen Saturation	Percent	0	85	106.33	1.84	15.9
		10	47	94.12	1.94	14.2
		30	22	76.93	1.48	9.0
Nitrate[a]	ug-at/L	0	24	5.98	1.37	112.7
		10	24	18.23	1.35	36.1
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	43	0.68	0.06	59.3
		10	41	1.63	0.09	33.9
		30	17	2.28	0.09	16.4
Chloro-phyll _a_	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	18	2.74	0.34	53.1
Sulfite Waste Liquor	Pearl Benson Index	0	63	17.33[b]	1.17	11.0
		10	25	6.44[b]	1.33	37.1
		30	3	21.97[b]	3.85	48.5
Fecal[a] Coliform Bacteria	No./100 mL	0	25	22.87[b]	1.54	32.6
		10	9	2.19[b]	1.29	58.6
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-3. POINT JEFFERSON STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	394	27.31	0.09	6.6
		10	224	28.35	0.07	3.6
		30	201	29.13	0.05	2.4
		100	73	29.79	0.06	1.6
		150	58	29.92	0.07	1.7
		200	38	30.12	0.04	0.7
Water Temperature	°C	0	544	12.26	0.08	14.6
		10	239	11.39	0.11	14.3
		30	219	10.38	0.09	12.6
		100	79	9.86	0.13	11.5
		150	60	9.83	0.12	9:8
		200	36	9.57	0.17	10.5
Dissolved Oxygen	mg/L	0	406	10.97	0.08	15.3
		10	238	9.73	0.07	11.7
		30	217	8.26	0.05	9.1
		100	82	7.48	0.08	9.9
		150	64	7.32	0.09	9.5
		200	37	7.08	0.10	8.6
Dissolved Oxygen Saturation	Percent	0	406	119.44	1.06	17.8
		10	238	103.89	1.01	15.1
		30	216	86.93	0.63	10.6
		100	82	76.82	1.14	13.4
		150	63	75.08	1.33	14.0
		200	37	74.00	0.97	7.9
Phosphate[a]	ug-at/L	0	29	1.41	0.12	44.9
		10	21	1.70	0.10	27.5
		30	19	2.08	0.09	18.5
		100	6	2.03	0.05	5.6
		150	6	2.08	0.05	6.0
		200	7	2.11	0.05	6.0
Chlorophyll a	ug/L	0	184	5.59	0.31	74.7
		10	22	1.64	0.42	121.0
		30	1	0.36	--	--
		100	0	--	--	--
		150	0	--	--	--
		200	0	--	--	--
Secchi Depth	m	--	495	4.69	0.10	47.4

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

TABLE E-4. SINCLAIR INLET STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	43	27.96	0.15	3.6
		10	36	28.40	0.11	2.3
		30	0	--	--	--
Water Temperature	°C	0	44	14.54	0.35	16.1
		10	37	12.84	0.30	14.1
		30	0	--	--	--
Dissolved Oxygen	mg/L	0	40	11.34	0.30	16.9
		10	34	8.88	0.24	15.8
		30	0	--	--	--
Dissolved Oxygen Saturation	Percent	0	38	133.98	3.88	17.8
		10	32	102.16	2.71	15.0
		30	0	--	--	--
Nitrate[a]	ug-at/L	0	38	2.72	0.59	134.0
		10	38	8.06	0.70	53.9
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	38	0.93	0.08	56.3
		10	38	1.28	0.09	45.5
		30	0	--	--	--
Chlorophyll *a*	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	28	3.53	0.26	38.9
Sulfite Waste Liquor	Pearl Benson Index	0	11	3.60[b]	1.37	44.5
		10	6	2.71[b]	1.58	63.3
		30	0	--	--	--
Fecal[a] Coliform Bacteria	No./100 mL	0	39	1.92[b]	1.26	128.5
		10	6	3.52[b]	1.69	57.7
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-5. CITY WATERWAY STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	44	23.33	0.44	12.4
		10	35	28.43	0.09	1.8
		30	0	--	--	--
Water Temperature	^oC	0	42	12.57	0.27	13.9
		10	33	10.97	0.26	13.5
		30	0	--	--	--
Dissolved Oxygen	mg/L	0	37	9.44	0.30	19.4
		10	29	9.08	0.25	14.6
		30	0	--	--	--
Dissolved Oxygen Saturation	Percent	0	37	104.53	3.42	19.9
		10	29	100.71	2.75	14.7
		30	0	--	--	--
Nitrate[a]	ug-at/L	0	36	14.14	0.93	39.3
		10	35	15.97	0.86	32.0
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	36	1.41	0.11	47.5
		10	35	1.44	0.12	48.2
		30	0	--	--	--
Chlorophyll a	ug/L	0	13	4.76	1.57	118.5
		10	13	1.78	0.41	82.8
		30	0	--	--	--
Secchi Depth	m	--	25	2.89	0.25	43.9
Sulfite Waste Liquor	Pearl Benson Index	0	40	4.74[b]	1.21	39.9
		10	30	2.43[b]	1.19	62.0
		30	1	5.00[b]	--	--
Fecal[a] Coliform Bacteria	No./100 mL	0	36	13.79[b]	1.34	28.2
		10	7	1.57[b]	1.19	69.3
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-6. CARR INLET STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	86	28.58	0.06	2.0
		10	84	28.80	0.05	1.5
		30	74	28.84	0.05	1.5
Water Temperature	°C	0	87	13.88	0.28	19.1
		10	84	11.54	0.17	13.3
		30	74	10.86	0.18	14.5
Dissolved Oxygen	mg/L	0	80	11.14	0.24	19.4
		10	77	9.56	0.20	18.1
		30	68	8.41	0.16	15.3
Dissolved Oxygen Saturation	Percent	0	79	128.47	2.63	18.2
		10	76	105.33	2.03	16.8
		30	67	91.36	1.59	14.2
Nitrate[a]	ug-at/L	0	50	3.61	0.83	140.0
		10	36	10.65	0.75	42.1
		30	36	14.63	0.75	30.6
Phosphate[a]	ug-at/L	0	69	0.89	0.05	50.7
		10	68	1.36	0.06	34.5
		30	64	1.57	0.06	31.2
Chloro-phyll _a_	ug/L	0	10	2.20	0.87	125.6
		10	10	5.18	1.51	92.2
		30	10	0.99	0.29	91.8
Secchi Depth	m	--	31	6.22	0.50	44.4
Sulfite Waste Liquor	Pearl Benson Index	0	5	3.62[b]	1.38	34.6
		10	2	0.00[b]	--	--
		30	2	2.24[b]	2.24	78.5
Fecal[a] Coliform Bacteria	No./100 mL	0	37	1.11	1.05	93.1
		10	0	--	--	--
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-7. NISQUALLY REACH STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	84	26.42	0.38	13.2
		10	57	28.67	0.07	1.8
		30	19	29.10	0.08	1.2
Water Temperature	°C	0	85	12.64	0.22	16.3
		10	57	11.87	0.23	14.3
		30	18	10.94	0.35	13.7
Dissolved Oxygen	mg/L	0	78	9.49	0.16	14.5
		10	51	8.97	0.14	11.3
		30	19	8.10	0.17	9.1
Dissolved Oxygen Saturation	Percent	0	77	105.61	1.85	15.4
		10	50	100.16	1.68	11.9
		30	18	87.11	1.50	7.3
Nitrate[a]	ug-at/L	0	37	10.79	0.64	36.3
		10	36	12.89	0.77	35.9
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	61	1.38	0.06	31.1
		10	51	1.50	0.06	29.9
		30	13	1.76	0.10	21.4
Chlorophyll _a_	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	31	6.51	0.48	41.2
Sulfite Waste Liquor	Pearl Benson Index	0	5	2.04[b]	1.55	74.6
		10	2	2.24[b]	2.24	78.4
		30	0	--	--	--
Fecal[a] Coliform Bacteria	No./100 mL	0	37	1.47[b]	1.12	83.1
		10	0	--	--	--
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-8. BUDD INLET STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	85	25.90	0.34	12.2
		10	60	27.95	0.26	7.1
		30	0	--	--	--
Water Temperature	°C	0	85	15.61	0.32	18.7
		10	59	12.96	0.23	13.5
		30	0	--	--	--
Dissolved Oxygen	mg/L	0	80	9.62	0.25	23.2
		10	59	7.93	0.31	29.6
		30	0	--	--	--
Dissolved Oxygen Saturation	Percent	0	79	114.62	3.26	25.3
		10	59	90.54	3.31	28.1
		30	0	--	--	--
Nitrate[a]	ug-at/L	0	61	1.95	0.29	115.1
		10	58	4.81	0.52	87.8
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	65	1.47	0.09	51.3
		10	57	1.51	0.10	51.7
		30	0	--	--	--
Chlorophyll *a*	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	50	3.11	0.21	48.6
Sulfite Waste Liquor	Pearl Benson Index	0	47	3.89[b]	1.11	32.5
		10	24	2.83[b]	1.22	52.7
		30	0	--	--	--
Fecal[a] Coliform Bacteria	No./100 mL	0	63	4.18[b]	1.26	100.3
		10	18	2.88[b]	1.39	79.6
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-9. TOTTEN INLET STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	80	27.91	0.08	2.5
		10	43	28.03	0.10	2.4
		30	0	--	--	--
Water Temperature	^oC	0	79	15.45	0.22	12.7
		10	41	14.47	0.29	12.9
		30	0	--	--	--
Dissolved Oxygen	mg/L	0	64	10.03	0.21	16.4
		10	40	10.15	0.21	13.3
		30	0	--	--	--
Dissolved Oxygen Saturation	Percent	0	63	120.16	2.44	16.1
		10	39	119.23	2.51	13.2
		30	0	--	--	--
Nitrate[a]	ug-at/L	0	31	1.77	0.38	119.8
		10	31	2.53	0.43	94.0
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	47	1.31	0.06	33.2
		10	40	1.37	0.07	33.0
		30	0	--	--	--
Chlorophyll a	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	43	4.26	0.23	35.3
Sulfite Waste Liquor	Pearl Benson Index	0	41	2.20[b]	1.10	53.0
		10	7	3.31[b]	1.12	31.4
		30	0	--	--	--
Fecal[a] Coliform Bacteria	No./100 mL	0	33	1.04[b]	1.03	97.1
		10	0	--	--	--
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-10. OAKLAND BAY STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	104	22.13	0.42	19.3
		10	28	25.45	0.25	5.2
		30	0	--	--	--
Water Temperature	°C	0	102	13.55	0.27	20.4
		10	28	12.82	0.47	19.3
		30	0	--	--	--
Dissolved Oxygen	mg/L	0	87	8.38	0.25	27.7
		10	27	9.85	0.28	14.7
		30	0	--	--	--
Dissolved Oxygen Saturation	Percent	0	81	92.44	2.97	28.9
		10	26	110.99	3.43	15.7
		30	0	--	--	--
Nitrate[a]	ug-at/L	0	43	4.62	0.66	93.0
		10	29	5.81	1.08	99.9
		30	0	--	--	--
Phosphate[a]	ug-at/L	0	38	1.19	0.07	36.8
		10	29	1.12	0.07	34.0
		30	0	--	--	--
Chlorophyll *a*	ug/L	0	21	2.31	0.17	34.5
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	53	2.84	0.10	24.6
Sulfite Waste Liquor	Pearl Benson Index	0	56	16.56[b]	1.25	19.5
		10	3	9.32[b]	1.45	12.8
		30	0	--	--	--
Fecal[a] Coliform Bacteria	No./100 mL	0	29	3.10[b]	1.25	61.5
		10	3	1.59[b]	1.26	67.5
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-11. DABOB BAY STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	66	26.63	0.19	5.7
		10	61	28.43	0.10	2.7
		30	61	29.25	0.08	2.2
Water Temperature	°C	0	65	14.03	0.37	21.3
		10	60	10.86	0.22	15.6
		30	60	9.26	0.13	11.0
Dissolved Oxygen	mg/L	0	64	10.45	0.20	15.2
		10	58	10.04	0.23	17.1
		30	58	7.22	0.19	20.2
Dissolved Oxygen Saturation	Percent	0	63	119.96	2.19	14.5
		10	58	109.85	2.74	19.0
		30	58	76.51	2.09	20.8
Nitrate[a]	ug-at/L	0	32	1.92	0.60	176.2
		10	33	5.69	1.16	117.4
		30	33	20.46	1.15	32.2
Phosphate[a]	ug-at/L	0	48	0.70	0.05	53.8
		10	49	1.19	0.09	54.9
		30	49	1.94	0.09	32.2
Chlorophyll _a_	ug/L	0	24	2.36	0.57	119.4
		10	24	4.12	0.84	99.5
		30	23	1.33	0.32	116.4
Secchi Depth	m	--	28	6.01	0.36	31.9
Sulfite Waste Liquor	Pearl Benson Index	0	6	1.26[b]	1.16	83.9
		10	2	1.00[b]	--	--
		30	2	2.24[b]	2.24	78.5
Fecal[a] Coliform Bacteria	No./100 mL	0	34	1.09[b]	1.04	94.2
		10	2	2.00[b]	--	--
		30	2	2.00[b]	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-12. MID-HOOD CANAL STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	55	25.03	0.30	9.0
		10	52	28.30	0.13	3.4
		30	52	29.04	0.15	3.7
Water Temperature	°C	0	55	14.94	0.35	17.6
		10	52	11.22	0.21	13.8
		30	52	9.57	0.15	11.5
Dissolved Oxygen	mg/L	0	52	10.06	0.18	12.8
		10	49	9.27	0.24	17.9
		30	49	6.82	0.22	23.0
Dissolved Oxygen Saturation	Percent	0	52	116.47	1.78	11.2
		10	49	102.02	2.03	20.1
		30	49	72.69	2.46	23.7
Nitrate[a]	ug-at/L	0	29	1.43	0.33	125.4
		10	29	6.55	1.32	108.9
		30	29	22.28	1.24	30.0
Phosphate[a]	ug-at/L	0	41	0.73	0.07	56.9
		10	41	1.27	0.10	48.6
		30	39	2.01	0.10	30.3
Chlorophyll a	ug/L	0	1	2.70	--	--
		10	1	3.10	--	--
		30	1	1.00	--	--
Secchi Depth	m	--	25	6.01	0.27	22.5
Sulfite Waste Liquor	Pearl Benson Index	0	5	1.90[b]	1.48	73.6
		10	3	1.71[b]	1.71	85.1
		30	3	0.00[b]	0.00	0.0
Fecal[a] Coliform Bacteria	No./100 mL	0	29	1.14[b]	1.06	91.1
		10	0	--	--	--
		30	0	--	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

TABLE E-13. SOUTH HOOD CANAL STUDY AREA

Variable	Units	Depth (m)	No. Obs.	Mean	Standard Error	Coeff. Variation (Percent)
Salinity	ppt	0	84	23.56	0.23	8.8
		10	74	28.32	0.12	3.5
		30	59	29.19	0.07	1.8
Water Temperature	°C	0	82	14.38	0.35	21.9
		10	74	10.44	0.19	15.7
		30	59	9.46	0.14	11.0
Dissolved Oxygen	mg/L	0	81	10.14	0.14	12.2
		10	71	7.39	0.31	35.1
		30	57	4.31	0.22	38.5
Dissolved Oxygen Saturation	Percent	0	79	115.21	1.34	10.3
		10	71	80.31	3.53	37.1
		30	57	45.93	2.32	38.1
Nitrate[a]	ug-at/L	0	40	1.75	0.74	266.6
		10	40	12.97	1.53	74.7
		30	40	26.98	0.85	20.0
Phosphate[a]	ug-at/L	0	66	0.84	0.06	56.9
		10	62	2.12	0.11	43.6
		30	54	2.90	0.11	27.6
Chlorophyll a	ug/L	0	0	--	--	--
		10	0	--	--	--
		30	0	--	--	--
Secchi Depth	m	--	33	4.79	0.28	32.9
Sulfite Waste Liquor	Pearl Benson Index	0	11	2.30[b]	1.36	68.8
		10	7	3.43[b]	1.39	40.5
		30	7	2.48[b]	1.60	78.8
Fecal[a] Coliform Bacteria	No./100 mL	0	40	1.48[b]	1.12	84.2
		10	3	2.00[b]	--	--
		30	3	2.00[b]	--	--

[a] The database contains values that are the actual analytical detection limits for samples that did not contain detectable amounts of nitrate, phosphate, or fecal coliform bacteria. Therefore, the means presented in Appendix E may overestimate the actual means, particularly for depths and locations where the value of the variable in question typically was at or near the analytical detection limit.

[b] Geometric mean.

APPENDIX F

SUMMARY OF CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES

TABLE F-1. PEARSON PRODUCT-MOMENT CORRELATION COEEFFICIENTS BETWEEN WATER QUALITY VAIRABLES IN THE BELLINGHAM BAY STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	-0.28[a]	0.31	ns[b]	ns	0.38	ns
Water Temp.		-0.31	ns	ns	ns	ns
Diss. Oxygen			ns	ns	0.96	ns
Nitrate				0.52	ns	ns
Phosphate					ns	0.61
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	ns	ns
Water Temp.		ns	-0.71	ns
Diss. Oxygen			ns	ns
Nitrate				ns

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	0.62	ns
Water Temp.		ns	ns	0.55
Diss. Oxygen			ns	ns
Nitrate				ns

[a] Numerical table entries are statistically significant ($P<0.05$ scaled with the Bonferroni inequality) correlation coefficients.

[b] ns = Not statistically significant ($P>0.05$ scaled with the Bonferroni inequality).

TABLE F-2. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE PORT GARDNER STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	-0.53[a]	ns[b]	ns	ns	ns	ns
Water Temp.		ns	-0.60	-0.47	ns	ns
Diss. Oxygen			ns	ns	0.96	ns
Nitrate				0.53	ns	ns
Phosphate					ns	0.68
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	ns	0.49
Water Temp.		ns	-0.60	ns
Diss. Oxygen			ns	ns
Nitrate				ns

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Phosphate
Salinity	ns	ns	ns
Water Temp.		ns	ns
Diss. Oxygen			ns

[a] Numerical table entries are statistically significant ($P<0.05$ scaled with the Bonferroni inequality) correlation coefficients.

[b] ns = Not statistically significant ($P>0.05$ scaled with the Bonferroni inequality).

TABLE F-3. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE POINT JEFFERSON STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Phosphate	Diss. Oxy. Sat.	Chlor. a	Secchi Disk Depth
Salinity	-0.33[a]	-0.30	0.60	-0.28	ns[b]	0.20
Water Temp.		0.15	-0.59	0.35	ns	ns
Diss. Oxygen			-0.78	0.92	0.54	-0.59
Phosphate				-0.81	ns	ns
Dissolved Oxygen Saturation					0.50	-0.59
Chlor. a						-0.58

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Phosphate
Salinity	-0.24	-0.39	ns
Water Temp.		ns	ns
Diss. Oxygen			-0.63

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Phosphate
Salinity	ns	-0.20	ns
Water Temp.		-0.39	ns
Diss. Oxygen			ns

Depth: 100 m

	Water Temp.	Dissolved Oxygen
Salinity	ns	ns
Water Temp.		-0.52

TABLE F-3. (Continued)

Depth: 150 m

	Water Temp.	Dissolved Oxygen
Salinity	ns	-0.40
Water Temp.		-0.38

Depth: 200 m

	Water Temp.	Dissolved Oxygen
Salinity	ns	ns
Water Temp.		-0.56

[a] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

[b] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

TABLE F-4. PEARSON PRODUCT-MOMENT CORRELATION COEEFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE SINCLAIR INLET STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	ns[a]	ns	ns	ns	ns	ns
Water Temp.		ns	ns	ns	ns	ns
Diss. Oxygen			-0.46[b]	ns	0.96	ns
Nitrate				ns	-0.61	ns
Phosphate					ns	ns
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	ns	ns
Water Temp.		ns	-0.47	ns
Diss. Oxygen			ns	ns
Nitrate				ns

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

TABLE F-5. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE CITY WATERWAY STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Chlor. a	Secchi Disk Depth
Salinity	-0.40[a]	ns[b]	ns	ns	ns	ns	0.52
Water Temp.		ns	-0.45	ns	ns	ns	-0.63
Diss. Oxygen			ns	ns	0.98	ns	ns
Nitrate				ns	ns	ns	ns
Phosphate					ns	ns	ns
Dissolved Oxygen Saturation						ns	ns
Chlor. a							ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Chlor. a
Salinity	ns	ns	ns	0.46	ns
Water Temp.		ns	ns	ns	ns
Diss. Oxygen			ns	ns	ns
Nitrate				ns	ns
Phosphate					ns

[a] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

[b] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

TABLE F-6. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE CARR INLET STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Chlor. a	Secchi Disk Depth
Salinity	ns[a]	ns	ns	0.49[b]	ns	ns	ns
Water Temp.		ns	ns	ns	ns	ns	ns
Diss. Oxygen			ns	-0.49	0.96	ns	ns
Nitrate				ns	-0.53	ns	ns
Phosphate					-0.56	ns	ns
Dissolved Oxygen Saturation						ns	ns
Chlor. a							ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Chlor. a
Salinity	0.36	-0.56	ns	ns	ns
Water Temp.		-0.48	ns	ns	ns
Diss. Oxygen			ns	ns	ns
Nitrate				ns	ns
Phosphate					ns

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Chlor. a
Salinity	ns	-0.55	ns	0.45	ns
Water Temp.		-0.52	ns	ns	ns
Diss. Oxygen			ns	ns	ns
Nitrate				ns	ns
Phosphate					ns

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

TABLE F-7. PEARSON PRODUCT-MOMENT CORRELATION COEEFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE NISQUALLY REACH STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	ns[a]	ns	ns	0.38	ns	0.50
Water Temp.		ns	-0.44[b]	ns	0.31	ns
Diss. Oxygen			ns	ns	0.93	ns
Nitrate				ns	ns	ns
Phosphate					ns	ns
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	ns	ns
Water Temp.		ns	ns	ns
Diss. Oxygen			ns	ns
Nitrate				ns

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	0.61	ns	ns	ns
Water Temp.		-0.61	ns	ns
Diss. Oxygen			ns	ns
Nitrate				ns

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 sclaed with the Bonferroni inequality) correlation coefficients.

TABLE F-8. PEARSON PRODUCT-MOMENT CORRELATION COEEFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE BUDD INLET STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	ns[a]	ns	ns	ns	ns	ns
Water Temp.		ns	-0.38[b]	ns	0.31	ns
Diss. Oxygen			ns	ns	0.97	ns
Nitrate				ns	ns	0.47
Phosphate					ns	ns
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	ns	ns
Water Temp.		-0.51	-0.48	ns
Diss. Oxygen			0.39	ns
Nitrate				ns

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

TABLE F-9. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE TOTTEN INLET STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	0.57[a]	ns[b]	ns	0.47	ns	ns
Water Temp.		ns	ns	ns	ns	ns
Diss. Oxygen			ns	ns	0.96	ns
Nitrate				ns	ns	ns
Phosphate					ns	ns
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	0.77	ns	ns	0.42
Water Temp.		ns	ns	0.43
Diss. Oxygen			ns	ns
Nitrate				ns

[a] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

[b] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

TABLE F-10. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE OAKLAND BAY STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	ns[a]	ns	ns	ns	ns	ns
Water Temp.		-0.33[b]	ns	ns	ns	ns
Diss. Oxygen			ns	ns	0.97	ns
Nitrate				ns	ns	ns
Phosphate					ns	0.68
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	0.72	ns	ns	ns
Water Temp.		ns	ns	ns
Diss. Oxygen			ns	ns
Nitrate				ns

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

TABLE F-11. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE DABOB BAY STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Chlor. a	Secchi Disk Depth
Salinity	-0.38[a]	ns[b]	ns	ns	ns	ns	ns
Water Temp.		-0.38	ns	ns	ns	ns	ns
Diss. Oxygen			ns	ns	0.92	0.67	-0.53
Nitrate				0.69	ns	ns	ns
Phosphate					ns	ns	ns
Dissolved Oxygen Saturation						0.57	ns
Chlor. a							-0.53

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Chlor. a
Salinity	-0.34	-0.39	ns	ns	ns
Water Temp.		ns	-0.49	ns	ns
Diss. Oxygen			-0.60	-0.69	ns
Nitrate				0.54	ns
Phosphate					ns

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Chlor. a
Salinity	-0.34	ns	ns	ns	ns
Water Temp.		ns	ns	ns	ns
Diss. Oxygen			-0.46	-0.47	ns
Nitrate				0.44	ns
Phosphate					ns

[a] Numerical table entries are statistically significant (P<0.05 scaled with the Bonferroni inequality) correlation coefficients.

[b] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

TABLE F-12. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE MID-HOOD CANAL STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	ns[a]	ns	ns	ns	ns	ns
Water Temp.		-0.56[b]	-0.50	ns	ns	0.55
Diss. Oxygen			ns	ns	0.92	ns
Nitrate				ns	ns	ns
Phosphate					ns	ns
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	-0.57	ns	0.41
Water Temp.		0.52	-0.70	-0.52
Diss. Oxygen			-0.76	-0.49
Nitrate				0.52

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	-0.45	-0.54	0.61	ns
Water Temp.		ns	ns	ns
Diss. Oxygen			-0.48	ns
Nitrate				0.50

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 sclaed with the Bonferroni inequality) correlation coefficients.

TABLE F-13. PEARSON PRODUCT-MOMENT CORRELATION COEFFICIENTS BETWEEN WATER QUALITY VARIABLES IN THE SOUTH HOOD CANAL STUDY AREA

Depth: 0 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate	Diss. Oxy. Sat.	Secchi Disk Depth
Salinity	ns[a]	ns	ns	ns	ns	ns
Water Temp.		-0.50[b]	ns	ns	ns	ns
Diss. Oxygen			ns	ns	0.85	ns
Nitrate				ns	ns	ns
Phosphate					ns	ns
Dissolved Oxygen Saturation						ns

Depth: 10 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	-0.44	-0.53	0.41	0.49
Water Temp.		0.45	-0.52	ns
Diss. Oxygen			-0.62	-0.47
Nitrate				0.62

Depth: 30 m

	Water Temp.	Dissolved Oxygen	Nitrate	Phosphate
Salinity	ns	ns	ns	ns
Water Temp.		-0.33	ns	ns
Diss. Oxygen			ns	-0.39
Nitrate				ns

[a] ns = Not statistically significant (P>0.05 scaled with the Bonferroni inequality).

[b] Numerical table entries are statistically significant (P<0.05 sclaed with the Bonferroni inequality) correlation coefficients.

* U.S. GOVERNMENT PRINTING OFFICE 1988; 523-243/00453