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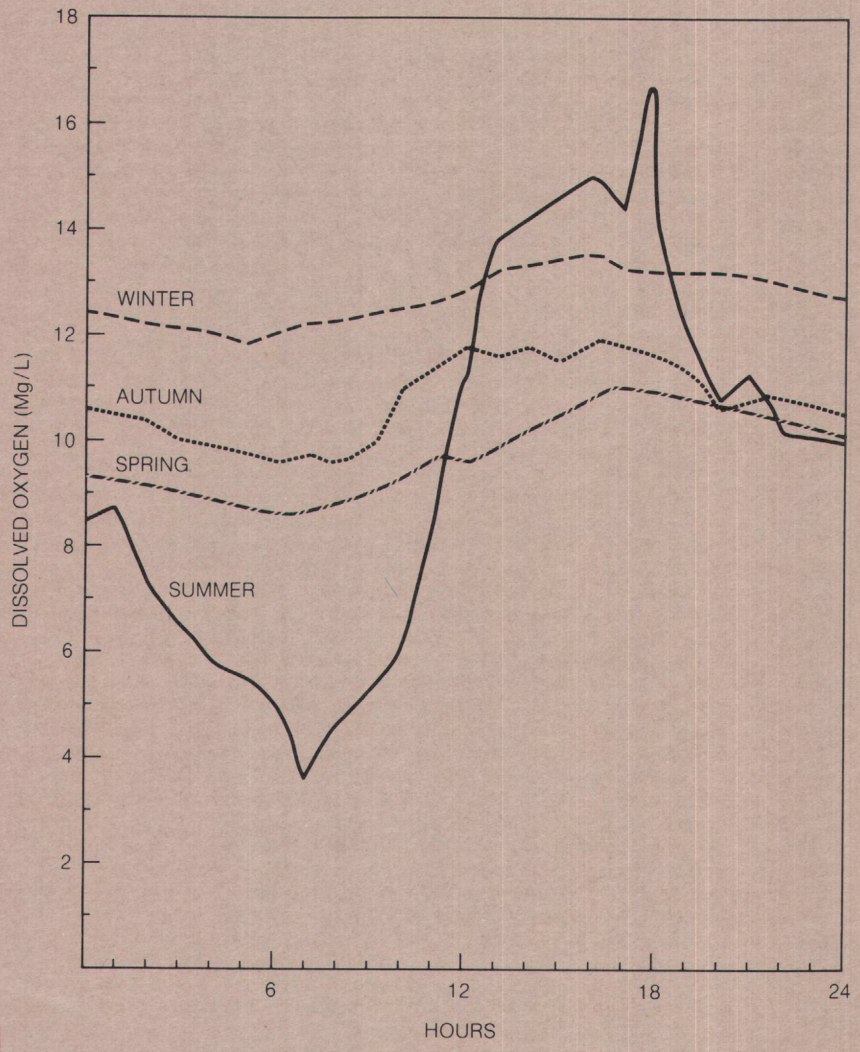
DIEL OXYGEN VARIATIONS IN THE RHODE RIVER ESTUARY, MARYLAND, 1970-1978



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CONTENTS

	Page
Abstract	1
Introduction	1
Materials & Methods	3
Results & Discussion	4
Summary & Conclusions	12
Acknowledgements	13
Literature Cited	13

ILLUSTRATIONS

Page

Figure 1. Map showing location of monitor 2

2. Hydroclimagraphs of water temperature vs. salinity. 5

3. Typical diel oxygen curves. 6

4. Daily change and maximum and minimum of dissolved oxygen 7

5. Quarterly average of temperature, oxygen and salinity 9

TABLES

Table 1. Nine year averages of temperature, salinity and oxygen 10

2. Temperature, salinity and oxygen correlations. 11

Abstract

Since April 1970 the U.S. Geological Survey has operated an estuarine water quality monitor in the upper reach of Rhode River, a small embayment on the northwestern shore of Chesapeake Bay. This report analyzes variations in diel oxygen over the period April 1970 through January 1979. The diel oxygen range is used as an indicator of open-water metabolism. Polygons of temperature versus salinity portray the monthly variations of the two dominant environmental factors which influence biological metabolism and reveal effects of events such as a cool versus a warm spring or salinity reduction due to tropical storm freshwater runoff. Seasonally the average daily oxygen pulse range increased from a winter low of 1.6 mg/L to summer high of 5.3 mg/L. Annually highest daily ranges occurred the summer of 1972 when nutrient laden runoff from tropical storm Agnes stimulated open-water metabolism to produce an average diel range of 6.3 mg/L. Spearman's ranked correlation coefficients were used to compare seasonal and annual variations in temperature and salinity versus diel oxygen range. There was high agreement between annual variations in spring temperatures and diel oxygen ranges and an inverse correlation between summer and autumn salinity and diel oxygen range.

Introduction

The Rhode River Estuary (Fig. 1.) is an embayment on the northwest shore of Chesapeake Bay, about 11 km south of Annapolis, Maryland. The estuary, adjacent waters and surrounding land mass have been under scientific scrutiny since 1967 following establishment of the Smithsonian's Chesapeake Bay Center for Environmental Studies.

From April 1970 to the present the authors have been responsible for the operation of a U.S. Geological Survey (USGS) water-quality monitor. The monitor, located at the end of the Smithsonian Institution's pier continuously measures temperature, salinity/conductivity, dissolved oxygen, hydrogen ion activity (pH), turbidity, tide stage and solar radiation. The principal purpose of the monitor's operation is to furnish baseline water-quality information in support of the Chesapeake Bay Center's ecosystem studies. A second purpose is to obtain diel oxygen curves with coincident temperatures and salinities to estimate daily values of open-water metabolism. Using Odum's method of diurnal oxygen analysis (Odum 1956) Cory (1975 and 1978) published reports on one year and then 5 years of estimates of production and respiration for the Rhode River estuary. Whereas a number of estimates of open-water metabolism are available in a variety of environments (Odum and Hoskin 1958; Odum and others 1959; Odum and Wilson 1962; Copeland and Dorris 1962; Cooke 1967; Manny and Hall 1969; Eley 1970; Kelly 1971; and Kelly and others 1974) repetitive collection of long-term metabolism data is rare. Odum (1967) combined nearly five years of single station metabolism analyses to construct annual curves for two Texas bays. Nixon and others (1976) using widely spaced single day analyses measured annual metabolism in a shallow marsh embayment; Cory (1974) using "selected" days typical of daily oxygen pulses, estimated Patuxent River

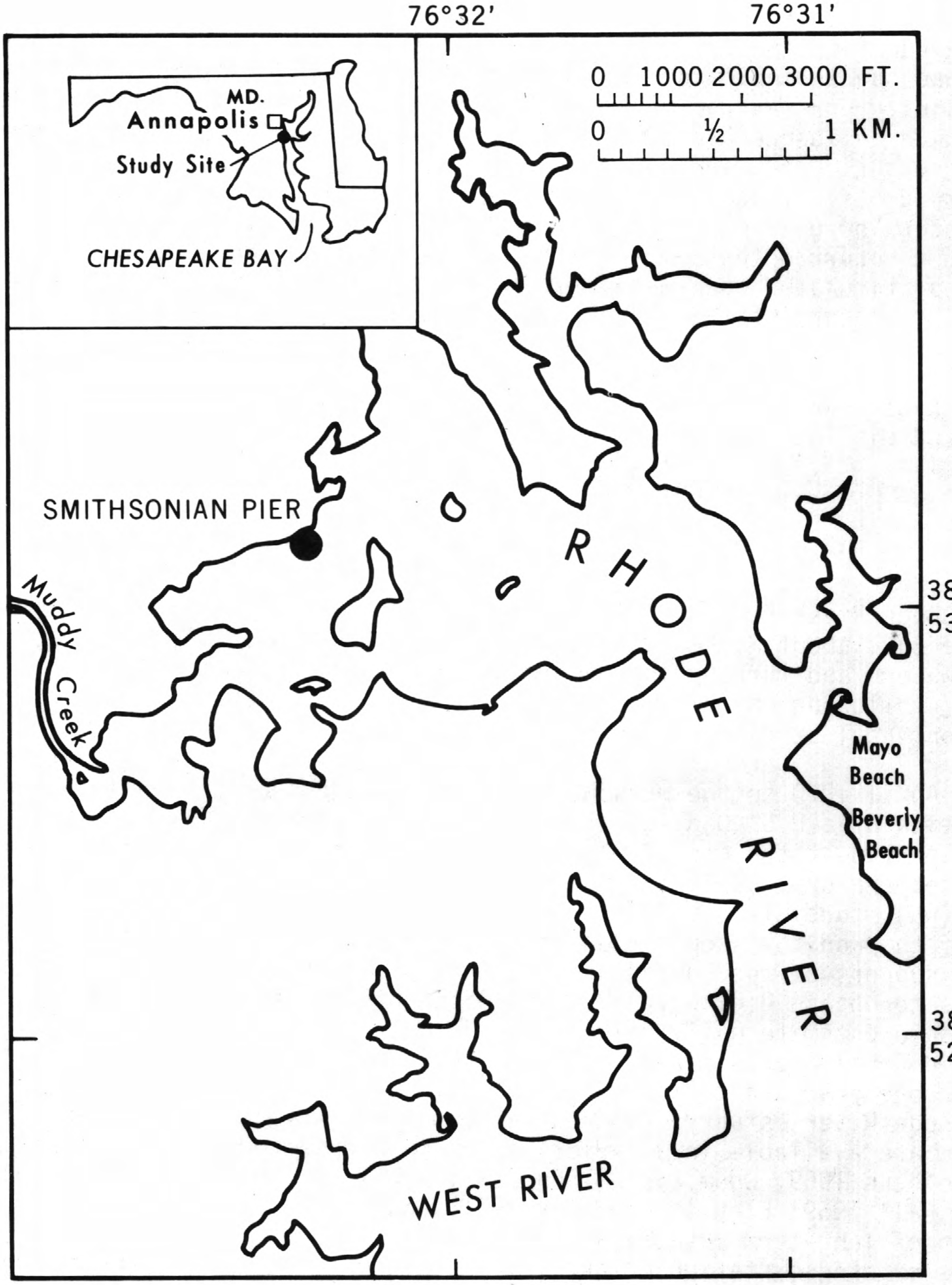

Fig. 1. Rhode River estuary, Maryland. U.S. Geological Survey water quality monitor located at Smithsonian Institution's pier.

metabolism over a six year period through 1969; and Cory (1975 and 1978) reported on 1 year and then five years of daily metabolism estimates for the Rhode River estuary.

In this paper, instead of estimating daily metabolism (production and respiration) daily oxygen pulses were analyzed, that is, daily maximum and minimum for a nine - year period, 1970 through 1978. This method of analysis was chosen because the data were readily available in published reports (Cory and others 1975; Cory 1977 and Cory and Dresler 1980), the correlation between daily pulse and open-water metabolic activity was well established (Cory 1975 and 1978) and the procedures based on 2 time intervals per day offered considerable savings in analytical time as compared to hourly or bi-hourly values for the metabolic estimates. The nine year period of record was sufficiently long to permit a correlation analysis of the seasonal change in oxygen pulse (metabolism) with that of water temperature and salinity.

Materials and Methods

From April 1970 to December 1978 water quality data were collected in Rhode River estuary (lat. 24°38.5'N, long. 76°32.3). At 50 meters from shore the pumped water sample was taken from a constant depth of 1.0 m from the water surface in water that averaged about 2.0 m in depth. The monitoring site is located about 1.2 km below the mouth of Muddy Creek, the principal stream entering the estuary. Water quality in the Rhode River estuary is principally controlled by the upper Chesapeake Bay waters. Except during high spring runoff, Muddy Creek exerts little influence on water quality at the monitor station (Han 1975).

The tidal waters sampled are largely confined to a semi-enclosed basin with a mean depth of 1.2m, a surface area of 8.1×10^5 m^2 and a volume of 9.7×10^5 m^3. The shoreline is bordered by trees and the basin is surrounded by slightly elevated land masses which reduce wind speed and damped wave action. The twice daily tidal change (0.5m) produces little vertical turblence as the waters move sluggishly back and forth past the monitor station. The conditions are favorable for monitoring dissolved oxygen as the surface diffusion rates are slow and surface-area-to-volume ratios are such that over 80 percent of the daily changes in oxygen are believed due to biological metabolism (Cory 1975). Most of the data were collected with a Honeywell, Inc.* water quality monitoring system which employs a polargraphic oxygen probe, thermo-couple for temperature, and temperature conpensated conductance cell for salinity. Data were strip chart recorded in sequence with six data points per hour for each variable.

The nine years of daily oxygen differences used in this report were obtained by substracting the observed weekly average of daily minimum values from the weekly average of daily maximum values. These figures closely approximated those which have been obtained by using daily values and greatly reduced the work load for the eight years of analysis. Temperature - salinity values used for the hydroclimagraphs are monthly averages of the daily maximum and minimum values. The above data are tabulated by daily and weekly increments in the data reports cited above.

*The use of named products in this report is for identification only and does not imply endorsement by the U.S. Geological Survey.

Results and Discussion

Water temperature and salinity are two of the dominant environmental factors controlling the biological systems of the Rhode River estuary. Seasonal variations of water temperature and bay salinity are pronounced. The seasonal patterns of both are strongly influenced by the modified continental climate that prevails over the upper Chesapeake region. Polygons or hydroclimagraphs of monthly average temperature versus salinity (Fig. 2) portray the seasonal as well as annual differences for each of the eight years studied. An average or typical year appears to be one where monthly average temperature ranges from a January/February low of about 2°C to a July/August high of 29°C and average salinity ranges from a spring low of 6 to an autumn high of 12 parts per thousand (ppt). Tropical storms yielding copious rainfall struck the area in 1972 and 1975. In June 1972, fresh water from tropical storm Agnes affected the entire Chesapeake Bay drainage area causing many short-term changes in the ecological system of the bay. The effects of the storm on the bay was the subject of a symposium (Chesapeake Research Consortium, Inc. 1976). In the symposium Cory and Redding (1976) and Loftus and Seliger (1976) reported significant increases in metabolism and phytoplankton productivity in the Rhode and West Rivers which they attributed to the storm's effect.

By way of comparison, fresh water runoff from tropical storm Eloise in early October produced an odd shaped hydroclimagraph and seemed to have little effect on the ecosystem of the bay. The difference appears to be that the early summer 1972 storm took place when temperatures were increasing to a maximum and fresh water runoff caused further reduction in salinity at the time of normal low salinity whereas the autumn 1975 storm came during a period of declining temperatures and the freshening effect of the runoff was offset by the seasonally higher bay salinity.

The magnitude of the daily dissolved oxygen pulse followed a distinct seasonal pattern (Fig. 3). The daily curves shown are reproduced from the monitor's analog chart and are typical seasonal patterns. There is of course a great deal of day-to-day variation in daily dissolved oxygen patterns depending on local weather conditions. Principal among the meteorologic factors affecting the variations is solar radiation, the driving force for growth in the phytoplankton dominated system. If there is any doubt the daily oxygen pulses are due to metabolic activity note that all of the curves show a consistent diel pattern with an early morning minimum, afternoon maximum and decline during periods of darkness. Deviations from these patterns caused by tidal movements of water with differing metabolic history are usually slight and the diel effect is independent of the phase of the tide cycle. Similar diel patterns occur throughout the Rhode and West Rivers and adjacent bay waters (Cory 1975).

The daily oxygen pulse averaged by weekly increments annually varies from winter low values of about 1 mg/L to summer highs of about 10 mg/L (Fig. 4A). Dissolved oxygen portrayed by weekly averages of the daily maximum and minimum values varies seasonally with minimum values declining from winter highs to summer lows. Plots shown in Figures 4A and B are from 1972. Although the plots typify the seasonal cycle which annually occurs at the monitor site it was an unusual year in that post tropical storm Agnes metabolism (after week 25) as indicated by the daily oxygen pulse was the greatest observed over the nine year period. On several occasions high daytime oxygen production was followed by equally large nighttime respiration which caused waters at the monitor site

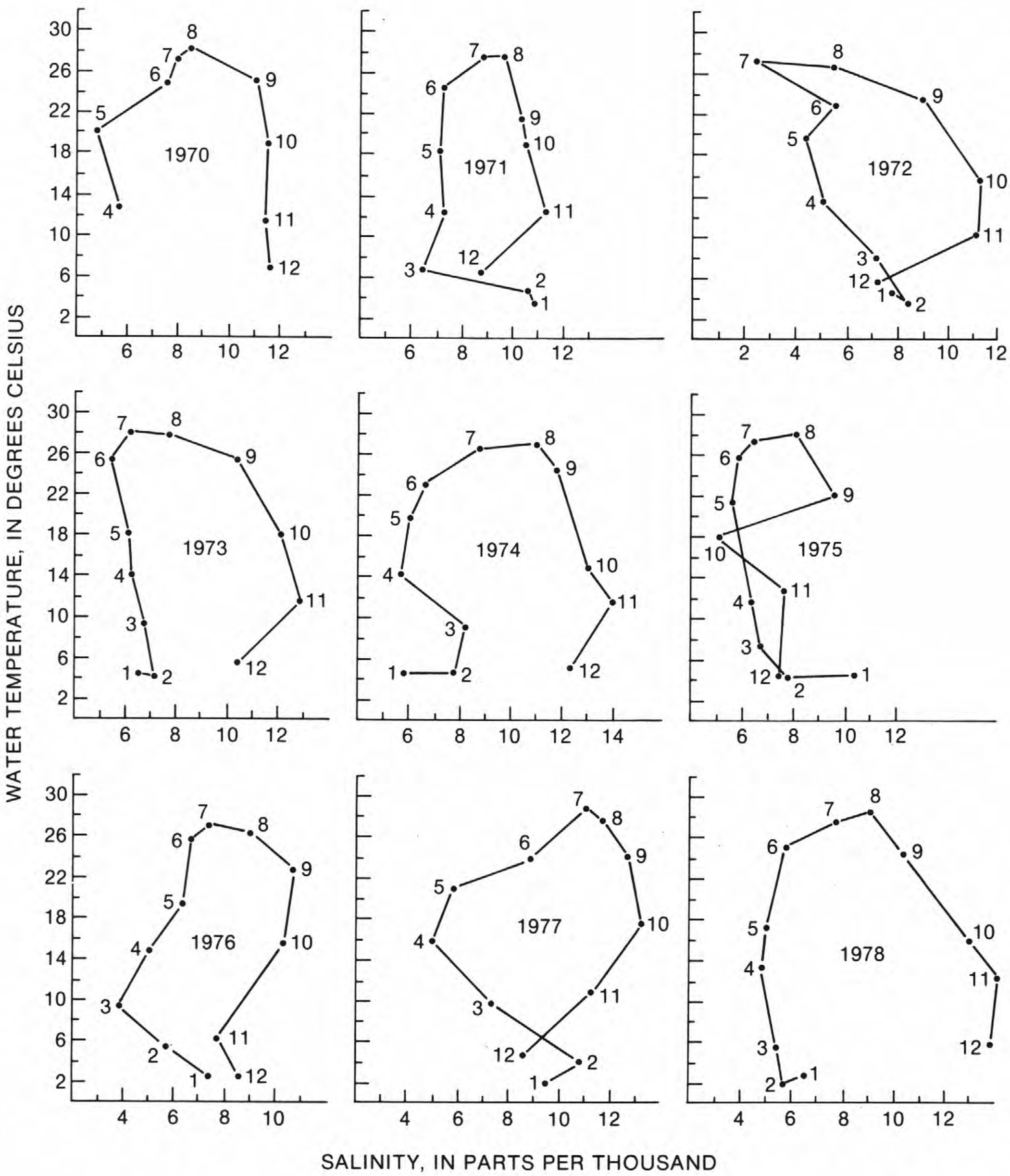

Fig. 2. Hydroclimagraphs of water temperature versus salinity at 1 meter depth. Smithsonian Pier, Rhode River, Maryland. Numbers indicate months and the dots are monthly averages of daily maxima and minima.

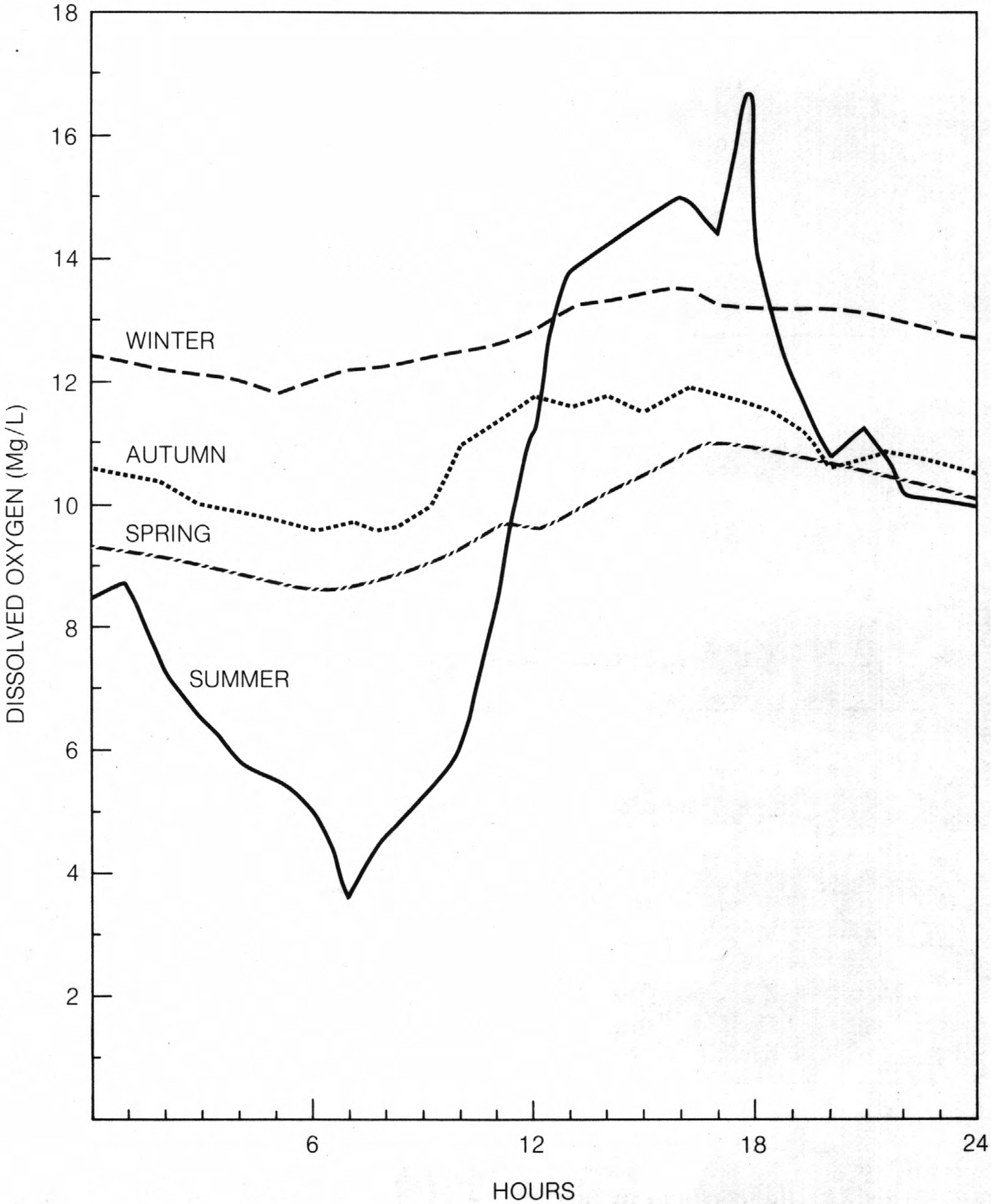

Fig. 3. Typical diel oxygen curves reproduced from U.S.G.S. water quality monitor record Rhode River, Maryland

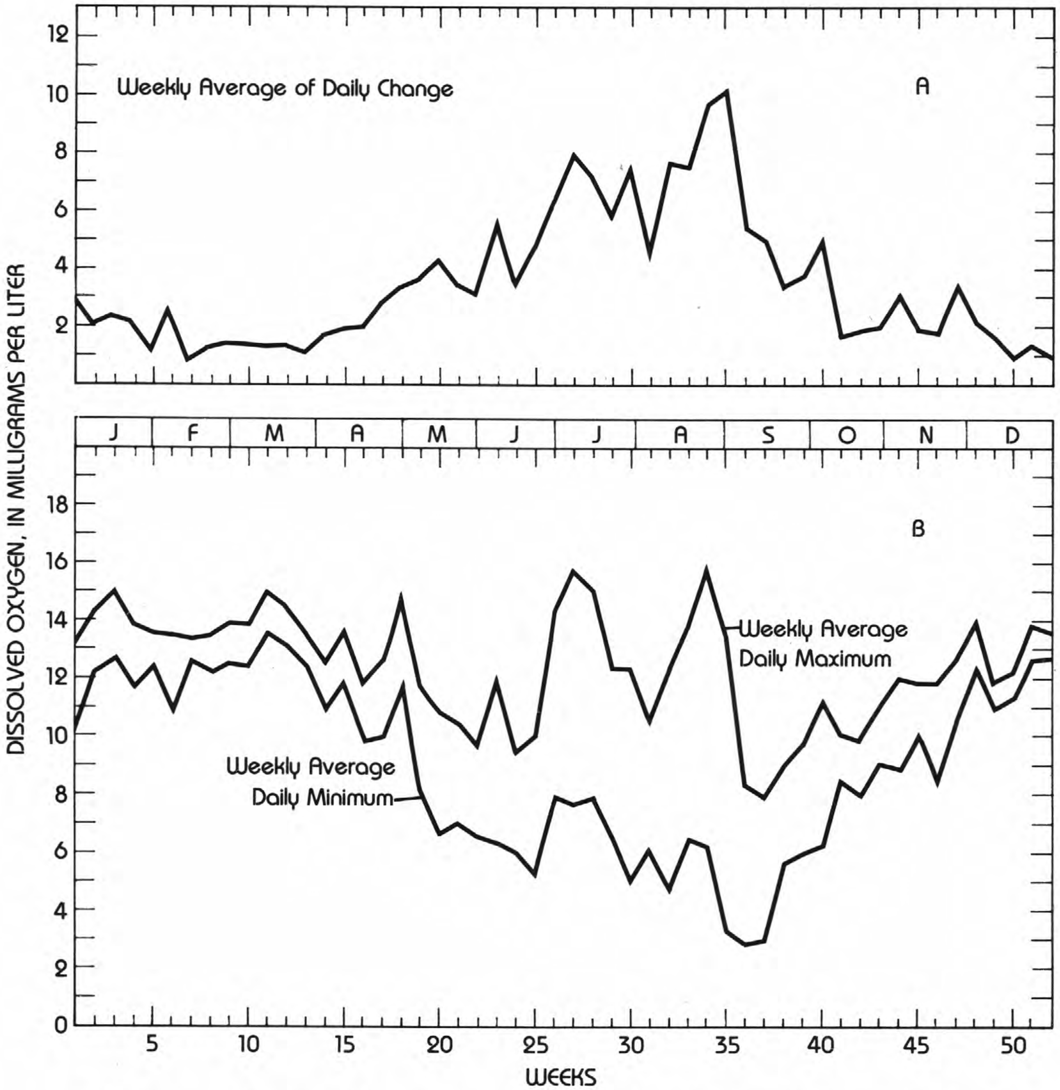

Fig. 4. (A) Weekly average of daily change in oxygen from early morning low to afternoon high. (B) Weekly average of daily maximum and minimum dissolved oxygen. Data from USGS water quality monitor of Rhode River Estuary for year 1972.

to become anaerobic during early morning hours. During the same time excessive phytoplankton growth elsewhere in the estuary, acting like an oxygen pump, created surface values in excess of 200 percent saturation. The result of these high surface values, which persisted for rather long time periods, was a net loss of dissolved oxygen by surface diffusion from the water to the atomsphere. Bottom waters in the central channel of the Rhode River estuary during 1972 and again in 1973 became anaerobic for a period of about 3 weeks during late August and early September (Cory 1975).

Weekly increments of average daily range in dissolved oxygen and weekly average of daily temperature and salinity were grouped seasonally and portrayed by histograms for the study period (Fig. 5). From the hydroclimagraphs (Fig. 2) it can be seem that for seven of the eight years of complete annual record (records began 1970) monthly average temperatures were lowest in December, January and Febrary. These months were then designated winter and the seasons were evenly divided into groups of 13 weeks each. From Figure 5 it can be seen that seasonal average temperatures ranged form a 1978 winter low of 2.5°C to a 1975 summer high of 27.5°C; daily dissolved oxygen range varied from 1973 and 1975 winter lows of 1.0 mg/L to a 1972 high of 6.7 mg/L and seasonal average salinity ranged from a summer 1972 low of 4.5 ppt to an autumn high of 12.9 ppt.

In order to compare annual variations with "average" conditions, data from each of the yearly seasonal increments were averaged for the entire study period (Table 1). This information may prove useful when looking for long term changes in water quality. For example, the winter temperatures of 1977 and 1978 were distinctly cooler than average.

Continuing the assumption that daily oxygen range is a measure of metabolic activity, if seasoanl averages are summed and percentages calculated for each season, summer accounts for about 43 percent of the annual total, spring 23 percent, autumn 21 percent and winter only 13 percent. The summer average daily oxygen pulse of 1972 (Fig. 5) was the largest observed over the nine-year period and accounted for over 46 percent of the yearly total. As noted above, the after effects of tropical storm Agnes were credited with inducing the observed high primary productivity. The once-in-a-100-year flood event flushed an abundance of organic material and nutrients into Chesapeake Bay stimulating phytoplankton growth. In Rhode River an initial influx of storm water was accompanied by high turbidity, drifting logs, and debris and decreased daily metabolism (Cory and Redding 1976). In June, after the storm passed, several days of decreased metabolism were followed by developingpatches of intense phytoplankton blooms. These patches were made visible by a rusty discoloration of the water and as they drifted by the monitor's intake large pulses in the dissolved oxygen record also revealed their presence. After a day or two these patches coalesced into one large bloom which persisted through the remainder of the summer. The effects of the June 1972 storm pulse may have persisted for several years. In 1973, the year of the second highest average daily summer oxygen change, the system's bottom waters again became anaerobic. The daily summer pulse remained high until 1977 when it dropped below 5 mg/L daily range similar to values observed during the two years preceding 1972 (Fig. 5).

Temperature and salinity are two of the principal environmental factors controlling the biota in estuarine ecosystems. Water temperature, which is a measure of heat energy and is a function of absorbed radiant energy at the water

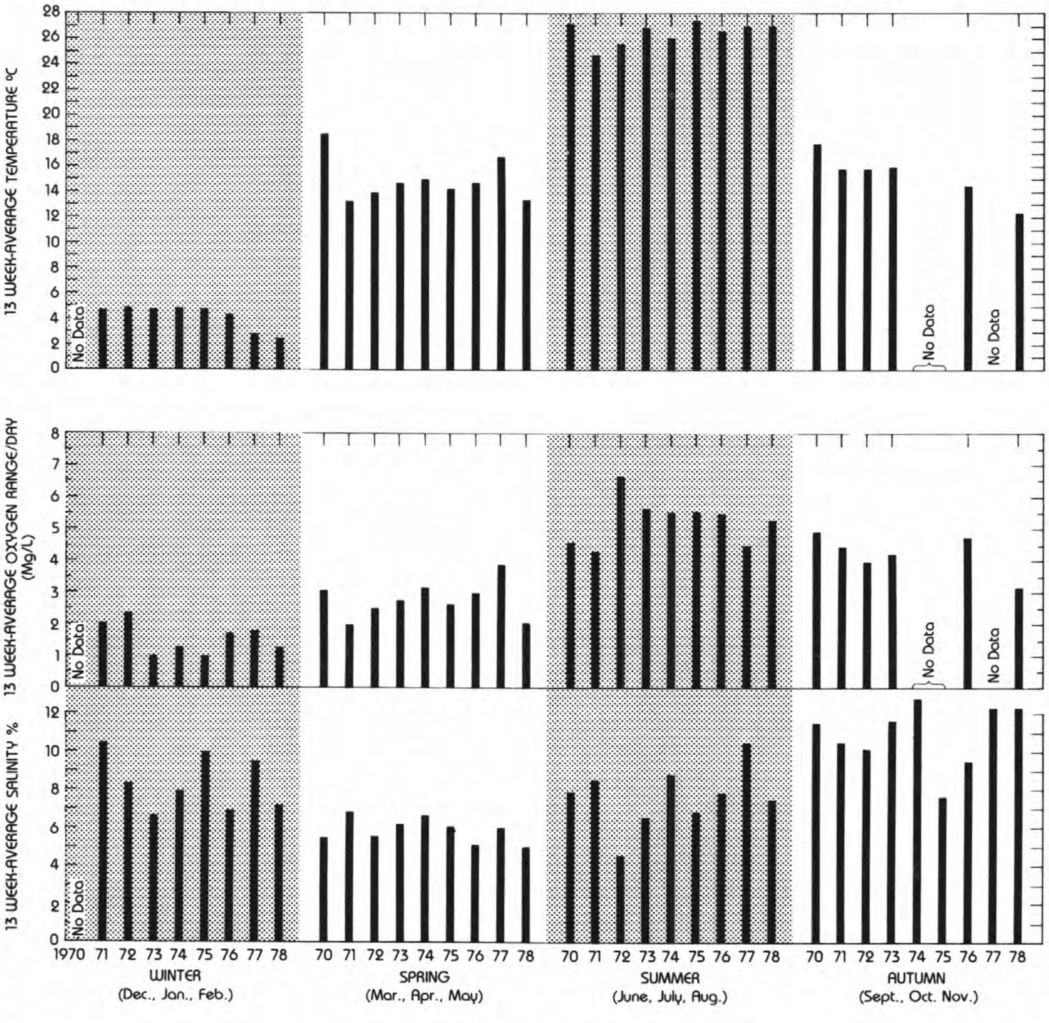

Fig. 5. Nine year summary of temperature, dissolved oxygen and salinity from the USGS water quality station Rhode River, Md.

surface is biologically one of the most significant factors controlling seasonal biotic fluctuations. Seasonal changes in the daily oxygen pulse are evident in the data graphed in Figures 3, 4A and 5 with minimum fluctuation during winter and maximum fluctuations in the summer and about equal changes in spring and autumn. A direct relationship seems to exist between seasonal temperature and open-water metabolism particularly when looking at yearly seasonal averages (Fig. 5). However, when comparing annual differences of seasonal averages, it is obvious that factors other than temperature are involved. In order to test correlations between annual seasonal differences in the daily oxygen pulse and temperature and salinity, ranked correlation coefficients were determined using

Table 1. Nine-year average of seasonal values of water temperature, daily dissolved oxygen range and salinity at the Rhode River water quality station.

Season	Temperature °C	Daily Oxygen Range mg/L	Salinity ppt
Winter (D,J,F)	4.18	1.64	8.46
Spring (M,A,M)	14.91	2.81	5.92
Summer (J,J,A)	26.34	5.33	7.62
Autumn (S,O,N)	15.37	2.56	10.94

Spearman's formula

$$r_s = 1 - 6 \frac{{}^{n}(R_1 - R_2)^2}{n\ (n^2 - 1)}$$

where R_1 and R_2 are paired variables, in this case oxygen pulse and temperature or oxygen pulse and salinity arranged by order of succeeding years (Sokal and Rohlf 1969). If the coefficient r_s is equal to 1.0 there is perfect agreement. Results of the test of oxygen difference versus temperature indicates high agreement (0.93) exists among annual fluctuations in spring average temperatures and average daily oxygen pulse (Table 2). There appears to be no agreement for the remaining seasons. It can be conjectured that because of low temperature the biotic system in winter is sluggish and slow to respond to outside stimuli such as increased light or nutrients. One need only observe the dinoflagellates which dominate the winter phytoplankton to understand this agrument. When observed directly from the cold water, cell movement is extremely sluggish; however, if allowed to warm to room temperature the minute organisms exhibit frenetic activity typical of their summertime counterparts. As radiant energy increases in spring, the temperature rises and with dissolved nutrients in abundance, phytoplankton readily respond to the favorable conditions and the daily oxygen

Table 2. Spearman's Ranked Correlation Coefficients

(1.0 = Perfect Agreement; 0.0 = No Agreement; -1.0 = Perfect Disagreement)

Season	O_2/Temp	O_2/Sal
Winter	0.12	.38
Spring	0.93	.08
Summer	-0.05	-.70
Autumn	-0.03	-.94

pulse begins to reflect their increased metabolism. In spring there is a lag between the warming of the surface waters and the warming of the underlying sediments. Consequently the open-water metabolism is probably less dependent on recycling of nutrients from the bottom muds and sedimented detritus than later in the season. It is during this period that daily oxygen production exceeds respiration and the entire water column becomes supersaturated with respect to air saturation and remains that way both day and night. Under these conditions variation in spring water temperature appears to have a controlling effect on the open-water metabolism (see Fig. 5 and Table 1).

In summer, the eutrophic estuarine ecosystem metabolizes at a high rate and water temperature is high enough or exceeds a point of temperature dependence so that it is no longer a controlling factor. Each day a vast amount of oxygen is released as a by-product of plant productivity and an equal or sometimes greater amount is consumed both day and night by respiration of plants and animals. In 1972, the year of highest average daily oxygen range, average summer temperatures were next to the lowest observed and as previously mentioned, the system probably was stimulated by the influx of nutrient laden runoff resulting from tropical storm Agnes.

In the autumn the correlation analysis again indicated no relationship between the metabolic activity and water temperature (Table 1). Because of equipment failures oxygen data were not collected in the autumn for the years 1974, 75, and 77 (Fig. 5); however, the indicated lack of direct correlation is probably correct. The normal seasonal pattern is for minimal streamflow in the latter part of the summer and early autumn, that is from August through October. Exceptions to this were the year 1975 when tropical storm Eloise dumped a large amount of precipitation in late September and the years 1976 and 1977 when streamflow was high because of heavy rains in those years. Cory (1975) and (1978) found that metabolic activity consistently peaked in August and dropped rapidly in September and October with November values nearly equalling the winter minima. It appears that after the high activity of late spring and summer, the system exhausts itself and as light levels, nutrients and temperatures all decline in the autumn, year to year fluctuations in water temperature have little effect on metabolism.

Correlation coefficients between seasonal average daily oxygen variations and average salinity indicate an inverse correlation exists during the summer and autumn months (Table 1). This relationship lends credence to previous metabolic interpretations, that is high streamflow which results in lowered salinity presumably flushes nutrients into the system and stimulates the aquatic metabolism. This is particularly evident in the summer during the year 1972 and again in 1978 (Fig. 5). Conversely when streamflow is low (salinity high) and nutrients presumably decline, so does metabolism (see summer 1977 and autumn 1978 Fig. 5).

Summary and Conclusions

Water quality data such as dissolved oxygen, temperature and salinity when measured continuously over periods of years can yield valuable information on the basic biologic phenomena of open-water metabolism, that is production and respiration. An understanding of this mechanism is a first step in control and management of aquatic ecosystems. Monthly averages of temperature and salinity plotted against each other furnish an easily interpreted hydroclimagraph which reveals annual differences in the hydro-climate caused by large scale meteorologic events such as precipitation from tropical storms or seasonal and yearly variations in temperature, insolation and runoff.

Daily changes in dissolved oxygen were used to indicate seasonal and annual variations in open-water metabolism. The results confirmed previous studies which had shown that metabolism was highest in the summer, lowest in winter and intermediate in spring and autumn. The oxygen data indicated a high rate of community metabolism following influxes of fresh water from the 1972 tropical storm Agnes. During 1972 and the following year the oxygen demand of the decomposing detritus flushed into the bay by the flood waters resulted in anaerobic bottom waters, a condition which now can be predicted by observing daily oxygen records.

Correlation coefficients between 13-week averages of daily oxygen differences and water temperatures indicated a high degree of agreement between annual elevations or depressions in water temperature and similar variations in springtime metabolism. Information of this type may be useful for predicting success and subsequent growth of spring spawners such as fish, shellfish, and other occupants of the estuary.

An inverse correlation between salinity and the daily oxygen pulse was indicated for the summer and autumn. This suggests a direct correlation between metabolic activity and freshwater runoff, presumably through the addition of nutrients which can stimulate the system in late summer and early autumn, a time of usual low streamflow.

Acknowledgements

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