Chapter IX

DISSOLVED OXYGEN AND ORGANIC MATTER

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INTRODUCTION

The dissolved oxygen (DO) concentration in small, forest streams strongly influences the character and productivity of the aquatic ecosystem. Fish and other aquatic organisms need dissolved oxygen to survive, grow, and develop.

Silvicultural activities may influence the dissolved oxygen concentration of a stream draining a logged area. If timber harvesting exposes the stream to direct solar radiation, the water temperature will increase, as discussed in chapter VII, resulting in a decrease in the saturation concentration of DO in the water. In addition, if large quantities of organic debris are allowed to enter and remain in the stream channel over an extended period, they may contribute to decreased DO levels by: (1) forming debris ponds, which enhance heating of water and reduce the reaeration rate; (2) releasing dissolved materials, such as sugars, nutrients, and phenolics, which are readily oxidized by microorganisms; and (3) forming a benthic mat that can inhibit the flow of DO into the intragravel water.

It is not possible to accurately predict the impact of silvicultural activities on the DO concentration of forest streams. The physicochemical properties of oxygen solubility, the pool and riffle nature of mountain streams, and the non-point source pollutants affecting DO concentration make such prediction very difficult. However, several mathematical models have been proposed for use with forest streams. In general, these models are merely extensions of methods developed for quiescent waters, such as rivers and lakes, and most have met with only limited success. One notable exception is a model by Berry (1975) specifically developed to predict the impact of logging debris on dissolved oxygen content in small forest streams. This model can be used to predict DO concentrations in the surface water of a stream where DO content has a critical bearing on a resource management decision. However, if only a rough estimate of the DO concentration in the surface water is required, the Streeter and Phelps (1925) DO sag method may be used. Little work has been done concerning oxygen dynamics in the intragravel zone of a stream. As a result, there are no models available to predict DO changes in the streambed gravels following logging.

Although accurate prediction may not be possible, a clear understanding of oxygen dynamics in a stream is essential to identify silvicultural activities that will adversely affect the DO concentration in a small forest stream. As a result, information on oxygen solubility, the dissolved oxygen balance, dissolved oxygen and logging, and land use practices to protect and maintain the oxygen concentration in a forest stream is explained prior to discussion of the Streeter-Phelps model. Evaluation of the impacts of silvicultural activities on DO concentrations is essential in identifying potential impacts on the fishery resource of a DO reduction caused by timber harvesting.

DISCUSSION

OXYGEN SOLUBILITY IN FRESH WATER

Although free oxygen is abundant in the atmosphere (20.9 percent by weight), it is relatively insoluble in water. The saturation concentration varies between 14.6 mg/l (ppm)[1] at 32° F (0° C) to 7.6 mg/l at 86° F (30° C) under 29.92 inches of Mercury (760 mm) atmospheric pressure. In fresh water, oxygen solubility, or saturation concentration, is determined by atmospheric pressure and the temperature of water. Figure IX.1 illustrates the relationship between temperature, pressure (elevation), and concentration of dissolved oxygen.

Atmospheric pressure. — The effect of pressure is described by Henry's law, which states that the solubility of a gas in a liquid is directly proportional to the pressure of the gas above the liquid. As the atmospheric pressure (partial pressure of oxygen) increases, there is a proportional increase in the water's capacity to hold oxygen. The pressure effect can be calculated by equation IX.1:

$$S^*_{(P)} = S\frac{P-p}{760-p} \qquad \text{(IX.1)}$$

where:

$S^*_{(P)}$ = the oxygen solubility in mg/l at atmospheric pressure P in inches (mm) of mercury,

S = the oxygen solubility at 29.92 inches (760 mm) of mercury, and

p = the pressure (inches or mm) of saturated water vapor at the temperature of the water (American Public Health Association, Inc. 1971).

At elevations below 3,000 feet (900 m) m.s.l. and temperatures below 77° F (25° C), p can be considered negligible. If the elevation (E in feet) is known, an approximate value of P can be calculated by:

$$P = 29.92 / exp\ (E/25{,}000) \qquad \text{(IX.2.)}$$

[1]*In fresh water (total dissolved solids <7,000 mg/l) 1 mg/l = 1 ppm (Hem 1970). As a result, the English unit of concentration will not be given throughout the balance of this chapter since it is equivalent to the mg/l of concentration.*

Water temperature. — The solubility of oxygen in water is inversely proportional to water temperature. This is important because some silvicultural activities expose the stream to direct solar radiation, resulting in an increase in the stream water temperature (chapter VII). As the water temperature increases, its capacity to hold oxygen decreases. The temperature effect can be calculated by:

$$S_{(T)} = 14.56 - 0.38163T + 0.0066366T^2 - 0.00005227T^3 \qquad \text{(IX.3)}$$

where:

$S_{(T)}$ = the solubility of oxygen (mg/l) in water of a given temperature, and

T = the temperature in °C.

IMPORTANCE OF DISSOLVED OXYGEN TO FISH

Adequate levels of DO in the surface and intragravel water are essential for survival of fish. An "adequate level" of DO is a vague term and varies with the species and age of the fish, prior acclimatization, temperature of the water, and concentration of other substances in the water (McKee and Wolf 1963). However, fishery biologists often use the following "rule of thumb" for minimum DO concentrations for freshwater biota: 5 mg/l for warm water species, declining to a lower limit of 4 mg/l for short periods, provided that the water quality is favorable in all other respects; and no less than 6 mg/l, or 7 mg/l during spawning times, for cold water species.

Fish often are exposed to DO concentrations well below 5 mg/l for prolonged periods. DO concentrations between 5 and 2.5 mg/l are generally considered sublethal to fish. Under such conditions, fish experience an oxygen stress, and if the exposure is extended, their activity, growth, and reproduction may be reduced.

Several responses to oxygen deficiencies by fish within the surface water and by fish eggs and embryos in the intragravel water have been reported. Shellford and Allee (1913) studied the avoidance reaction of 16 species of fish to different

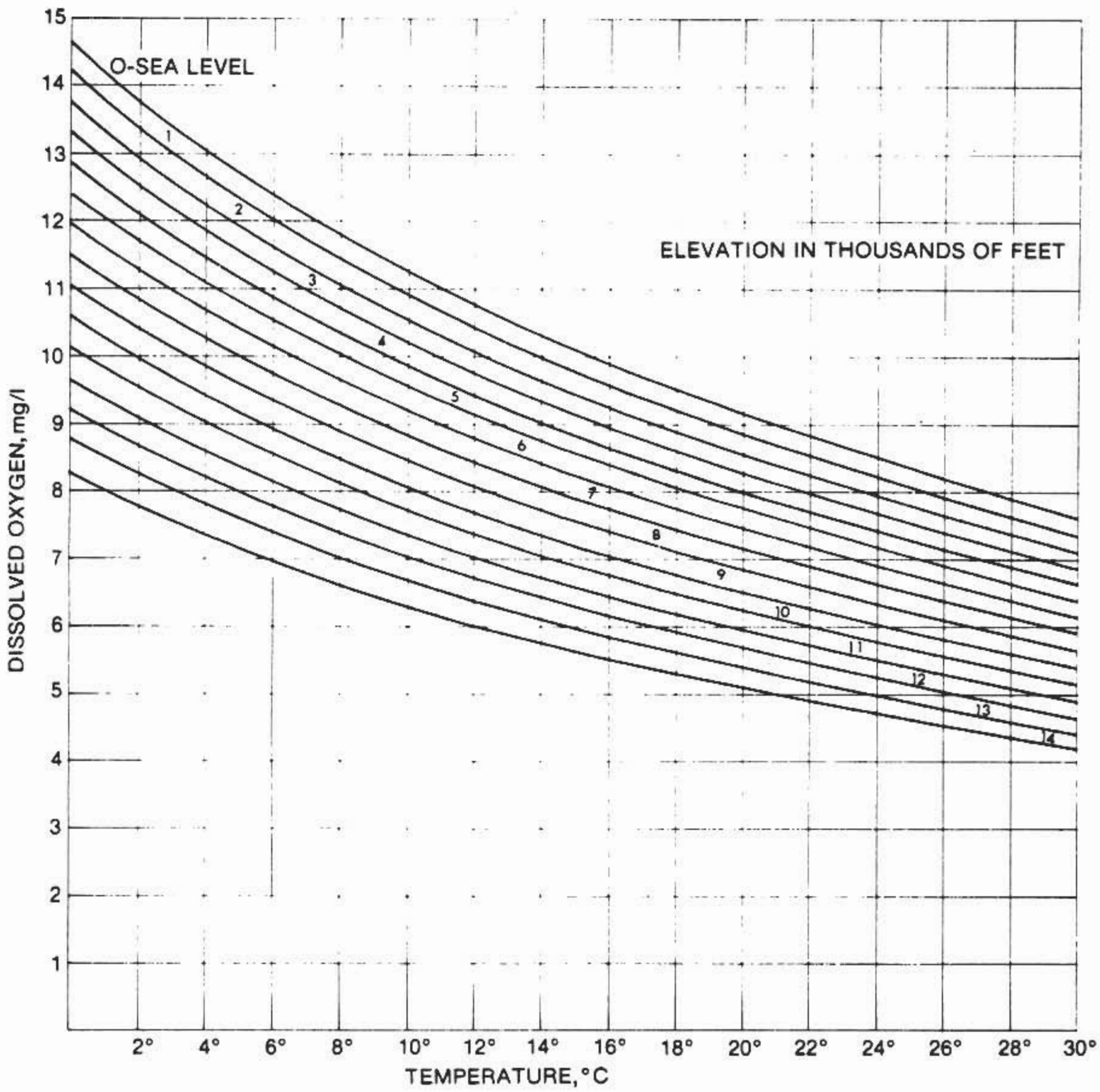


Figure IX.1.—Relationship between temperature, pressure (elevation), and dissolved oxygen.

concentrations of oxygen. They reported a definite effort by all the fish to avoid water substantially deficient in oxygen. Jones (1952) ran a similar experiment with stickleback, minnows, and trout fry. At temperatures near 68° F (20° C), all three species reacted violently and retreated rapidly when they swam into water containing 0.5 to 1.0 mg/l of DO. At a concentration of 3.5 mg/l, the reaction was again one of rejection but much slower. Whitmore and others (1960) conducted avoidance tests with juvenile chinook and coho salmon, large mouth bass, and bluegill. They found all four species markedly avoided water containing less than 4.5 mg/l of DO; some coho avoided concentrations of 6 mg/l.

Davison and others (1959), studying dissolved oxygen requirements of cold water fishes, reported that at a temperature of 64° F (18° C), young coho salmon survived for 30 days at a DO level of 2.0 mg/l. During this period the fish ate little and lost weight. At a higher DO level, near 3.0 mg/l, the fish ate more food and gained weight. However, this gain was much less than that of similar fish in oxygen-saturated water. Herrmann and others (1962) further examined the influence of oxygen concentration on growth and food consumption of juvenile coho salmon. They found that at 68° F (20° C), both growth and food consumption over a prolonged period declined gradually as the oxygen level dropped from 8.3 to about 5.5 mg/l. The decline of each was rapid as the oxygen level dropped from about 5 to 1.8 mg/l, and fish often died at DO levels below 1.0 mg/l. The fish ate very little and lost weight at oxygen levels at or below 2 mg/l.

These studies indicate that fish attempt to avoid areas significantly deficient in oxygen, and that when fish are exposed to such water for a prolonged period, their growth and food consumption rates decrease.

The value of high oxygen levels in the intragravel water is often overlooked. However, it is critical for Pacific Coast salmonoids, as well as other sport and commercial fish that spawn in small forest streams. The salmonoid species deposit their eggs 10 to 12 inches (25 to 30 cm) deep into the stream gravels. The eggs hatch, and the embryos develop for approximately 3 months before the fry emerge into the surface water (Lantz 1971). Continuously high oxygen levels during embryo development are very important. If oxygen becomes deficient, the percent egg survival, rate of embryo development, and quality of fish produced may decrease significantly.

Shumway and others (1964) examined the influence of oxygen concentration and water movement on the growth of steelhead trout and coho salmon embryos. In their experiment, embryos raised from fertilization to hatching were exposed to different concentrations of DO ranging from 2.5 to 11.5 mg/l and water velocities ranging from 2 to 138 in/hr (3 to 350 cm/hr) under a near constant temperature of 50° F (10° C). They found that fry produced from embryos raised at oxygen levels of less than 4.0 mg/l hatched later and were smaller at hatching than fry from embryos raised at oxygen levels near saturation. They also reported that reduced water velocities affected the fry in much the same manner as reduced oxygen levels, although the effect was not as pronounced.

Garside (1966) conducted a similar experiment which examined the effects of oxygen and temperature on brook and rainbow trout embryo development. The embryos of each species were exposed to oxygen concentrations of 2.5, 3.5, and 10 mg/l at each of four temperatures — 36° F (2.5° C), 41° F (5.0° C), 45° F (7.5° C), and 50° F (10° C) — from the time of fertilization to late development. The development rate slowed and the hatching period increased for both species of fish as temperature levels increased and oxygen levels declined.

THE OXYGEN BALANCE IN A STREAM

The oxygen concentration in a stream is determined by the addition and depletion of dissolved oxygen by biological and physical processes. Under undisturbed conditions, a forest stream is in a state of oxygen balance. Aquatic animals and decomposition agents continuously withdraw free oxygen while, at the same time, oxygen is supplied intermittently by green plants during daylight, and continuously by direct absorption from the atmosphere.

The oxygen system within a stream may be described using the mass balance approach. The change in mass of DO (ΔDO_m) within a fixed volume of stream is equated to the inputs ($DO_{m(i)}$) minus the outputs ($DO_{m(o)}$) of oxygen and may be expressed as:

$$\Delta DO_m = DO_{m(i)} - DO_{m(o)} \qquad (IX.4)$$

If an oxygen balance exists, there will be no net change in the oxygen mass within the volume, and the equation may be reduced to:

$$DO_{m(i)} = DO_{m(o)} \qquad (IX.5)$$

The oxygen balance of a section of mountain stream (fig. IX.2) under undisturbed conditions is illustrated diagrammatically in figure IX.3. The size of the arrows between components indicates the magnitude of oxygen transfer.

A mountain stream is replenished with oxygen from three sources: the direct absorption at its surface, the photosynthetic process of green aquatic plants, and, to a minor extent, the influent ground water.

Surface water is supplied with oxygen primarily by direct absorption (reaeration) from the atmosphere. The reaeration rate is a function of the DO concentration at the surface, while the dispersion of oxygen thoughout the water is controlled by simple molecular diffusion and mass transfer. In

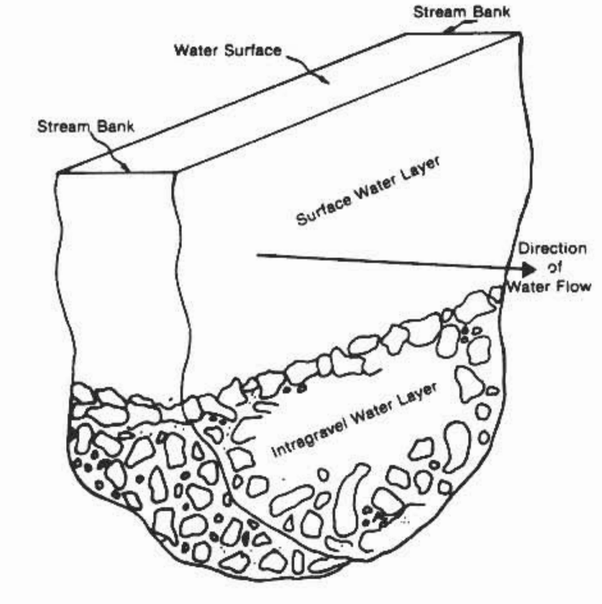


Figure IX.2.—Hypothetical section of stream channel to be considered in the dissolved oxygen mass balance.

general, the rate of reaeration in a still water body, such as a pond or lake, is relatively slow. However, forest streams often have steep gradients that result in turbulence, which produces vertical and horizontal mixing as well as oxygen entrainment, all of which greatly increase the reaeration rate.

During daylight, plankton and algae that are often present in quiet pools photosynthesize and produce free oxygen as a byproduct. In large, low gradient streams or lakes, photosynthesis may serve as a major source of oxygen; however, in small forest streams, it is generally only a very minor source of oxygen (Camp 1965).

The intragravel water is supplied with oxygen primarily by mass transfer and diffusion from the overlying surface water. The rate of this transfer and diffusion is relatively slow, because the mixing agents present in the surface water are inhibited in the intragravel water. Water velocity through the intragravel layer is much lower than the surface layer: 1 to 2 in/hr (2 to 5 cm/ hr) compared to 20 to 60 in/sec (50 to 150 cm/sec) (Narver 1971).

A second, and generally very minor, input of oxygen into the intragravel water is oxygen carried in by influent ground water (Vaux 1968). Sheridan (1962) found that oxygen input by ground water in pink salmon streams in southeast Alaska was very small. He concluded that the major intragravel oxygen source was direct diffusion from the surface layer.

The predominant dissolved oxygen sink in an unpolluted mountain stream, both in the surface and intragravel water, is biochemical oxygen demand (BOD). DO will be lost to a lesser extent to respiration by larger aquatic life and plants, to the atmosphere by direct diffusion — if the stream is in a state of oxygen supersaturation — and to effluent ground water flow.

Biochemical oxygen demand imposes the greatest drain on a stream's DO supply. The BOD process in a mountain stream is illustrated diagrammatically in figure IX.4. The decomposition agents (decomposers) may be separated into two classes: dispersed and attached organisms. Dispersed organisms flow freely within the stream; attached organisms remain stationary, attached to rocks and other fixed objects. Both exert an oxygen demand. In a small forest stream, where the gradient is high and the flow turbulent, dispersed organisms generally predominate. In streams where the gradient is low and there are a number of quiescent pools, attached organisms may exert a significant demand. In general, the decomposers are comprised primarily of bacteria, protozoa, fungi, and, to a lesser extent, larger aquatic life (insects and fish).

The substrate, or food source, is composed of suspended material (finely divided plant material), dissolved material (nutrients and simple sugars leached from plant material), and benthic deposits (organic material that has settled to the stream bottom).

Once the material is ingested, the assimilative process is one of wet oxidation within the decomposers. This process may be expressed by the following reaction:

$$\text{Substrate} + O_2 \xrightarrow{\text{organism}} CO_2 + H_2O + \text{energy} + \text{other byproducts} \qquad (IX.6)$$

In this process, the decomposers utilize oxygen to break down the substrate to produce carbon dioxide, water, energy for growth and reproduction, and other byproducts.

Larger aquatic life impose another sink on a stream's dissolved oxygen supply (fig. IX.3). Although a mountain stream may appear to be relatively free of larger aquatic life, it generally supports a multitude of organisms, such as snails,

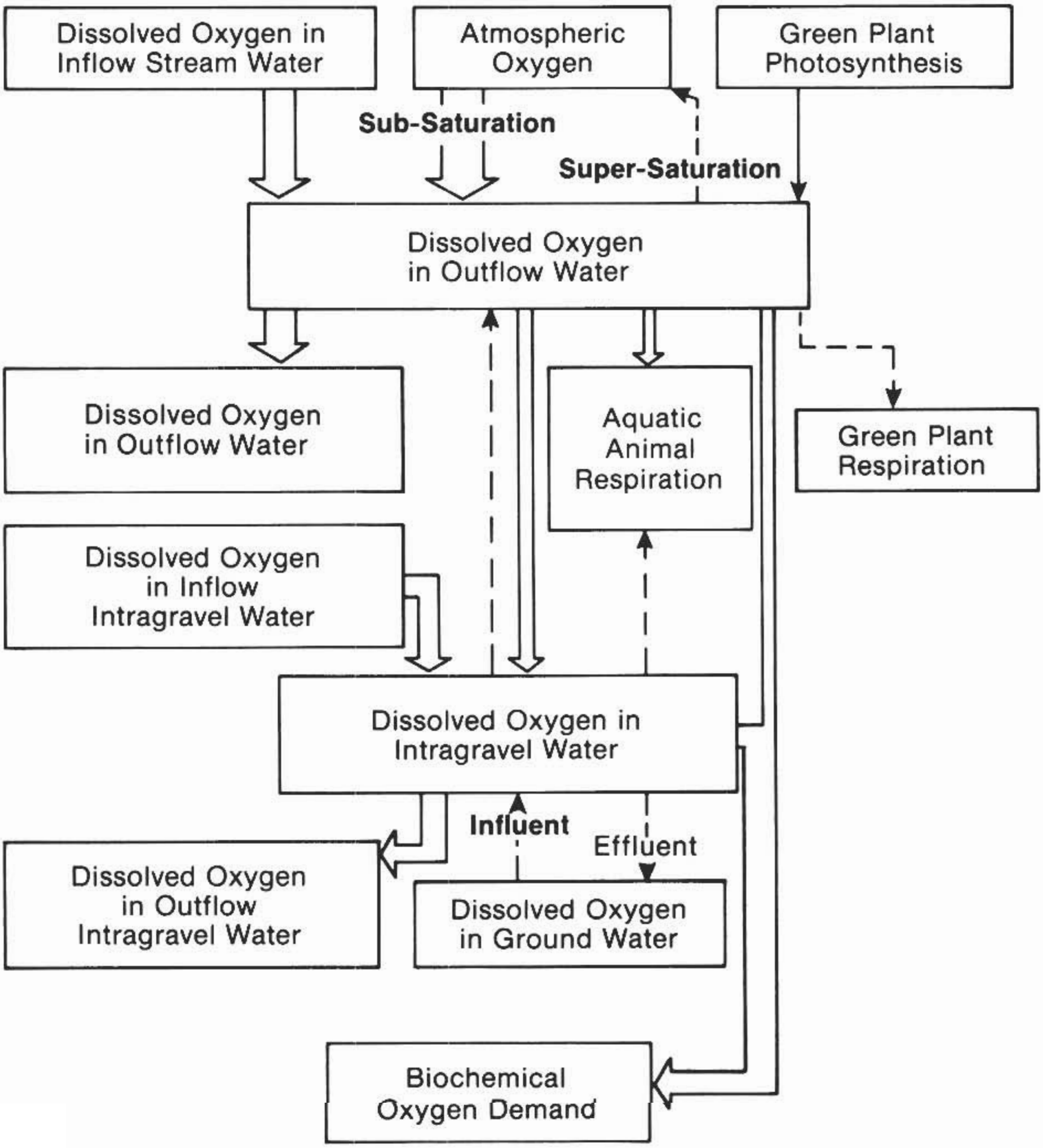
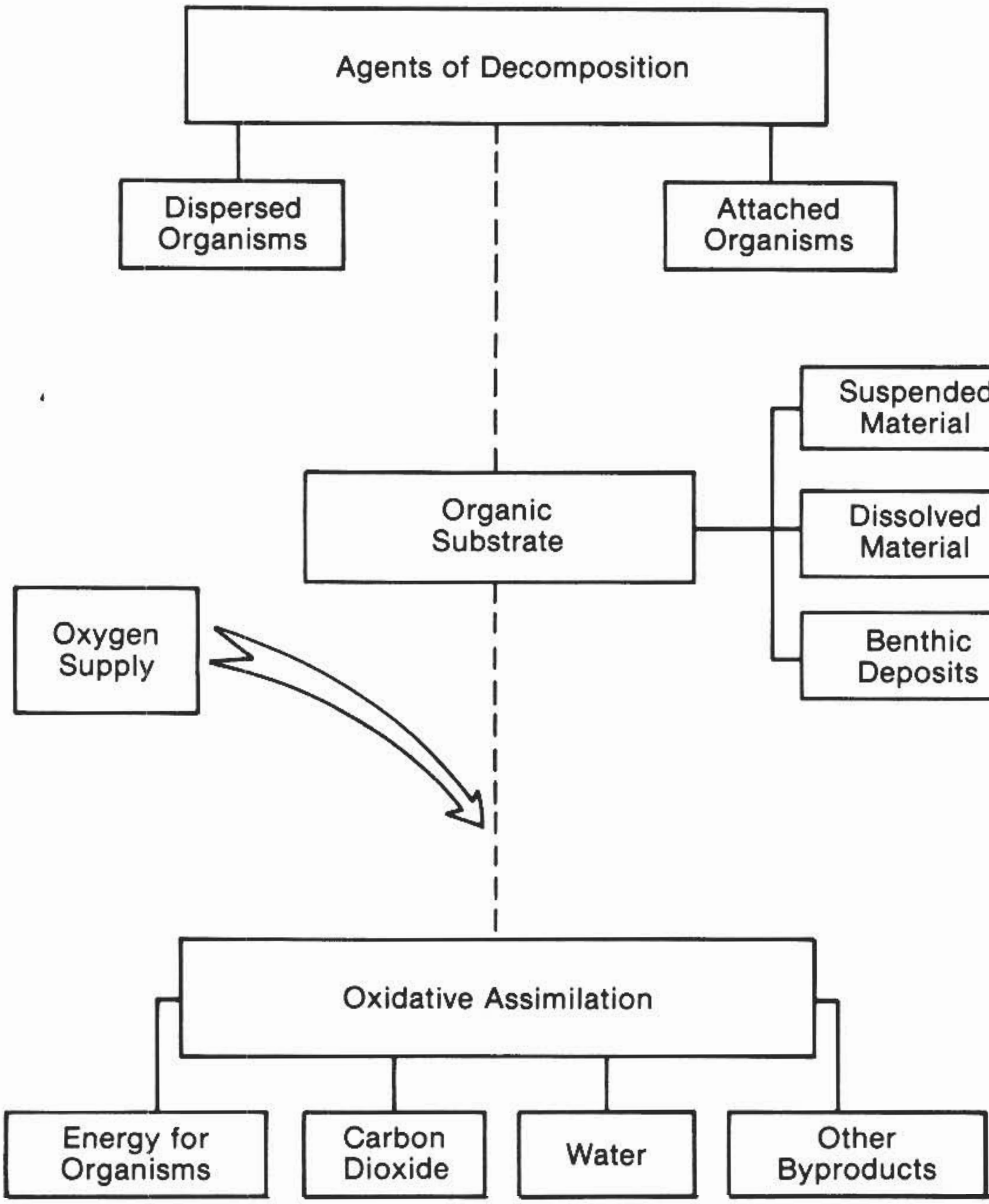


Figure IX.3.—Sources and sinks of dissolved oxygen in a mountain stream under undisturbed conditions (Ponce 1974b).



$$\text{Substrate} + O_2 \xrightarrow{\text{organism}} CO_2 + H_2O + \text{energy} + \text{other byproducts}$$

Figure IX.4.—The biochemical oxygen demand process in a mountain stream (Ponce 1974b).

insect nymphs, crayfish, and fish. All these organisms require oxygen. The rate of oxygen removal by these organisms is a function of the species present and their environment.

The oxygen balance is an important water quality concept. Alteration of any of the sources or sinks will result in a new oxygen equilibrium concentration and may have a pronounced effect on the aquatic life present.

DISSOLVED OXYGEN AND LOGGING

Timber harvesting can have a substantial impact on the DO balance in upland streams, particularly if logging debris are allowed to enter and remain in the stream channel. Timber harvesting may affect dissolved oxygen concentrations in small forest streams in several ways.

Water Temperature Increases

Logging may alter the temperature regime in a small stream (chapter VII). Brown and Krygier (1970) evaluated the effect of two different methods of clearcutting on stream temperature in Oregon's Coastal Range. They found that the maximum temperature increased from 57° to 85° F (13.9° to 29.4° C) on the completely clearcut watershed 1 year after cutting. In terms of oxygen decrease, due only to temperature fluctuation, the saturation concentration of oxygen would have dropped 28 percent (from 10.3 to 7.4 mg/l). Temperature levels in the stream draining the watershed, which was patchcut with vegetation buffer strips left along the channel, showed no significant change in stream temperature due to timber harvesting, and maintained DO levels near those of the control stream.

Similar trends have been observed in the Appalachian highlands. Eschner and Larmoyeux (1963) report that, prior to treatment, there was little difference between water temperatures of the control watershed and the watershed to be entirely clearcut. However, the first year following cutting, the maximum water temperature measured on the clearcut watershed was 75° F (23° C), 20° F (11° C) greater than the maximum recorded on the control stream. In terms of DO solubility in the stream, the saturation concentration would have dropped 19 percent (9.0 to 7.3 mg/l).

Logging Debris

Slash is a byproduct of logging. It is composed of limbs, branches, needles, and leaves of trees. This debris, along with forest floor material, may accumulate in the stream channel, particularly if log yarding across the channel is permitted. Once this organic material enters the channel, it may adversely affect the DO concentration in several ways: (1) by exerting a high BOD, (2) by restricting flow and reducing reaeration, and (3) by accentuating water temperature increases.

The oxygen demand (BOD) by plant matter has been well documented. Plant materials contain simple sugars and other nutrients that are readily leached in water (Currier 1974, Ponce 1974b). Microorganisms consume these leached constituents and, in turn, exert a demand on the stream's oxygen supply. This demand for oxygen may continue for a relatively long period.

Chase and Ferullo (1957) studied the effect of autumn leaf fall on the oxygen concentration in lakes and streams in the eastern United States. After 1 year, maple leaves demanded about 750 mg of O_2/g of initial dry weight, while oak leaves and pine needles required about 125 mg of O_2/g of initial dry weight. The oxygen uptake was relatively rapid: by day 100 maple had achieved about 70 percent, and oak and pine 55 percent, of the demand exerted in 1 year.

Slack and Feltz (1968) examined the effect of leaf fall on quality changes in a small Virginia stream. They reported no significant change in oxygen consumption as the leaf fall rate increased from 0 to 0.05 lb/ft^2/day (0 to 2 g/m^2/day). As the rate increased from 0.05 to 0.28 lb/ft^2/day (2 to 12 g/m^2/-day), however, there was a corresponding drop in DO from 8 mg/l to less than 1 mg/l. Upon natural flushing of the stream by a storm, the DO responded by climbing to near saturation concentration (11 mg/l).

Ponce (1974a) determined the BOD of Douglas-fir needles and twigs, western hemlock needles, and red alder leaves in stream water. The oxygen demand by these materials was measured for 90 days at 68° F (20° C) and for 5 days under the condition of temperature fluctuation similar to patterns observed in clearcut watersheds of the Oregon Coastal Range. Selected results of Ponce's work are presented in tables IX.1 and IX.2. It is apparent that this material exerts a substantial oxygen demand: 101, 178, and 273 mg of O_2/g for Douglas-fir,

Table IX.1.—Mean[1] cumulative BOD in milligrams of O_2/g (dry weight) by Douglas-fir needles and twigs, western hemlock needles, and red alder leaves in stream water at 20° C (Ponce 1974a)

Vegetation type	Days 5	10	20	45	60	90
	milligrams of O_2/g					
Douglas-fir needles	63	76	97	99	96	101
Western hemlock needles	32	88	130	169	176	178
Red alder leaves	79	124	169	239	260	273
Douglas-fir twigs	25	47	75	100	---	---

[1]The mean of four replications for each species

Table IX.2.—Mean[1] cumulative BOD in milligrams of O_2/g (dry weight) by Douglas-fir, western hemlock, and red alder leaves under conditions of temperature fluctuation (Ponce 1974a)

Vegetation type	Days 1	2	3	4	5
	milligrams of O_2/g				
Douglas-fir needles	46	62	124	175	190
Western hemlock needles	24	55	81	92	97
Red alder leaves	72	131	124	207	237

[1]The mean of three replications for each species.

western hemlock, and red alder leaves, respectively, over 90 days; and 100 mg of O_2/g for Douglas-fir twigs over 45 days at 20° C. This demand is exerted relatively rapidly with 96, 73, and 62 percent of the 90-day demand achieved in 20 days for Douglas-fir, western hemlock, and red alder leaves, respectively. When the temperature fluctuated, the oxygen demand increased by a factor of 3 for each leaf type over the 5-day test period.

The toxicity of the leachate extracted from each of these vegetative species was determined on guppies and steelhead trout fry. The concentration of leachate needed to produce toxic effects was so high that oxygen depletion probably would be responsible for death long before the leachate effect would.

Hall and Lantz (1969) reported the effects of logging on habitat of coho salmon and cutthroat trout in coastal streams of Oregon. Two small watersheds were studied, one completely clearcut, the other patchcut with buffer strips. They were compared with a third watershed that served as a control. Felling on the clearcut watershed began in the spring. Timber was felled along the stream, and logs were yarded uphill by cable across the stream to landings. This resulted in the accumulation of considerable quantity of debris in the channel, which restricted flow and formed pools. The large material remained in the channel throughout the summer. In early fall, the channel was cleared of the large material to permit free flow.

DO concentration was substantially reduced in surface and intragravel waters of the clearcut watershed (figs. IX.5 and IX.6). The DO reduction was noted first in the intragravel water, after felling began along the stream. A layer of debris on the gravel and ponding of the surface water caused a substantial decrease in the rate of oxygen transfer from the surface to the intragravel water. This decrease, coupled with an oxygen demand by the decomposing debris, caused a rapid decline in DO in the intragravel water. DO concentrations in the surface water from late spring through most of the summer were too low to support salmon and trout in one-third of the streams available to the salmonoids; juvenile coho salmon placed in liveboxes there survived less than 40 minutes. The lowest oxygen concentration reported, 0.6 mg/l, was observed in a pool resulting from a dam composed of debris. During this period, oxygen concentration of the control stream and the stream

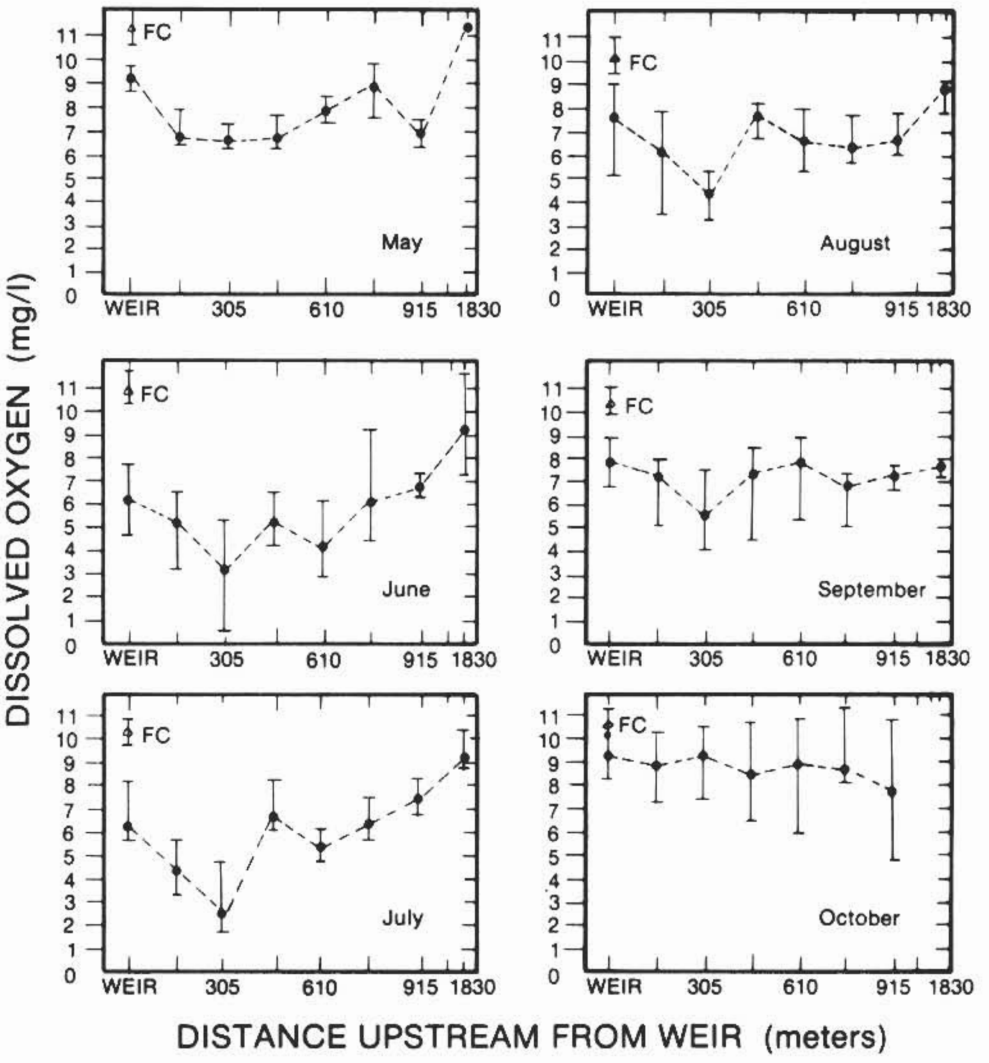


Figure IX.5.—Surface dissolved oxygen levels (mean and range) taken twice weekly in the clearcut watershed (Needle Branch) and control watershed (Flynn Creek) during the year of timber harvest (1966). Sampling on Needle Branch occurred at 500 feet (152 m) in the area accessible to salmon and 6,004 feet (1,830 m) (upper edge of clearcut). Samples from Flynn Creek were taken only at the weir (Hall and Lantz 1969).

draining the patchcut watershed remained at near saturation levels. Upon removal of large debris from the channel and establishment of free-flowing conditions, the DO concentration rapidly returned to near pre-logging conditions in the surface water. Intragravel oxygen concentrations, however, remained about 3.0 mg/l lower than the pre-logging concentrations for the next 2 years, and continued to decline over the next 4 years to levels less than 2.0 mg/l at several locations.

Although a portion of the intragravel DO decline was attributed to long-term BOD by organic matter that intruded the gravel, it was concluded the major cause for the prolonged reduction was restriction of water flow through the gravel due to sedimentation in the gravel bed. Garvin (1974) found that, in the absence of sedimentation, logging debris intrusion into streambeds resulted in a large, but short-term, reduction of DO concentration in the gravel. Within 6 months, DO levels returned to almost normal.

It is apparent that logging debris may be responsible for severe oxygen deficits within small forest streams. However, it should be noted that the pollution impact of this material, particularly the finely divided debris, depends not only on the amount that enters the stream, but also the season it enters the stream. Debris deposited in an Oregon Coastal Range stream between early fall and late winter generally caused only minor oxygen deficit. During this period, winter freshets provide the streams the energy to flush the material through the system. However, if the material is deposited between early spring and late summer, serious oxygen deficit is much more likely. During this period, the streams are generally at low flow and do not have sufficient energy to transport the debris.

PREDICTING DISSOLVED OXYGEN DEFICITS, THE DO SAG METHOD

Berry (1975) developed a working computer model to predict the impact of logging debris on dissolved oxygen concentrations in small forest streams. Since this model appears to yield reliable results, it can be used to predict DO concentration

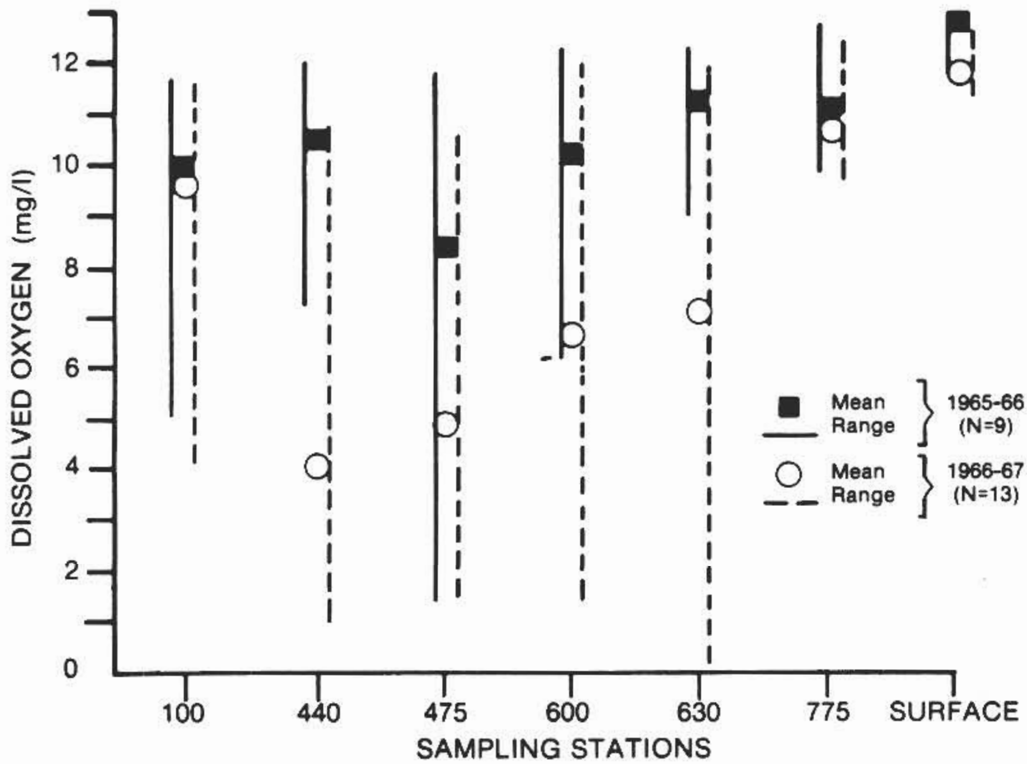


Figure IX.6.—Intragravel dissolved oxygen levels in the clearcut watershed (Needle Branch) from December 1965 to May 1966 (before logging). (All standpipes in Needle Branch were removed during logging; the six for which data are shown were replaced in their previous locations). Surface dissolved oxygen levels are shown for comparison (Hall and Lantz 1969).

for resource management decisions. However, if only a coarse estimate of the oxygen deficiency is required, it may be obtained by using the DO sag method developed by Streeter and Phelps (1925). The numerous limitations associated with this method that greatly affect the accuracy of the prediction will be noted later.

The DO sag concept is illustrated in figure IX.7. It is assumed that the rate change in oxygen deficit is governed by two independent reactions which occur simultaneously: reaeration and biochemical oxygen demand (depletion). Each of these processes, in turn, may be described by a differential equation.

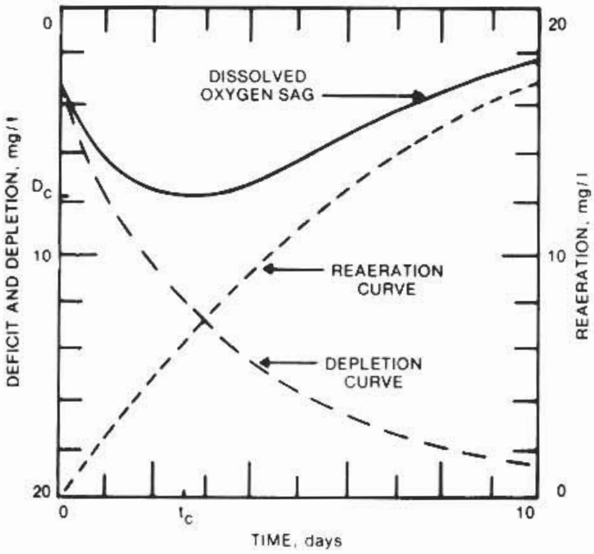


Figure IX.7—The dissolved oxygen sag.

In the reaeratation equation, it is assumed that rate of oxygen absorption by the water is proportional to the oxygen deficit in the water. This relation may be expressed as:

$$\frac{dD}{dt} = -K_2D \qquad \text{(IX.7)}$$

where:

D = the oxygen deficit in mg/l
t = time in days, and
K_2 = is the reaeration constant (base e) in units of l/day.

In the depletion equation, it is assumed that the rate of biochemical oxygen demand (BOD) due to biochemical oxidation is proportional to the amount of BOD present. This may be expressed as:

$$\frac{dL}{dt} = -K_1L \qquad \text{(IX.8)}$$

where:

L = the BOD concentration in mg of 0_2/g,
K_1 = the BOD rate coefficient (base e) in units of l/day, and
t = is as previously defined.

Equation IX.8 also may be expressed in terms of oxygen deficit, D. Since BOD concentration is measured in terms of the quantity of oxygen consumed, it follows that the rate change in BOD is equal to the rate of oxygen depletion. The rate of oxygen depletion may be expressed as the rate change in oxygen deficit:

$$-\frac{dL}{dt} = \frac{dD}{dt} \qquad \text{(IX.9)}$$

Substituting equation IX.8 in IX.9 yields equation IX.10:

$$\frac{dD}{dt} = K_1L \qquad \text{(IX.10)}$$

Equations IX.7 and IX.10 may be combined and solved for D, which enables the calculation of oxygen deficit at any given time, resulting in equation IX.11:

$$D = \frac{K_1La}{K_2-K_1}\left[exp\,(-K_1t) - exp\,(-K_2t)\right] + Da\; exp\,(-K_2t) \qquad \text{(IX.11)}$$

where:

La and Da are, respectively, the initial BOD concentration and initial oxygen saturation deficit in units of milligrams of O_2/l at time (t) equal to O, *exp* is the base of natural logarithms, and the remaining terms are as previously defined. Equation IX.11 is commonly referred to as the Streeter-Phelps equation, and may be used to predict any point on the dissolved oxygen sag curve (fig. IX.7).

Of particular interest is the point of maximum deficit, D_c (mg of O_2/l) — the lowest point in the DO sag curve — and the time it occurs, t_c (days). The point of maximum deficit may be calculated by equation IX.12 developed by Fair (1939):

$$D_c = \frac{K_1}{K_2} La\; exp\,(-K_1t_c) \qquad \text{(IX.12)}$$

The critical time, t_c, is obtained from equation IX.13 developed by Fair (1939):

$$t_c = \frac{K_1}{K_2-K_1} \ln \frac{K_2}{L_1} \left[1 - \frac{Da\,(K_2-K_1)}{K_1 La}\right] \quad (IX.13)$$

All terms in equations IX.12 and IX.13 are as previously defined.

Predicting Components Of The DO Sag Method

Although the DO sag method appears to be simple to apply, it is difficult to obtain reliable results because of the lack of accurate values for K_1, K_2, and La. Berry (1975) suggests the following equations to predict these components.

The reaeration rate constant. — The reaeration rate constant can be predicted with equation IX.14 developed by Holtje (1971):

$$K_{2(T)} = 1.016^{(T-20)}[181.6\,E - 1657\,S + 20.87] \quad (IX.14)$$

where:

$K_{2(T)}$ = the reaeration rate constant (l/day) at the water temperature T (°C),

E = energy of dissipation (ft^2/sec^3 or m^2/sec^3), and

S = the average channel slope (ft/ft or m/m).

The energy of dissipation can be calculated by:

$$E = (S)(U)(g) \quad (IX.15)$$

where:

U = the average velocity (ft/sec or m/sec), and

g = the gravitational acceleration constant (32.2 ft/sec^2 or 980 cm/sec^2).

The leachate BOD rate constant. — The leachate BOD rate constant, $K_{1(T)}$ (liter/day), can be determined by the set of equations developed by Zanoni (1967):

$$K_{1(T)} = 0.796\,[1.126^{(T-20)} K_{1(20)}]; \quad 2° \le T < 15° C \quad (IX.16)$$

$$K_{1(T)} = 1.000\,[1.047^{(T-20)} K_{1(20)}]; \quad 15° \le T < 32° C \quad (IX.17)$$

$$K_{1(T)} = 1.728\,[0.985^{(T-20)} K_{1(20)}]; \quad 32° \le T < 40° C \quad (IX.18)$$

where:

$K_{1(T)}$ and $K_{1(20)}$ are values of the reaeration rate constant in liter/day at water temperature T and 20° C, respectively. Values of $K_{1(20)}$ for various types of organic matter can be obtained from table IX.3.

The leachate concentration. — The leachate concentration, $La_{(T)}$ (mg/l), may be determined by equation IX.19 or IX.20 developed by Zanoni (1967):

$$La_{(T)} = La_{(20)}[1.0 + 0.0033(T-20)]; \quad 2° \le T < 20° C \quad (IX.19)$$

$$La_{(T)} = La_{(20)}[1.0 + 0.0113(T-20)]; \quad 20° \le T < 35° C \quad (IX.20)$$

where:

$La_{(T)}$ and $La_{(20)}$ are the leachate BOD concentration milligrams of O_2/g at water temperature T and 20° C, respectively. Values of $La_{(20)}$ for various types of organic matter can be obtained from table IX.3.

Table IX.3—$K_{1(20)}$ and $La_{(20)}$ values for selected tree species and materials

Vegetation type	$K_{1(20)}$ (liter/day)	$La_{(20)}$ O_2 of (mg/g)	Reference
	liter/day	milligrams of O_2/g	
Douglas-fir needles	0.125	[1]110	Ponce (1974a)
Douglas-fir twigs	0.056	[2]110	Ponce (1974a)
Western hemlock needles	0.640	[1]166	Ponce (1974a)
Red alder leaves	0.047	[1]286	Ponce (1974a)
Maple leaves[3]	[4]0.006	[1]525	Chase and Ferullo (1957)
Pine needles[3]	[4]0.005	[1] 68	Chase and Ferullo (1957)
Oak leaves[3]	[4]0.006	[1] 80	Chase and Ferullo (1957)

[1]Ninety-day ultimate demand.
[2]Forty-five-day ultimate demand.
[3]Species not given.
[4]Represent $K_{1(25)}$ values.

APPLICATIONS, LIMITATIONS, AND PRECAUTIONS

The applications of the DO sag method have been discussed earlier. However, the method has several important limiting factors. The oxygen sag method does not account for the following:

1. The continuous redistribution of both the BOD and oxygen by the effect of longitudinal dispersion.
2. Changes in channel configuration that alter the characteristics of surface turbulence and the reaeration rate, K_2.
3. Diurnal variation in oxygen content and water temperature.
4. The variation of K_1 over time.
5. The removal of oxygen from the water by diffusion into the intragravel layer.
6. The addition of BOD below the point of reference.
7. The effect of suspended and dissolved substances on the rate of diffusion of oxygen from the surface into the main body of the stream.
8. Nitrogenous BOD (the method assumes nitrogenous BOD does not occur).
9. Ponding.

CONCLUSIONS

Changes in dissolved oxygen concentration in streams resulting from silvicultural activities usually can be linked to changes in stream temperature and introduced organic debris. Control practices and abatement goals that meet temperature and sediment standards will also minimize the reduction of dissolved oxygen.

Introduced organic matter may contribute additional stress on dissolved oxygen concentration beyond that produced by increased water temperature. Primarily, the magnitude of the impact of organic matter on dissolved oxygen increases with:

1. The amount and type of organic debris entering the stream either directly or indirectly through runoff;
2. The extent to which the debris dams the stream course and produces pools, thus facilitating heating and reduction of reaeration; and
3. The length of time the debris remains in the stream water.

Steep slopes near the stream channel increase the probability of debris washoff, and a decrease in the stream channel gradient reduces the rate of reaeration.

Introduction of solid organic debris during silvicultural activities can be minimized or eliminated. Finer organic particles normally will enter a stream along with the surface eroded materials. For organic material to enter the stream via surface erosion in sufficient quantity to adversely affect the aquatic ecosystem, the quantity of eroded soils would have to be so large that it would present a problem in itself, overshadowing any deterioration of water quality due to the organic matter component.

Large debris can be prevented from entering the stream by felling trees away from the stream, by avoiding the stream in all skidding operations, and/or by leaving an adequate streamside zone. Froehlich (1976) found accelerated debris loading through logging to be most strongly related to the timber felling process. Conventional felling resulted in a fivefold increase in organic loading, whereas directional felling only doubled the load. Streamside zones provided a debris barrier that limited or totally prevented the loading increase, with effectiveness in restricting organic loading varying with width of the area.

Large debris deposited in a stream during a silvicultural activity normally should be removed as soon as possible. However, some large debris within a watercourse can provide stable and diverse habitats for biota. Removal of debris that have been in position for any extended period and have trapped considerable sediment normally should not be undertaken until the full impact (loss of habitat, increased turbidity, realignment of stream, etc.) is evaluated. A general policy for removal of all debris in a stream is unreasonable and could result in damage to water quality and aquatic habitat (Triska and Sedell 1977).

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