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OXYGEN-CONSUMING ORGANICS IN NONPOINT SOURCE RUNOFF

A LITERATURE REVIEW

by

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The objectives were to survey the recent literature, especially EPA Research Reports, and to summarize the findings on loadings of oxygen consuming material discharged to freshwater by nonpoint source runoff. Once the loadings of oxygen-using material were available, the next objective was to estimate the impact of these loadings upon the dissolved oxygen resources of freshwater systems and the ecological effects upon freshwater environments.

Unfortunately, there is a serious shortage of data upon surface accumulation rates, stream-side loading rates, and dissolved oxygen concentrations resulting from nonpoint source inputs all measured concurrently within the same watershed. The data available indicate that the oxygen-demanding loadings from urban runoff can be very significant, but that estimates of effects upon fish and other aquatic organisms must await more information.

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The objectives were to survey the recent literature, especially EPA Research Reports, and to summarize the findings on loadings of oxygen-consuming material discharged to freshwater by nonpoint source runoff. Once the loadings of oxygen-using material were available, the next objective was to estimate the impact of these loadings upon the dissolved oxygen resources of freshwater systems and the ecological effects upon freshwater environments.

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INTRODUCTION

Runoff from urban and rural areas can result in nonpoint source (NPS) pollution of the receiving waters (49, 64, 67, 70, 71, 77, 81, 83, 85, 88, 90, 94). Urban runoff has been shown to contain concentrations of biochemical oxygen demand (BOD), suspended solids, and coliform bacteria as great or greater than treated sewage effluents along with heavy metals and other toxic materials (2, 6, 11, 15, 56, 68, 70). Street dust, dirt, airborne particulates, and other such debris contribute much of the polluting material in urban runoff (2, 6, 60, 61, 68). Research shows this urban runoff contains suspended solids up to 2,000 mg/l, COD as high as 1,000 mg/l, total phosphorus as great as 15 mg/l, and fecal coliforms up to several thousand organisms per 100 ml (9, 11, 12, 15, 47, 94, 95, 100). Heavy metal concentrations are usually greater than in untreated domestic sewage (6, 21, 61, 70).

Rural NPS runoff, on the other hand, can include sediments, plant nutrients, pesticides, organic matter, minerals, and microorganisms. Agricultural, silvicultural, mining, and construction activities can be major sources of rural NPS (16, 33, 44, 48, 49, 79, 89, 91). Both urban and rural runoff have been shown to contain oxygen-consuming organic matter, a potential pollution problem addressed in this report (5, 11, 15, 31, 33, 34, 35, 38, 48, 50, 52, 62, 63, 64, 71, 77, 79). The oxygen-demanding capacity of both urban and rural NPS runoff will be characterized and the impact of the resulting deoxygenation upon fish will be explored.

Masses of pollutants and areal loading rates given in English units in literature references were recomputed in metric units for use in this report. A conversion table is included as an appendix.

SECTION 2

URBAN SOURCES OF NPS BIODEGRADABLE ORGANICS

Analyses of urban stormwater have been reported by several investigators (7, 9, 11, 12, 15, 17, 19, 21, 25, 26, 28, 35, 40, 47, 49, 50, 52, 60, 63, 64, 67, 68, 100). Estimates have been made of loading rates, often in terms of pounds per curb mile per day or kilograms per curb kilometer per day. Bradford (9) found an average loading rate of 44 kg per day per curb km of solids representing 0.87 kg BOD per curb kilometer per day.

Bryan initiated study of a 433-hectare drainage basin within the municipality of Durham, North Carolina. Runoff from the study basin was monitored for flow rate and for several important measures of water quality during 1969 and 1970. The urban basin gave an annual yield of 94.1 kg BOD/hectare along with 1,165 kg chemical oxygen demand (COD) per hectare, or 0.26 and 3.2 kg/hectare/day of BOD and COD, respectively. Most of the discharges took place during approximately 40 days of heavy rainfall which occurred during the two-year study, so the effects of pollutants in the receiving stream were considerably amplified (11).

Colston (15) studied the same basin as Bryan, continuing and expanding the effort from December 1971 through March 1973. The results indicate that urban runoff can influence downstream water quality during and following storms to a greater extent than sewage treatment plant effluent. Colston found that storm runoff carried 95 percent of the oxygen-demanding material (as COD) during periods of rainfall which amounted to 19 percent of the time during the study period (15). Colston also reported that the average BOD was 35 mg/l (calculated from COD data). Problems observed with the BOD determinations were thought to result from inhibitory compounds present in the urban runoff. Colston found that as much as 41.3 kg of BOD/hectare/day washed off the urban watershed under study during a severe storm while the average annual loading rate was 358 kg/hectare/year (15).

Sartor et al. reported a mean of 3.8 kg BOD per curb km for street surface contaminants (67, 68). This weighted average assumes from 2 to 10 days buildup since the last rain or street sweeping. They also calculated that a 1-hour storm on a city with a population of 100,000 and an area of 5,670 hectares would result in the discharge of 2,540 kg of BOD per hour from urban runoff to the receiving stream, about 5 times greater than the BOD in the raw sewage generated in the city during that 1-hour period.

Field and Lager reported on the state-of-the-art in urban runoff control (28). Whipple et al. found from 0.27 kg BOD/ha/day to 0.485 kg BOD/hectare/day loadings for New Jersey urban areas. These investigators suggested that for planning purposes, a value of 9.1 to 13.6 grams BOD/person/day be used in predicting NPS loadings from clean urban areas (100). Yu et al. reported stream water BOD values as high as 100 mg/l in streams receiving urban-industrial NPS runoff with an increase from a mean of 9.0 mg/l in dry weather to a mean of 17.4 mg/l in wet weather. Loadings of oxygen-demanding materials increased as much as 10-fold after rainfall washed urban NPS materials into the stream (105). Whipple has published extensively on urban runoff pollution (97, 98, 99, 101).

Angino et al. found that the BOD concentration in runoff from an area of 186 hectares of residential housing in Lawrence, Kansas approximately doubled following a rainstorm, rising from 6.7 mg/l to 11.4 mg/l (3).

Wanielista et al. sampled urban stormwater in central Florida with BOD concentrations up to 700 mg/l. BOD loadings rates of 75 kg/hectare/year were also given (91). Mills reported that flow-weighted mean concentrations of BOD in urban runoff ranged from 4 mg/l to 188 mg/l for different storms monitored in East York, Canada (55).

Lager and Smith prepared an assessment in 1974 for the U.S. Environmental Protection Agency (EPA) covering characteristics of urban stormwater, environmental effects and management alternatives and technology (47). A similar update was published in 1977 (46).

Pitt and Amy reported on the toxic materials found in street surface contaminants collected during the project URS Research Company did for EPA (61). Sartor and Boyd reported on the street surface contaminants in a separate report (67). The greatest loading rates for heavy metals came from industrial land-use areas. Metals in street runoff were found to be present in greater concentrations than in sanitary sewage. Other toxicants were also found. Perhaps the inhibitory effect of toxic compounds in urban runoff are the cause of problems with BOD determinations reported by several investigators (61).

The American Public Works Association contracted with the Federal Water Pollution Control Administration to perform an early study of the water pollution aspects of urban storm water (2). The emphasis of this report was on the sources of street surface contaminants and the effects of different control measures. The Franklin Institute prepared abstracts of papers on urban storm water runoff (30). Cleveland et al. studied the stormwater pollutant loadings from 12 small drainage areas in Tulsa, Oklahoma. They found BOD loadings as high as 34 kg/ha over the spring season with an annual average loading of 34 kg/hectare/year for all the basins (14).

Field edited the proceedings of a workshop on management of urban runoff which includes data from case studies (27). A series of urban stormwater studies have been sponsored by EPA. Davis and Borchardt described the Des Moines, Iowa and Des Moines River situation with respect to combined sewer overflows and urban storm drainage. They found urban stormwater averaged 53 mg/l BOD yielding 1,210,200 kg BOD per year from 18,225 hectares served by separate storm sewers. The annual average loading rate was thus 66.4 kg BOD/hectare/year (19). Holbrook et al. presented an update of the Atlanta stormwater situation (39).

The Sacramento, California situation was studied by the Envirogenics Company. There it was found that storm runoff from separate storm drains had BOD values as high as 280 mg/l. Reliable flow data were not available, so loading rates were not computed (25). AVCO Economic Systems Corporation studied the Tulsa, Oklahoma stormwater runoff situation. Those findings resulted in calculated average yearly loads of BOD for each of the 15 test basins ranging from 13.4 to 54 kg/hectare/year (6). Wullschleger et al. recommended standard procedures for collecting data on quality and quantity of urban storm runoff (104). Field et al. reviewed the EPA urban pollution control group's programs presenting a useful listing of reports and publications as well as a summary of past projects (29).

A three-volume evaluation of combined sewer overflows and urban stormwater discharges was prepared for EPA by the American Public Works Association in cooperation with the University of Florida (36, 50, 81). Volume II covers cost assessment and impacts of storm runoff (36). Heaney et al. used data from 25 drainage basins in seven cities to compute an average annual loading rate proportional to precipitation for storm runoff in urban areas with separate sewer systems (36). This average loading rate was then used to predict loadings for other studies. The average value for the United States was 34 kg/hectare/year for urban areas with separate sewer sytems. The loading rate for different urban areas with separate sewers ranged from a low of 3.9 kg/hectare/year for Las Vegas, Nevada to a high of 69 kg/ha/year for New Orleans, Louisiana. The authors took great pains to point out the many assumptions involved in the development of the equation used in these predictions. They stated

> "... Unquestionably, the data base for estimating pollutant loads is very weak, and the resulting estimating equation, supported by such a weak foundation should be used with extreme caution." They also omitted data from Durham, North Carolina; Bucyrus, Ohio; and Atlanta, Georgia in computing the averaged factor for loading rate as a function of a population density and annual precipitation because "... Atlanta, Bucyrus, and Durham ... produce very high results compared to the bulk of the data" (36).

Manning et al. in Volume III of the series did a good job in characterizing urban stormwater quality, sources of pollution, and receiving water impacts (50). The other volume in this series is an executive summary of the entire project (81). It also includes additional details on some of the model studies and a case study of receiving water impacts for the Des Moines, Iowa situation (81).

Oberts presented a literature review of best management practices for urban runoff control (59). Sylvester and Brown reported on the relationship between land use and quality of storm runoff in California (83).

SECTION 3

RURAL SOURCES OF NPS BIOEGRADABLE ORGANICS

NPS runoff resulting from agriculture, silviculture, and construction activities can also carry oxygen-demanding organic matter into receiving streams (5, 61, 43, 44, 48, 49, 76, 77, 89, 90, 91).

Weidner et al. found up to 134 kg BOD/hectare/year washed from Ohio corn fields (96). Whipple and Hunter reported 8.75 to 51 grams BOD/hectare/day from New Jersey farmlands. Woodlands in New Jersey yielded from 10 to 19 grams/hectare/day (99). Wanielista et al. reported average loading rates in Florida of 11 kg BOD/hectare/year for pasture land, and 5 kg/hectare/year for woodland (91).

Harms et al. reported COD loadings for various rural land uses. Cultivated land produced an average loading of 4 kg g/hectare/year while pasture land averaged 28 kg/hectare/year and alfalfa and brome grass contributed only 13.4 kg/hectare/year (33).

BOD concentrations from 6 to 15 mg/l were found in streams draining agricultural lands during the Black Creek Project. Estimates of loading rates included 0.33 kg/hectare during a 7.1 cm rainfall event (48). Loehr reported BOD concentrations of 7 mg/l in range land runoff with loading rates from 0.017 to 0.094 kg/hectare/day for agricultural lands used for manure disposal (49).

Hall and Lantz reported depletion of dissolved oxygen downstream from logging operations in the Oregon Coast Range. Dissolved oxygen concentrations lower than 1 mg/l were measured (31). Slack found leaf fall resulted in reduced dissolved oxygen concentrations in stream pools (76). Slack and Feltz also reported tree leaf fall responsible for reducing DO concentrations to less than 1 mg/l in a small Virginia stream. At the same time increases in manganese, bicarbonate, specific conductance and color were measured (77).

Yu et al. reported the BOD in streams draining woodland increased during wet weather, with cropland streams showing greater BOD than woodland streams, while streams in residential areas contained even more BOD than those in croplands (105).

Hobbie and Likens found that from 10.44 to 13.84 kg/hectare/year of organic matter (sum of dissolved and particulate) were exported from Hubbard Brook forested watersheds (38).

Stewart *et al*. reported on the measures useful in controlling water pollution from cropland (79). Seitz *et al*., in a report for EPA, presented alternative policies for controlling agricultural sources of NPS pollution (69). Another EPA report covers methods for evaluating NPS pollutants from agriculture, silviculture, mining, and construction (86).

Many of the articles and reports on rural NPS runoff ephasize particulates from soil erosion or plant nutrients such as phosphates and nitrates and do not report on oxygen-demanding organic matter (16, 22, 43, 44, 48, 79). Others refer to physical changes which may occur along with nonpoint source pollution (82).

SECTION 4

THE IMPACT OF NPS UPON STREAM DISSOLVED OXYGEN

The significant organic matter content of urban NPS runoff has been reasonably well documented (8, 9, 11, 15, 21, 35, 47, 64, 68, 88, 90, 91, 94). There is even some evidence of the oxygen-demanding capacity of rural NPS runoff (31, 49, 76, 77, 96). On the other hand, there is almost no direct evidence of the effect of stormwater runoff on the dissolved oxygen resources of receiving waters. Vitale and Spey stated in a report for the Council on Environmental Quality, "... unfortunately, monitoring of DO profiles during storm events is a rarity. DO profiles taken simultaneously with measured storm loads are almost nonexistent" (88). Because of this lack of empirical data, the projection of stormwater impacts upon DO has usually been made using various mathematical models of stream deoxygenation/reaeration along with measured or estimated loading rates for storm runoff, sewage treatment plant discharges, and upstream BOD loads.

Colston compared the total annual yield of pollutants from urban runoff to sewer-carried municipal wastewater pollutants for a drainage basin in Durham, North Carolina. He reported that urban runoff and upstream additions provided 48 percent of the BOD, 41 percent of the ultimate BOD, and 95 percent of the suspended solids produced in the basin, including raw municipal wastewater (15).

Colston made model studies of the oxygen sag in Third Fork Creek resulting from the combination of urban runoff and sewage treatment plant effluent. During storm events, the model simulation showed the effects of sewage treatment plant effluent to the undetectable in oxygen sag computations. Storm runoff was found to contain 82 percent of the COD, 77 percent of the ultimate BOD, and 99 percent of the suspended solids added to the receiving stream during the storm (see Table 1).

TABLE 1. TOTAL YIELD OF POLLUTANTS DURING STORM PERIODS FROM URBAN RUNOFF AND RAW MUNICIPAL WASTES IN KG/HECTARE DURING 1972. From Colston (15).

Parameter	Raw municipal wastes	Urban runoff	Total	Percent	
				Municipal	Runoff
COD	218	1,000	1,220	18	82
Ultimate BOD	146	500	646	23	77
Suspended Solids	72	7,410	7,482	1	99

Colston concluded that even if Durham provided 100 percent removal of pollutants from municipal wastewater during wet weather, "... it would represent an overall reduction of only 18, 23, and 1 percent of BOD, ultimate BOD, and suspended solids to the receiving water course." In addition, Colston found that approximately 20 percent of the time downstream water quality was controlled by urban runoff rather than municipal waste discharges (15).

Davis and Borchardt investigated the NPS problem in Des Moines, Iowa (19). Sullivan et al. (81) summarized the impact of the Des Moines urban runoff reported by Davis and Borchardt. Taking the total upstream drainage area of the Raccoon River and the Des Moines River, which join within the city, and adding the urban area NPS loadings to the upstream loadings indicated that total loadings per year were 31,751,466 kg of BOD, 11,521,250 kg of nitrate, and 3,606,059 kg of phosphate. The urban area loadings represent 15 percent of the total BOD, 3 percent of the total nitrate, and 51 percent of the total phosphate loadings to the river. The available data were then applied to simulations of runoff and stream dissolved oxygen. Stream DO was simulated using a Streeter-Phelps formulation. Based on National Oceanographic and Atmospheric Administration records, the total precipitation during the study year (1968) was 70.1 cm. The estimated runoff was 26.1 cm over a watershed area of 19,600 ha for an overall urban area runoff coefficient of 0.37. Four alternatives for reduction of water pollution were explored:

1. secondary treatment for dry weather flow alone;

2. tertiary treatment of dry weather flow alone;

3. secondary treatment of dry weather flow with 75 percent treatment of wet weather flow;

4. secondary treatment of dry weather flow with 25 percent treatment of wet weather flow.

The simulation results indicated that wet weather flow (urban runoff) greatly affected dissolved oxygen during storm events. Secondary treatment of dry weather flow along with removal of 25 percent of the BOD from wet weather flow resulted in fewer violations of BOD standards than would result from tertiary treatment of dry weather flow alone--and at much less cost. Removal of 75 percent of the BOD in wet weather flow along with secondary treatment of dry weather flow was predicted to result in violation of DO standards during only 3 percent of the precipitation events, and still cost less than tertiary treatment of dry weather flow alone (see Figure 1). Davis and Borchardt found that during storms ranging from 4.4 mm to 152.3 mm, the pollution loading from the Des Moines metropolitan area greatly exceeded the average daily loading from dry weather sources (19).

These results point up the serious need to consider the results of urban runoff before requiring tertiary treatment, and that control of wet weather discharges can be very important in achieving "fishable, swimmable waters."

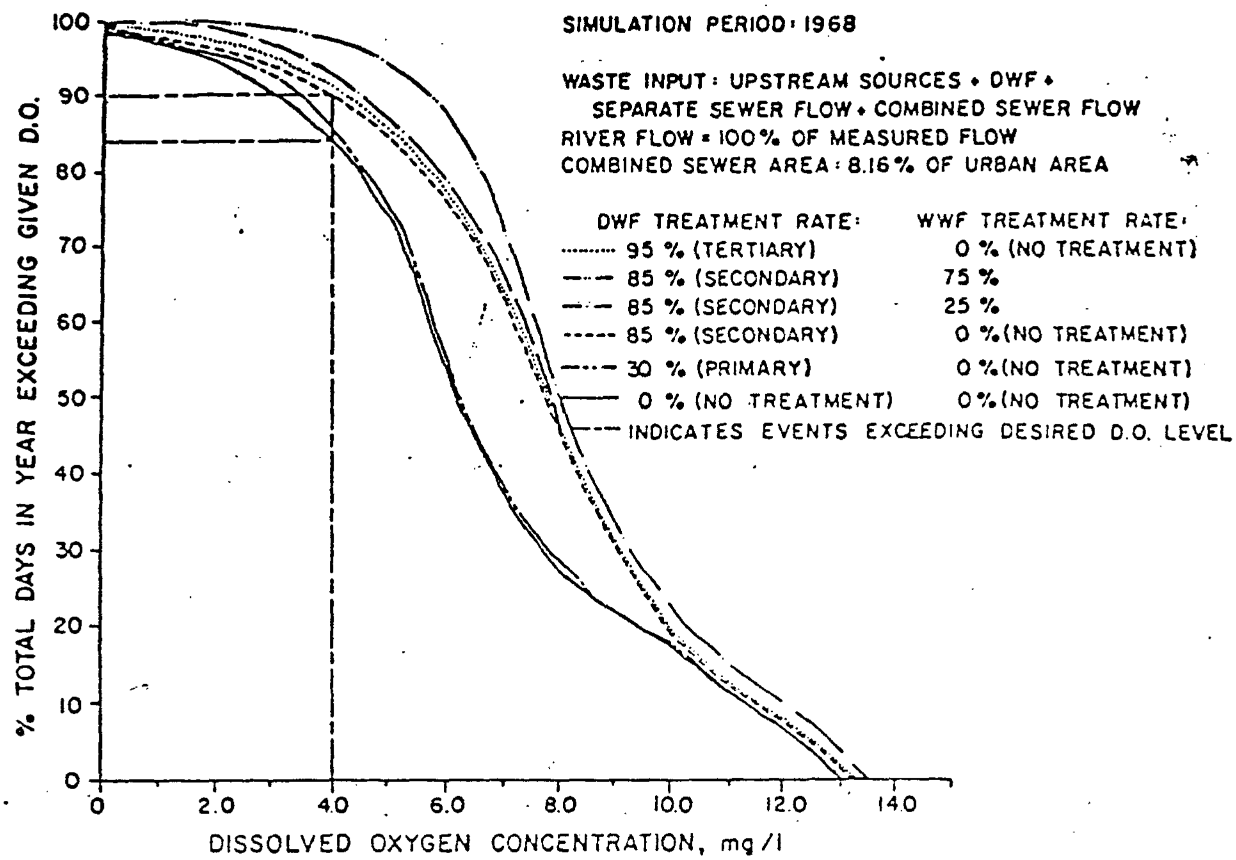

Figure 1. Annual minimum DO frequency curves. From Sullivan et al. (81).

Sartor and Boyd (67) reported the results of a study of street surface contaminants in twelve U.S. cities. They summarized the significance of street surface runoff upon receiving water quality by comparing the runoff from the streets of a hypothetical city with a population of 100,000 persons, total land area of 5,670 hectares, 644 curb kilometers of streets, and an average sewage flow of 45,420 cubic meters per day. Table 2 taken from the report by Sartor and Boyd indicates that over 50 times as much BOD would be washed off by a 1-hour storm event than would be discharged from a good secondary treatment plant serving the city. Even if untreated sewage is used for comparison, the runoff during the first hour of a storm could be expected to wash more pollutants into the receiving stream than would be discharged during that time by untreated sewage produced within the city (see Table 3).

Holbrook et al. used the dissolved oxygen model DOSAG to simulate the effects of rainfall in the Peachtree Creek basin. Results indicated a significant reduction in the DO for the Chattahoochee River from even a 1.0 cm rain. The DO at the sag point dropped to 1.4 mg/l (39).

Hammer cited data for the Passaic River which indicated that reductions in dissolved oxygen followed increases in stream flow after storms. The suggestion was made that the increased consumption of oxygen was caused by nonpoint source runoff input as well as resuspension of oxygen-demanding

TABLE 2. COMPARISON OF POLLUTIONAL LOADS FROM HYPOTHETICAL CITY-STREET RUNOFF vs GOOD SECONDARY EFFLUENT. From Sartor and Boyd (67).

	Contaminant Load on Receiving Waters Street Surface Runoff (kg/hr)	Effluent from Good Secondary Treatment Plant		Ratio (Street/Sewage)
		(% removal)[a]	(kg/hr)[b]	
Settleable + Suspended Solids[d]	254,016	90	59	4,300
BOD[d]	2,540	90	50	51
COD[d]	5,897	90	54	110
Total Coliform Bacteria	40×10^{12} Organisms/hr	99.99	4.6×10^{10} Organisms/hr	870
Kjeldahl Nitrogen[d]	400	90	9.1	44
Phosphates[d]	200	95	1.1	180

[a] Typical removal efficiences for waste treatment plants.
[b] Loadings discharged to receiving waters (average hourly rate).
[c] Ratio of loadings: street runoff/sanitary discharge.
[d] Weighted averages by land use, all others from numerical means.

Metric units computed from English units in reference (67).

TABLE 3. COMPARISON OF POLLUTIONAL LOADS FROM HYPOTHETICAL CITY-STREET RUNOFF vs RAW SANITARY SEWAGE. From Sarton and Boyd (67).

	Contaminant Loads on Receiving Waters Street Surface Runoff (kg/hr)	Raw Sanitary Sewage		Ratio Street/Sewage[b]
		(mg/l)	(kg/hr)[a]	
Settleable + Suspended Solids[c]	254,016	300	590	430
BOD_5[c]	2,540	250	499	5.1
COD[c]	5,897	270	544	11
Total Coliform Bacteria	40×10^{12} Organisms/hr	250×10^{6} Organisms/liter[e]	4.6×10^{14} Organisms/hr	0.0087
Kjeldahl Nitrogen[c]	400	50[f]	95	4.2
Phosphates	200	12[d]	23	8.7
Zinc	118	0.20[h]	0.38	310
Copper	36	0.04[h]	0.08	450
Lead	104	0.03[h]	0.06	1,733
Nickel	9.1	0.01[h]	0.019	480
Mercury	13	0.07[g]	0.12	108
Chromium	20	0.04[h]	0.08	250

[a] Loadings discharged to receiving waters (average hourly rate).
[b] Ratio of loadings: street runoff/sanitary discharge.
[c] Weighted averages by land use, all others from numerical mean.
[d] Reference 10.
[e] Reference 35.
[f] Reference 36.
[g] Reference 37.
[h] San Jose-Santa Clara Water Pollution Control Plant, averages for January 1970, personal communication.

Metric units computed from English units given in reference (67).

sediments from the river bed. No attempt was made to assign a fraction of total oxygen demand to nonpoint source runoff or to resuspended sediment. However, the immediate cause of increased oxygen consumption seemed to be storm-runoff activated (32). Hammer cited the Castro Valley Creek, California study, referenced by Lager and Smith (47), which seems to be a case of increased BOD due to storm runoff resulting in lower DO concentrations in the receiving water (32) (see Table 4).

Rimmer *et al*. reported an average reduction in stream DO of about 1 mg/l following storm events in the Research Triangle area of North Carolina (65).

TABLE 4. STORM SEWER DISCHARGE QUALITY FROM A 5 SQUARE MILE URBAN WATERSHED TO CASTRO VALLEY CREEK, CALIFORNIA. From Lager and Smith (47).

		San Francisco Bay[a] 1960-1964			Castro Valley Creek							
Parameter		South Bay	Lower Bay	Upper Bay	Storm of 11 Nov 71	Storm of 13 Nov 17	Storm of 2 Dec 71	Storm of 9 Dec 71	Storm of 22 Dec 71	Storm of 27 Dec 71	Storm of 25 Jan 72	Storm of 5 Apr 72
Temperature, °C	low	9.3	10.7		14.5		9.5	8.5		8.0	7.5	
	mean	16.3	14.8	14.5		13.0			11.0			15.0
	high	24.0	21.0		15.0		10.5	10.5		9.0	8.5	
pH	low	7.2	7.8		6.7	6.7	5.4	6.6	6.0	6.6	6.2	
	mean	7.6	7.9	7.7								7.2
	high	8.0	8.1		7.0	6.9	6.4	7.4	6.4	6.9	6.8	
DO, mg/l	low	0.7	7.0		4.4		9.5	9.0	9.4			6.4
	mean	5.1	7.4	7.9		8.1				10.4		
	high	8.3	8.5		5.1	6.9	10.3	9.6	10.0			6.9
DO, % saturation	low	9	81		43	84	79	85			63	
	mean	55	90	77					88			68
	high	92	99		50	90	86	90			68	
BOD_5, mg/l	low	0.5	0.4		6.7	6.7	4.0	10.0	1.7	1.7	4.7	2.6
	mean	10	0.8	0.8	44							
	high	48	1.5				9.5	11.0	5.0	2.2	6.0	37.0
Ammonia nitrogen, mg/l	low	---	0.06		1.2	0.4	0.3	0.1	0.2	0.1	0.3	0.3
	mean	3	0.12	0.1								
	high	11	0.21		2.3	0.6	0.7	0.4	0.3	0.2	0.4	1.0
Nitrage nitrogen, mg/l	low	0.05	0.08		0	1.5	0.6	0.3		1.8	0.6	0
	mean	0.35	0.34	0.3					---			
	high	1.1	0.55		1.4	1.7	1.2	3.3		2.3	0.9	4.2
Dissolved silica, mg/l	low	2.3	2.9									
	mean	8.7	5.4	6.5	7.1	3.3	1.5	12.0	2.2	7	3.1	7.6
	high	16	7.7									
Total coliform bacteria,	low	10	10					4,200	9,500	5,200	*	16,000
	mean	20,000	500	1,000	---	---	>16,000				*	
	high	3×10^8	30,000					41,000	12,500	16,200	*	63,000

[a] From "Interim Water Quality Control Plan, San Francisco Bay Basin," California Regional Water Quality Control Board, San Francisco Bay Region, June 1971.
* Determination pending.

SECTION 5

EFFECTS OF DO DEPLETION UPON FISH

Several reports summarize the literature on the oxygen requirements of fish (4, 18, 23, 24, 41, 58, 84, 87, 92, 93). More attention has been given to salmonids than to other groups of fish (18, 20, 31, 37, 51, 72, 75, 102, 103). Separate standards have often been proposed or established for coldwater salmonids and for warmwater fish (4, 41, 84).

SALMONIDS

Salmonids are often considered especially sensitive to dissolved oxygen concentration not only because their normal habitat is cold, well-oxygenated water, but also because of their spawning habits and the oxygen requirements of the developing eggs and larvae (1, 4, 13, 18, 37, 51, 58, 75).

Warren (92) reported reduced growth of coho salmon at 20°C when held in water containing 5 mg/l DO compared to controls maintained near air saturation (7.9 - 8.5 mg/l). Even at 6 mg/l, some depression of growth was observed. Alderdice et al. reported on the effects of low dissolved oxygen on salmon eggs (1). Davison et al. did experiments on the dissolved oxygen requirements of salmonids (20).

Hermann et al. reported on the continuing efforts of an Oregon State University group on oxygen requirements of salmon (37). Another paper from that group reported on the interaction of dissolved oxygen concentration with water velocity in regard to the developing embryos of steelhead trout and chinook salmon (75).

Doudoroff and Warren summarized the dissolved oxygen requirements of fish at a seminar held in 1962 (24). They discussed the effects of DO concentration on swimming performance, appetite and growth, embryonic development, and avoidance reactions. It was their conclusion that the complex DO standard proposed by the Ohio River Valley Water Sanitation Commission (ORSANCO) Aquatic Life Advisory Committee (4) is not easy to enforce and does not seem to be supported by the results of intermittent exposure of coho salmon and largemouth bass to diurnal variations of DO. They concluded that "... Simpler criteria apparently can be at least as satisfactory and defensible." However, they did not make exact recommendations as to what the criteria should be (24).

Whitworth found that reducing the DO concentration from 10.6 mg/l to 5.3 mg/l in a diurnal manner resulted in reduced growth of brook trout (102). Mason found that embryos and fry of coho salmon exposed to 3 mg/l or 5 mg/l DO were smaller at hatching than were controls exposed to 11.0 mg/l (51).

Doudoroff and Shumway recommended dissolved oxygen criteria based on allowable perturbations from the seasonal minimum concentration. They presented curves of allowable DO for four different levels of protection depending upon the importance of the fishery and the most beneficial use of the waterway (23).

Itazawa measured the DO concentration required to maintain arterial blood at normal oxygen levels. He found rainbow trout required about 60 percent saturation at temperatures near 10°C and carp required about 50 percent saturation from 13 - 23°C (42).

Warren et al. proposed minimum DO requirements for different temperatures using largemouth bass and coho salmon as examples of warmwater fish and coldwater fish, respectively. A reduction of 10 percent in production of coho salmon resulted at 5.0 mg/l DO and water temperatures of 18 - 20°C or at 5.7 mg/l and a water temperature of 22°C (93).

The National Academy of Sciences/National Academy of Engineering (NAS/NAE) prepared a volume on water quality criteria for the Environmental Protection Agency (58). Those experts preparing the dissolved oxygen criteria for freshwater aquatic life adopted the approach of Doudoroff and Shumway (23) and presented four levels of protection. Levels of Nearly Maximum, High, Moderate, and Low protection were presented with levels of allowable DO reduction referenced to seasonal minima under "natural" conditions. Equations of the curves prepared by Doudoroff and Shumway are given to allow calculation of the allowable minimum DO concentration at existing water temperatures. A minimum concentration of 4.0 mg/l is recommended as a floor value and consideration is given to the situation within stratified lakes (58).

Carlson and Siefert reported that reduction of DO to any concentration less than saturation resulted in slowing the larval growth of lake trout (13). Davis, in a report for the National Research Council of Canada, also followed the lead of Doudoroff and Shumway in setting several levels of protection with respect to DO concentration. Davis made extensive use of blood oxygen dissociation curves in establishing what he called "incipient dissolved oxygen response thresholds" which he then used in setting minimum DO requirements. Tables of percent saturation at temperatures of 0, 5, 10, 15, 20, and 25°C are presented for each level of protection (18).

The U.S. Environmental Protection Agency officially adopted quality criteria for water based on the NAS/NAE REPORT. Dissolved oxygen standards for freshwater fish were adopted with a minimum concentration required to maintain a healthy fish population set at 5.0 mg/l. For salmonid spawning beds, a minimum of 5.0 mg/l should be present in the interstitial water of the gravel (87).

NON-SALMONID FISH

A number of investigators have explored the oxygen requirements of warmwater fishes. Katz and Gaufin found that low DO resulting from wastewater discharges made stream habitat unavailable for warmwater fish. They also reported the absence of fish from zones of a sewage-polluted stream where "sewage fungus" covered the stream bottom, even when oxygen was plentiful in those reaches (45).

The Aquatic Life Advisory Committee of ORSANCO set 5 mg/l as the minimum DO concentration for maintenance of a balanced fish population. However, their suggested criteria would allow declines below 5.0 mg/l for up to 8 hours per day if the minimum was never below 3.0 mg/l (4).

In 1958, Tarzwell recommended 5.0 mg/l as the minimum DO concentration for warmwater fish and 6.0 mg/l for salmonid fish (84). Moss and Scott studied the oxygen requirements of three warmwater fish--bluegills, largemouth bass, and channel catfish. All three species were reported able to survive for 24 hours at approximately 1.0 mg/l DO at a temperature of 25°C (57). For warmwater fish, Huet recommended 70 percent of the saturation concentration with temporary depressions allowed to 3.0 mg/l (41).

LONG TERM EFFECTS OF REDUCED DO

Doudoroff and Warren point out that "... it is now generally realized that fishes cannot be expected to thrive in their natural habitat at barely nonlethal oxygen concentrations." Swimming speed of largemouth bass was reported to be virtually independent of oxygen concentration above 5 mg/l, but decreased when DO was decreased below 5 mg/l. Juvenile largemouth bass and bluegills avoided concentrations of DO near 1.5 mg/l but showed little or no avoidance near 3.0 and 4.5 mg/l. The growth rates of largemouth bass were reduced at constant DO concentrations of 5.0 mg/l (24).

Stewart et al. found that reductions of DO below saturation resulted in a decreased growth rate of largemouth bass held in constant DO concentrations. They also reported that bass subjected to diurnal variations in DO grew more slowly than those held at constant DO concentrations near the mean of the alternate high and low concentrations (80).

Doudoroff and Shumway reviewed worldwide data on oxygen requirements of fish. Their report covered warmwater fish as well as the salmonids mentioned earlier (23).

Brungs carried out life cycle studies with fathead minnows grown under different concentrations of dissolved oxygen. Egg production per female at 3 mg/l or greater DO concentration was comparable to those at the 7.2 mg/l control concentration. However, only 6 percent of the hatch survived at 3 mg/l for 30 days after fertilization and only 24 percent at 4 mg/l. Hatch survival at 5 mg/l DO was comparable to the controls, but growth was significantly less than under the control conditions of 7.2 mg/l (10).

Itazawa found that carp required approximately 50 percent air saturation at temperatures from 13 - 23°C in order to maintain the normal levels of oxygen in arterial blood (42). Siefert et al. reported that northern pike embryos and larvae survived amost as well at 50 percent saturation and 15°C as at 100 percent saturation (73). Carlson and Siefert studied the effects of reduced oxygen concentration upon largemouth bass embryos and larvae. They found comparable hatching and survival at 70 percent saturation at 20 or 23°C, but growth of the fry was reduced at both temperatures compared to controls held at air saturation (13).

Siefert et al. reported on the effects of reduced oxygen concentration on the early stages of smallmouth bass. Nearly a 20 percent reduction in survival and a reduced growth rate was noted for smallmouth bass exposed to a continuous DO concentration of 50 percent saturation and a temperature of 20°C. At 7°C survival was similar in both 50 percent and 100 percent air saturation, but hatching was delayed from 7 to 11 days at 50 percent (74).

Warren et al. used largemouth bass as a representative warmwater fish. They reported that growth rate was reduced upon exposure to reduced concentrations of DO. Minimum DO concentrations were proposed based on the concentrations resulting in reductions of 10 percent in growth rate. These concentrations were 4.7 mg/l, 5.1 mg/l, and 5.5 mg/l at temperatures of 26°C, 29°C, and 20°C, respectively.

The U.S. Environmental Protection Agency adopted quality criteria for water after consideration of the NAS/NAE report. Five mg/l was chosen as the minimum concentration of dissolved oxygen for aquatic life. This standard does not allow for excursions of DO below 5 mg/l even for short periods (87).

There is a lack of reliable data about the effects of transient low DO conditions upon fish. The deoxygenation effects resulting from storm runoff can be expected to persist for only a few hours at a particular stream location. If the low DO concentration does not reach a lethal level, what will the impact be upon fish and other aquatic organisms? Depletion of DO lasting for 8 to 12 hours out of each 24 seems harmful to the growth of fish (23, 24, 80, 93, 102). However, these data do not tell us what would result from one depletion period of 12 hours a week. Research is needed to explain the effects of such intermittent pollution. Meaningful experiments could perhaps be performed in artificial streams where dissolved oxygen could be controlled, but where other conditions could be kept realistic. Such controlled conditions would also allow separation of transient DO effects due to storm runoff from the related effects of combined sewer overflows and point source discharges.

SECTION 6

DISCUSSION AND CONCLUSIONS

The oxygen-consuming effects of urban nonpoint source runoff have been well documented (26, 28, 47, 50, 94). Input of BOD from nonpoint sources has been shown by modeling and simulation to be the controlling influence on dissolved oxygen concentrations during and after storm events (6, 15, 19, 47, 50, 67, 100). Several studies have shown that collection and treatment of urban runoff to about 75 percent removal of BOD would be more beneficial and cost effective than tertiary treatment of dry weather wastewater flows (15, 18, 81). Table 5 contains a compilation of data from 19 locations around the nation comparing annual average NPS loadings to the BOD loadings which occur during rain storms. Note the spread of loading rates from areas of different land use and different rainfall. Also note the great difference in loading rates between the annual average (or dry weather rate) and the short term rate during and after rainfall. The shock loads of oxygen-demanding material washed into rivers by storm runoff can cause intermittent problems of greater severity than the average loadings would if discharged continuously.

It is not easy to show widespread problems resulting from rural NPS oxygen demands. There have been reports of leaf fall resulting in deoxygenation in stream pools (76, 77). Certain silviculture operations can cause deoxygenation in small streams (31). Deoxygenation can also result from cattle feedlot runoff, but this type of problem is usually considered with point source discharges. The water quality problem resulting from rural NPS runoff are generally related to soil erosion and sediments, plant nutrients from agricultural lands, or toxic materials such as pesticides (16, 33, 49, 105).

The impact of nonpoint source deoxygenation upon fish is difficult to assess. The effects of even the more obvious urban runoff situations are usually confused because of the presence of point source discharges and/or other constituents in urban runoff such as suspended solids, heavy metals, and organic toxicants. For this reason, mathematical modeling has been heavily used to demonstrate the effects of NPS upon dissolved oxygen (15, 21, 36, 54, 78, 81, 89, 90).

It has been well documented that continuous depletion of DO is harmful to fish even at levels well above the lethal level. This seems equally true for salmonids and for those species usually considered warmwater dwellers such as largemouth bass (13, 18, 23, 24, 37, 57, 58).

TABLE 5. SURFACE BOD LOADING RATES FOR NPS RUNOFF

Location	Site or Station	Land Use	Wet Weather Rate (kg/hectare/day)	Annual Average or Dry Weather Rate (kg/hectare/day)	Reference
Durham, NC	M (10/2/69)	Urban	2.86	0.258	11
" "	M (7/26/69)	Urban	0.487	0.258	11
" "	Main (Storm 17)	Urban	3.09	0.980	15
" "	(Storm 21)	Urban	41.31	"	15
Mile Run, NJ	-----	Urban	1.40	0.484	100
Morristown, NJ	-----	Urban	0.269	0.133	100
Orlando, FL	-----	Residential	0.631	0.204	91
" "	-----	Commercial	0.848	0.137	91
" "	-----	Rural	0.0843	0.0266	91
Maryland	Rock Creek	Suburban, Residential	0.222	0.0526	63
West Lafayette, IN	Urban	Residential	1.79	-----	53
Greenfield, MA	-----	Urban	0.470	0.102	21
Des Moines, IA	D-11	Urban	1.86	0.181	19
Tulsa, OK	Site 15	Urban	2.15	0.0772	6
Atlanta, GA	Station 5	Urban	1.29	0.782	8
Occoquan Watershed, VA	Lower Bull Run	Residential/ Urban	0.403	0.037	64
" " "	Flat Branch	Urban	0.627	0.046	64
" " "	Portner Avenue	Commercial/ Urban	0.784	0.072	64
Roanoke, VA	24th Street	Urban Mix	0.171	0.051	35
" "	Murray Run	Residential/ Suburban	0.332	0.102	35
" "	Trout Run	Residential/ Urban	0.436	0.019	35
Washington, DC	Good Hope Run (8/9/69)	Urban	1.17	0.0735	66
" "	" " " (7/28/69)		1.06	0.0735	66

On the other hand, the effects of transient DO depletions due to storm runoff is less clearcut. Fluctuating DO concentrations between the air saturation concentration and concentrations of 60-65 percent of saturation have been shown to result in reduced growth rates for juvenile fish when the daily exposure periods at the high and low concentrations were both about 12 hours. In fact, fish held under these conditions grew only slightly faster than comparable groups of fish held continuously at the lower concentration (23, 24, 80, 93, 102). Fish kills could result from NPS runoff, of course, if oxygen concentration were depressed to lethal levels.

There seems to be no readily available answer to the crucial question about NPS deoxygenation. What is the impact of occasional reductions in oxygen concentration caused by NPS pollutants? No unequivocal answer is available. However, from the information which is available, it seems probable that even short term depressions of DO concentration resulting several times per year from NPS runoff could possibly result in decreased growth and productivity of balanced fish populations. Concentrations of DO somewhat above lethal concentrations probably affect reproductive success, decrease growth rates, and affect competitive interactions. When the deoxygenation occurs along with increased sediment loadings and potentially toxic materials such as heavy metals (also carried by NPS runoff), there is increased probability of damage to fish.

Controlled experiments designed to quantitatively measure the impact of transient low DO concentrations upon fish or other aquatic organisms would seem difficult, expensive, and time consuming. However, they are necessary in order to conclusively answer this crucial question. The ecological effects of other aspects of NPS runoff such as heavy metals, sediments, increased peak flows, and channel modification would also seem deserving of attention.

Some encouragement has been given to EPA for the development of separate criteria for water quality during storm flows, often called "wet weather criteria." Such criteria would give consideration to the transient nature of storm events and allow for decreased water quality during such periods. Arguments in favor of such relaxed criteria include reduced costs for storage and treatment, current failure to meet existing criteria during storm events, and little evidence of harm to aquatic life during storm runoff.

On the other hand, there is little evidence that storm discharges do not harm aquatic life, especially from solids which settle in receiving streams to continue affecting water quality long after the storm flow subsides. Such solids can destroy habitat, use dissolved oxygen, and release potentially toxic compounds over long periods of time. They may become resuspended during the next storm event and again contribute to another acute episode.

The same measures which would reduce organic loadings in NPS runoff can also be expected to reduce the loadings of other pollutants such as sediments, toxic chemicals, and plant nutrients. Therefore, encouragement should be given to those practices which can reduce the BOD load of NPS runoff, help meet stream standards for dissolved oxygen concentration, and at the same time result in other improvements in water quality.

This study revealed two areas where research is badly needed. Controlled experiments on the impact of occasional transient depletion of dissolved oxygen upon fish are entirely lacking. Such research is needed in order to estimate the effects of deoxygenation due to storm runoff upon fish in the receiving water and to aid in evaluating the results from field research.

Another glaring lack of data is actual measured dissolved oxygen concentrations in streams receiving storm runoff. A complete study which relates surface accumulation rates of pollutants to end-of-pipe loadings and downstream oxygen concentrations is needed.

CONCLUSIONS

1. Urban NPS runoff has been shown to contain large quantities of oxygen-demanding materials. Although few direct measurements have been made of the oxygen demands actually exerted in streams, modeling studies have indicated that the DO demand from urban NPS runoff can result in low DO concentrations, either alone or in combination with point source discharges.

2. It is more difficult to show serious oxygen depletion due to NPS runoff from rural areas. More serious rural NPS pollutants seem to be sediments from soil erosion, plant nutrients, and toxic materials such as pesticides.

3. Continuous exposure to dissolved oxygen concentrations significantly lower than air saturation concentrations seems to be harmful for fish. This seems true for both salmonid fishes and such warmwater fishes as largemouth bass.

4. Exposure to fluctuating DO concentrations between air saturation and 60-65 percent of saturation can reduce the growth rate of fish if the high and low concentration exposure periods are approximately equal (12 hours each) during each day.

5. Efforts should be made to achieve the appropriate DO standards by reducing the loads of BOD in NPS runoff as well as point source discharges. Reduction of the BOD loadings from NPS runoff should result in other improvements in receiving water quality by reducing the loadings of suspended solids, plant nutrients, and potentially toxic materials.

6. Research should be carried out to directly relate stream impact to end-of-pipe loadings and surface accumulation rates of urban NPS pollutants.

7. Research should be performed to evaluate the effects upon the growth rate of fish of one exposure of 12 hours per week to oxygen concentrations of 2, 3, and 4 milligrams per liter.

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APPENDIX

CONVERSION TABLE

Multiply	By	To Obtain
lbs	0.4536	kilograms
acres	0.405	hectares
miles	1.609	kilometers
square miles	259	hectares
lbs/acre	1.12	kg/hectare
lbs/curb mile	0.2819	kg/curb kilometer
lbs/sq mile	1.75×10^{-3}	kg/hectare
MGD	3.785×10^{3}	cubic meters per day
kilograms	2.20	lbs
hectares	2.47	acres
kilometers	0.62	miles
hectares	3.86×10^{-3}	square miles
kg/hectare	0.893	lbs/acre
kg/hectare	571	lbs/sq mile
kg/curb km	3.55	lbs/curb mile
cubic meters per day	2.64×10^{-4}	MGD