SOME CONSIDERATIONS OF OXYGEN UTILIZATION RATES IN PUGET SOUND[1]

By

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ABSTRACT

Concentrations of dissolved oxygen in tributary basins of the fjord-like Puget Sound region (Washington) have been determined during monthly surveys of water characteristics. By selecting periods when a consideration of conservative properties suggests that the effects of advection and diffusion are small, the local rates of change in oxygen concentration have been determined; it is assumed that these rates approximate the utilization or consumption rates. These rates, which averaged 5.8 ml/l/yr, were somewhat higher in shallow basins than in deep basins, decreased with increase in time after the water entered the basin, and were considerably higher than values that have been reported for oceanic waters.

INTRODUCTION

The concentration of dissolved oxygen in marine waters has long been of concern to oceanographers and fisheries biologists. More recently, with expanding waterfront populations and increased discharge of domestic and industrial wastes into coastal waters, sanitary engineers and others concerned with pollution problems have been paying increasing attention to the concentration of dissolved oxygen in inshore waters. Of all the nonconservative variables in the sea, the distribution of dissolved oxygen is perhaps the best documented because it is routinely determined on most oceanographic surveys. Richards (1957) has recently reviewed the subject of dissolved oxygen in the ocean. Despite the rather widespread knowledge of oxygen distribution, the rate at which oxygen is used *in situ* remains an open question, with various authors quoting quite different rates for ocean waters. Measurements using the rate of

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change of oxygen concentration in water contained in small bottles are open to the criticism that an impounded sample behaves differently from that *in situ* (Zobell and Anderson, 1936; Rakestraw, 1947).

In the photic zone of the sea the oxygen concentration tends to be altered by local production, diffusion and advection, exchange of oxygen across the sea surface, and biochemical utilization. Too little is known of these individual processes to use the oxygen concentration or its change with time as a basis on which to estimate oxygen utilization rates. Below the photic level the situation is somewhat less complex, a steady state implying a balance between the processes of diffusion and advection on the one hand and utilization on the other. If natural situations can be selected wherein the effects of diffusion and advection are negligible compared to the rate of utilization, the local rate of change in oxygen concentration should then indicate the rate of oxygen utilization.

Certain of the fjord-type regions, such as Puget Sound, provide natural situations in which relatively dense water is at times entrapped behind sills in deep basins or in certain appendages. This water may remain there for periods varying from a few months to more than a year, during which time the overlying water is somewhat less dense than that below sill depth. During these periods the concentration of dissolved oxygen at depth in the basins gradually decreases, then suddenly increases when the basin water is replaced by water of greater density that flows in over the sill. In general, the most active period of replenishment throughout most of the Puget Sound system occurs in late summer or fall following the subsurface intrusion of relatively low-temperature, high-salinity water into the Strait of Juan de Fuca from the Pacific Ocean. This water is associated with upwelling and is usually present in maximum amount in August (University of Washington, 1953).

In their discussion of fjords in British Columbia, Thompson and Barkey (1938) called attention to the low concentrations of dissolved oxygen in embayed waters tributary to the Northeast Pacific Ocean; they suggested a mechanism by which water, partially depleted of oxygen when it is in contact with the bottom, might later appear at an intermediate depth to provide a zone of minimum oxygen. Additional data (largely unpublished) collected by Thompson with his coworkers and students also showed relatively low concentrations of dissolved oxygen in the deep waters of certain partially isolated basins of the Puget Sound system. Oxygen utilization rates were not determined. In the present study an attempt has been made to

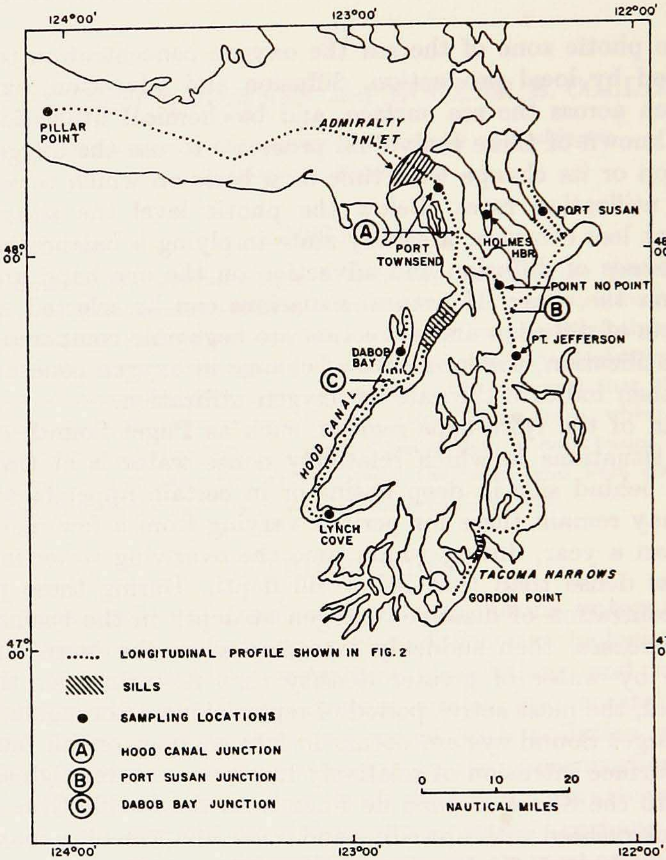

Figure 1. Plan view of Puget Sound showing sills and selected sampling locations.

determine oxygen utilization rates by using selected observations obtained from certain tributary basins in the Puget Sound area at periods of time when advection and diffusion of basin waters appeared to be minimal and during which periods dissolved oxygen concentrations decreased progressively with time.

SAMPLING LOCATIONS AND OBSERVATIONS

Fig. 1 shows the principal sills and selected sampling locations in Puget Sound. Fig. 2 is a schematic longitudinal profile of the Puget Sound basin and selected appendages. The sampling was done at monthly intervals during 1953 and 1954. No attempt was made to determine the microstructure of the water behind the sills or to measure short-period changes in concentration, although recent unpublished data[2] for Dabob Bay show the existence of oxygen microstructure which is apparently associated with a complex thermal microstructure described for this Bay by Shaw and Garrison (1959). Fig. 3 shows local dissolved oxygen concentrations during 1953 and 1954 for representative basin waters during rather extended intervals of time when circulation at depth in the selected locations was considerably restricted. Table I gives the concentrations of dissolved oxygen and the associated values of temperature, salinity, and density. The Winkler method, as modified by Thompson and Robinson (1939), was used to determine the dissolved oxygen content. Conventional oceanographic methods were employed to determine temperature and salinity. The situations prevailing in three different subdivisions of Puget Sound are as follows:

Dabob Bay. This was judged to be the location least affected by advection and diffusion. The selected sampling depth of 180 m was about 50 m below sill depth and as much as 10 m off the bottom, depending on the tide stage and displacement from the selected station position. According to Gran and Thompson (1930), the compensation depth for nearby waters varies from 10 to 18 m, thus photosynthetic processes are presumably negligible in the deep waters of this Bay. Vertical gradients of temperature and salinity at 180 m usually were less than 0.05° C and 0.05 $^0/_{00}$ per 10 m. The drifts in temperature and salinity were 0.1° C and 0.2 $^0/_{00}$ respectively during the 8-month period from January 22 to September 22, 1953, when the oxygen concentration dropped from 4.03 to 1.08 ml/l. This corresponds to a local rate of change in oxygen of 0.012 ml/l/day. In general, below sill-depth the spatial gradients of oxygen concentration were small, changes apparently being more of a function of time than of space. While the decrease in oxygen concentration continued between September and October 1953 at a reduced rate

[2] University of Washington Department of Oceanography, Brown Bear Cruise 221, March 3–5, 1959.

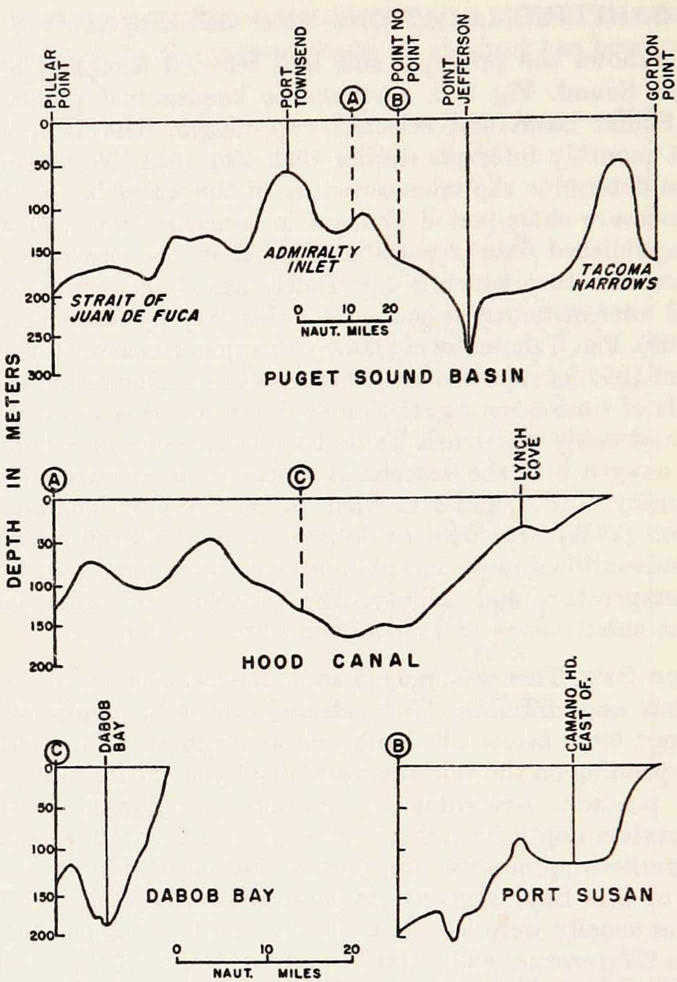

Figure 2. Schematic longitudinal section of the Puget Sound basin and selected appendages.

compared to previous months, a relatively larger change occurred in both temperature and salinity, suggesting an increased effect of advection and diffusion (see Table I). From June to September 1953 the density of the available water entering over the entrance sill to Hood Canal and Dabob Bay increased rapidly, but the density at the sill did not reach that of the bottom waters in Dabob Bay. A small amount of denser water probably passed over the sill in

October 1953, for water of relatively high oxygen concentration was found that month at the very bottom of Dabob Bay (193 m); however, it was found at only one location and not at intermediate levels below sill depth. Apparently this denser water was missed because measurements on the sill that month were made near the

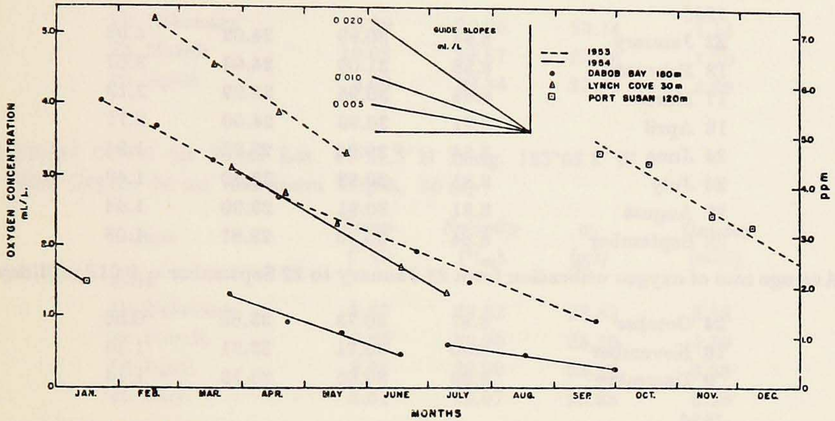

Figure 3. Dissolved oxygen concentrations in Puget Sound sub-basins. (Parts per million, ppm, are expressed on a weight basis, using an average density of 1.023 for basin waters.) Guide slopes should read ml/l/day.

end of an ebb tide when the lowest density water of a particular tidal cycle is usually found. Moreover, denser water occurring in the entrance channel during certain periods within a month could easily be missed on monthly sampling cruises. The flushing which began in October 1953 stopped in its early stages, most likely as a result of heavy rainfall and runoff which decreased the density of the mixed water that flowed across the sill. After December 1953 the water characteristics fluctuated somewhat erratically until the period of March to June 1954 (see Table I). During this latter period the temperature and salinity changed but slightly while the concentration of dissolved oxygen decreased at approximately 0.010 ml/l/day, a slightly lower rate than that during the period January to September 1953.

In June 1954 the density at sill depth increased so that it was slightly above that at basin depths (σ_t 23.46 as compared to 23.43), and some new water penetrated into the bottom of the Bay. The density of the water at the sill decreased again between June and

TABLE I. Water Properties in Puget Sound Basins

DABOB BAY (at 180 m) Lat. 47°44.8′ N Long. 122°49.8′ W
(Sill Depth, Entrance to Hood Canal, 50 m; Hood Canal to Dabob Bay, 130 m; Maximum Depth, 190 m)

Date	*Temp.* (° C)	*Salinity* (‰)	σ_t (*g/l*)	*Oxygen* (*ml/l*)
1953				
22 January	8.94	30.99	24.02	4.03
18 February	8.88	31.00	24.03	3.67
17 March	8.93	30.95	23.99	3.19
18 April	8.91	30.96	24.00	2.71
24 June	8.84	30.90	23.96	1.94
20 July	8.85	30.83	23.90	1.49
21 August	8.81	30.81	23.90	1.44
22 September	8.84	30.79	23.87	1.08
Average rate of oxygen utilization from 22 January to 22 September = 0.012 ml/l/day				
24 October	8.87	30.73	23.82	0.86
16 November	8.80	30.71	23.81	1.14
9 December	9.09	30.65	23.73	1.14
1954				
15 January	9.45	30.64	23.66	1.48
19 February	9.66	30.58	23.58	1.37
25 March	9.76	30.59	23.57	1.32
22 April	9.78	30.52	23.52	0.91
18 May	9.75	30.48	23.51	0.76
17 June	9.74	30.41	23.43	0.45
Average rate of oxygen utilization from 25 March to 17 June = 0.010 ml/l/day				
9 July	9.60	30.36	23.42	0.63
17 August	9.55	30.30	23.39	0.46
30 September	9.56	30.27	23.37	0.24
Average rate of oxygen utilization from 9 July to 30 September = 0.005 ml/l/day				
17 November	9.74	30.36	23.39	3.71

PORT SUSAN (at 120 m) Lat. 48°04.0′ N Long. 122°19.7′ W; (Sill Depth, 100 m; Maximum Depth, 125 m)

Date	*Temp.* (° C)	*Salinity* (‰)	σ_t (*g/l*)	*Oxygen* (*ml/l*)
1953				
23 September	11.14	30.56	23.32	3.36
16 October	11.19	30.65	23.38	3.20
17 November	11.14	30.62	23.37	2.45
7 December	11.10	30.62	23.36	2.31

Date	*Temp.* (° C)	*Salinity* (°/oo)	σ_t (*g/l*)	*Oxygen* (*ml/l*)
1954				
12 January	11.10	30.53	23.31	1.47

Average rate of oxygen utilization from 23 September 1953 to 12 January 1954 = 0.017 ml/l/day

16 February	10.80	30.25	23.14	1.14
23 March	10.08	29.87	22.96	1.70
19 April	8.08	29.34	22.84	4.69

LYNCH COVE (at 30 m) Lat. 47°21.5′ N Long. 123°03.8′ W
(Sill Depth, 35 m; Maximum Depth, 50 m)

Date	*Temp.* (° C)	*Salinity* (°/oo)	σ_t (*g/l*)	*Oxygen* (*ml/l*)
1953				
18 February	8.37	29.52	22.88	5.18
18 March	8.56	30.00	23.30	4.56
18 April	8.62	29.99	23.29	3.86
21 May	8.61	29.97	23.28	3.29

Average rate of oxygen utilization from 18 February to 21 May = 0.020 ml/l/day

25 June	8.90	29.74	23.05	2.07
20 July	9.17	29.76	23.02	1.70
21 August	9.40	29.73	22.96	1.51
22 September	8.94	29.95	23.20	1.31
23 October	9.24	30.18	23.35	1.43
17 November	9.44	30.26	23.38	1.43
9 December	9.64	30.20	23.29	1.23
1954				
15 January	9.73	29.81	22.97	3.21
18 February	9.60	29.68	22.89	3.08
26 March	9.10	29.24	22.64	3.09
21 April	9.20	29.52	22.84	2.73
17 May	9.26	29.56	22.85	2.32
17 June	9.34	29.76	22.99	1.69
9 July	9.44	29.49	22.77	1.27

Average rate of oxygen utilization from 26 March to 9 July = 0.018 ml/l/day

17 August	9.40	29.53	22.80	0.90
30 September	9.42	29.83	23.03	1.50
17 November	10.14	30.24	23.25	2.31

July 1954, reflecting the effect of accumulated runoff from melting snow. Rapid and apparently complete flushing of the water below sill depth occurred between October and November 1954, at which time the density of the water at the sill was greater than that of the water behind the sill.

That some vertical diffusion occurs at all times was indicated by the continuing change in temperature and salinity and by the decrease in density during those periods when the density below sill depth was greater than that in the overlying layers. The associated diffusion of oxygen was downward; however, the system never reached a steady-state condition of constant oxygen concentration in which the local consumption was balanced by downward diffusion. During the period July to September 1954 the concentration of dissolved oxygen decreased by 0.005 ml/l/day, the lowest rate observed. Thus there was a definite decrease in the apparent rate of oxygen utilization with time as the basin water aged and as the concentration of dissolved oxygen decreased. In general, the change in curvature of the oxygen concentration curves with depth ($\partial^2 [O_2]/\partial Z^2$) favored an accumulation of oxygen at the 180 m level; thus the actual utilization rates are probably somewhat greater than those shown by the rate of decrease of oxygen with time.

Port Susan. A slightly different situation existed in Port Susan, which flushed out between August and September 1953 and which was then affected relatively little by diffusion and advection through January 1954; a second flushing started in February, with complete replacement in March. The local change in dissolved oxygen at a depth of 120 m in Port Susan averaged 0.017 ml/l/day for the period September 1953 to January 1954, or roughly 40 % higher than the change below sill depth in the deeper Dabob Bay.

Lynch Cove. In relatively shallow Lynch Cove, the circulation is restricted by the lateral configuration of the basin rather than by an entrance sill. At a depth of 30 m, two periods of decreasing oxygen concentration occurred, one in the spring of 1953 and another in the spring of 1954. The rates averaged 0.020 and 0.018 ml/l/day respectively, or about 70 % higher than for Dabob Bay water entrapped during comparable periods.

GENERAL DISCUSSION

In all, some 150 separate determinations of changes in local oxygen concentration for Puget Sound waters gave an average decrease of 0.016 ml/l/day (5.8 ml/l/year), with the rates being somewhat higher in the shallow waters than in the deep basins. These rates in Puget Sound are high compared to consumption rates reported by others for the open sea: Redfield (see Rossby, 1936) estimated an oxygen consumption of 0.36 ml/l/year for a stagnant pool of water below sill depth in the Gulf of Maine; for the open Pacific off the California Coast at depths of 200, 400 and 700 m, Sverdrup and Fleming (1941) reported respective rates of 1.8, 0.6 and 0.05 ml/l/year; Riley (1951) estimated 0.21 ml/l/year for a depth of 200 m in the Atlantic Ocean, with rates decreasing at greater depths. The higher rate of oxygen utilization in the Puget Sound waters, as compared to offshore waters, may be due in part to the presence of a higher concentration of freshly-formed organic material in the water. It should be noted that water at a depth of 180 m in Puget Sound has not been away from the surface for more than a year or two at most, whereas water at 200 m and deeper off the California Coast may have been away from the surface for many years. Particulate matter, partly organic in nature, is subject to oxidation as it settles through the water mass. Presumably the relative concentration of the less-easily oxidized matter increases with depth below the surface although the total concentration decreases. Riley (1951) estimated that in the Atlantic only 10 $^0/_0$ of the organic matter produced in the photic zone is oxidized below a depth of 200 m.

However, the depth of water behind sills, as in Puget Sound, is not a true measure of its isolation from the surface because the local water often circulates quite freely throughout the water column above sill depth, more or less continuously resupplying new-mixed water from near the surface to that depth. This would insure a rather rapid feed-rate of organic matter to depth, which is in agreement with the quite high rate of oxygen decrease below sill depth.

The higher rates of decrease in concentration with time in the shallow basins of Puget Sound as compared to those of deep waters probably represent a real difference in the rate of utilization, but the effects of diffusion and advection are especially difficult to estimate in shallow water. An example of the type of advection which can lead to high rates of change in local oxygen concentration, erroneously high if interpreted as oxygen utilization rates, is that which occurs at the heads of inlets. Water in the bottom of a basin, when displaced by new water of greater density during the flushing period, will rise to a level just below the halocline in the upper layers. This low oxygen water in turn displaces local water of high oxygen concentration from its previous position. The local change in oxygen concentration, which in such cases may amount to 0.27 ml/l/day, is due primarily to the effects of advection and not to the effect of local utilization. Associated with this vertical movement, which normally occurs in the fall, concentrations as low as 1.0 ml/l or 14 % saturation have appeared within 5 m of the surface in Lynch Cove. Fish-kills have been reported in the fall in Holmes Harbor at about the time when low-oxygen water is normally displaced from the bottom and rises toward the surface, but an association of these events has not been documented.

The water entering the Puget Sound system near Port Townsend varies in dissolved oxygen concentration from 6 to 3 ml/l at the time of entrance. On the basis of an average oxygen utilization rate of 0.016 ml/l/day, and in the absence of downward diffusion, water remaining at basin depth in the system for about one year would be depleted of oxygen. The effect of locally introduced pollutants in reducing local oxygen concentrations cannot be evaluated correctly in the absence of suitable background knowledge of the natural oxygen regime and circulation patterns. Lack of this background information has confused industrial, plant, and sanitary engineers in assessing the effects of industrial waters in Puget Sound. It is of interest to note that at midchannel locations the rate of decrease in dissolved oxygen concentration with time was essentially the same in Dabob Bay and Lynch Cove, both of which border thinly populated nonindustrial areas, as it was in Port Susan near a heavily populated industrial area. In contrast to midchannel locations, however, waters near shore may be appreciably affected by local contamination.

The difference in concentration of dissolved oxygen from place to place along a given flow pattern, in conjunction with local utilization rates, can be used to obtain the difference in relative "age" of water between various places or to obtain a measure of the time it takes for water to move from one place to another. In this rough approximation it is assumed that the effect of diffusion on the oxygen concentration is negligible compared to the rate of chemical utilization. Using this approach, it has been computed on the basis of a year's observation that bottom water at Point Jefferson averages about 10 days older than that at Point No Point, located 10 miles upstream toward the entrance sill. This is roughly the order of magnitude found from a consideration of the temperature of bottom water following the onset of a period of unusually cold weather in the Puget Sound area in mid-January 1954. Since the gradients in oxygen concentration are at times much greater than those of the conservative properties of temperature and salinity, the distribution of oxygen and its changes with time should lead to a more realistic interpretation of circulation patterns below the photic zone than is possible from consideration of only the conservative properties.

SUMMARY

The changes of local oxygen concentration with time have been determined for selected basin waters in the Puget Sound system. The average rate of oxygen utilization was 5.8 ml/l/year (0.016 ml/l/day), which is high in comparison to offshore water. The oxygen utilization rates in the best documented regions of Puget Sound decrease somewhat with a decrease in the concentration of dissolved oxygen, and individual localities show that there is a definite decrease in the rate of utilization with an increase in the time that the water had been standing in the basin. The next step in this study should provide a picture of the changing oxygen regime in selected deep basins at close-spaced intervals of time and space. For example, by monitoring discrete clouds of water in Dabob Bay, where unique temperature and salinity characteristics are exhibited, it may be possible to evaluate oxygen changes in the absence of the usual boundary effects and thus estimate more closely the rates of utilization as associated with individual parcels of water.

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