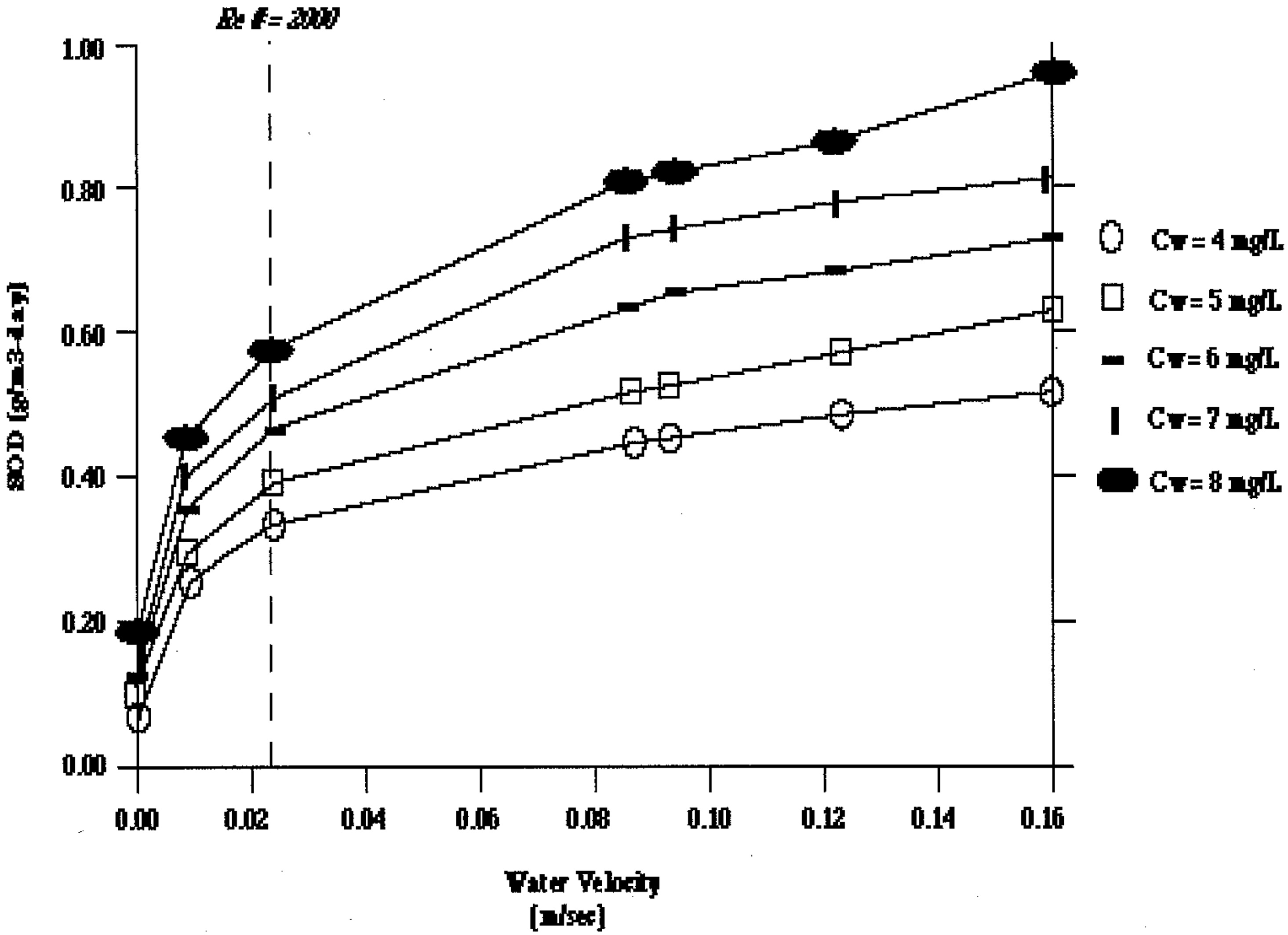
Induced Oxygen Demand

- Entrainment of sediment particles into hypolimnion
- Accelerated breakdown of particulate materials derived from planktonic productivity in epilimnion
- Inhibition of sestonic settling i.e. longer retention in hypolimnion
- Increased Sediment Oxygen Demand

Experimental Incubations of Newman Lake Sediments

- SOD increases at higher water velocities
- Reynolds No. of ~2000 describes transition into turbulent from laminar flow
- Turbulent flow produces breakdown in diffusion gradient
- Transition from oxygen limitation to substrate limitation

SOD vs. Water Velocity in Newman Lake Sediments



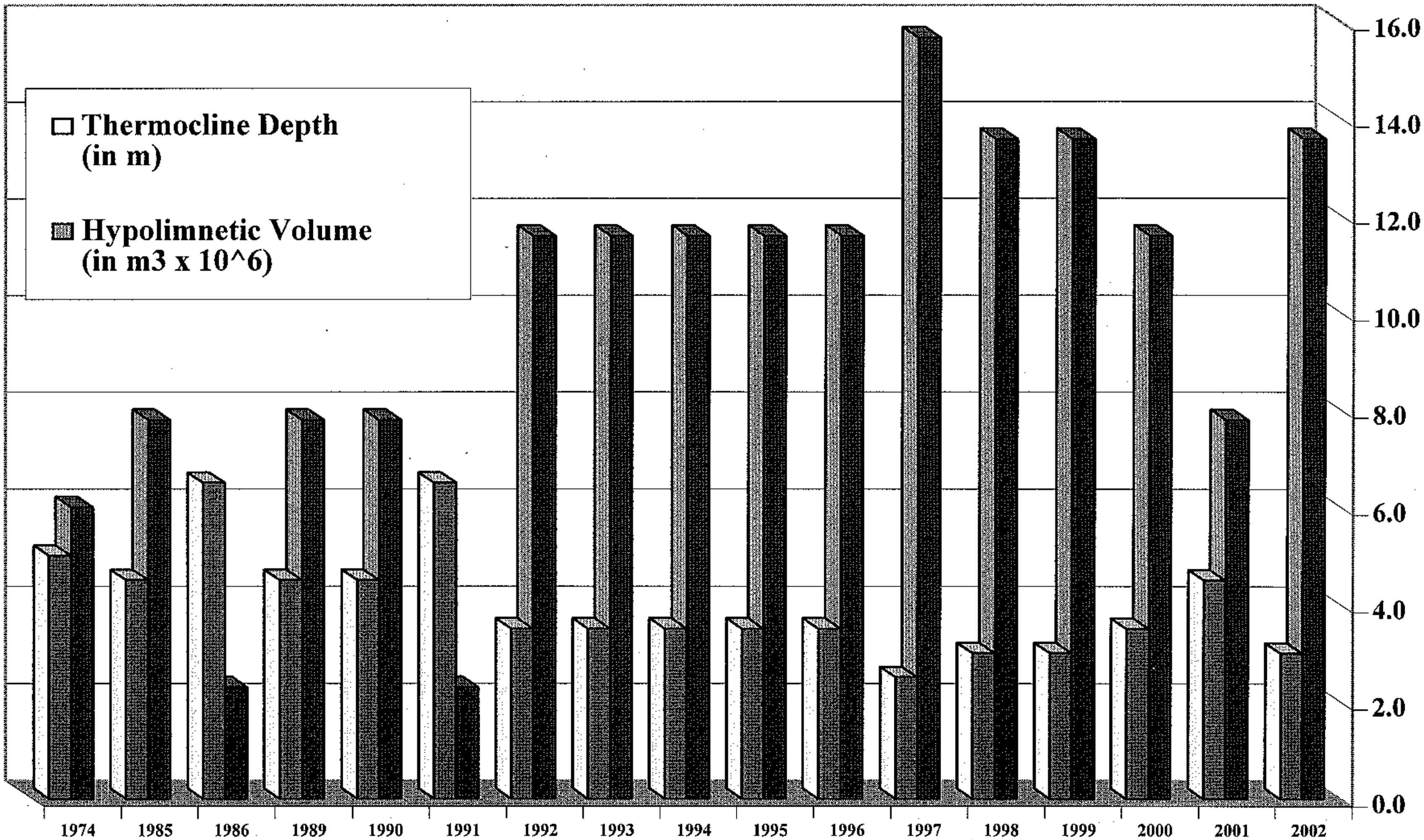
Overcoming induced oxygen demand requires maintaining <u>substrate</u> limitation, avoiding <u>oxygen</u> limiting conditions

Ref: Moore et al. 1996. A model for predicting lake sediment oxygen demand following hypolimnetic aeration. ***J. Amer. Water Res. Assoc. 32(4):723-731.***

Lesson 2: Long term data sets are necessary for the matching system capacity with lake O2 requirements

i.e. You get what you pay for.

Thermocline Depths and Hypolimnetic Volumes in Newman Lake



Lesson 3: Determine post-oxygenation ODR by most articulate means available

i.e. Explicit modeling of induced oxygen demand with assessment of range of likely conditions

System Design

- Determine maximum hypolimnetic volume
- Estimate oxygen consumption rate (ODR)
- Calculate total oxygen delivery rate
- Size system to satisfy total hypolimnetic demand

-modified from Ashley (1985)

Water Res. 19:735-740

O_2 Flow ($kg \cdot day^{-1}$) = $ODR \cdot A_h \cdot 2 \cdot 10^{-6}$

- ODR is oxygen delivery rate in $mg \cdot m^{-2} \cdot day^{-1}$
- A_h is hypolimnetic area in m^2
- 10^{-6} converts mg^{-1} to kg
- 2 is factor to accommodate "unmeasured O_2 demand" *McQueen et al. 1984* (i.e. fudge factor)

Post Oxygenation O_2 Demand

- “Traditional” method (Lorenzen and Fast 1977) predicted 913 kg/day (2000 lbs/day) oxygen consumption rate
- Newman Lake cone design at 1360 kg/day (3000 lbs/day)
- Model predicted post-aeration rate of 1430 kg/day (3150 lbs/day),
- Therefore, Newman Cone design value is at total oxygen demand for most observed years, less for lower probability conditions

CONCLUSIONS

- **Speece Cone is appropriate technology for hypolimnetic aeration and oxygenation applications**
- **Significant cost savings in capital investment and operating costs compared to full lift HA**
- **Oxygen delivery must be at rate sufficient to satisfy total oxygen demand**

Issues for Improved System Design for Hypolimnetic Aeration Applications

- Better modeling of oxygen demand <u>after</u> aeration, to include quantification of sediment oxygen demand, induced oxygen demand, lake oxygen demand (from annual productivity)

- Explicit statement of cost/risk to be factored into design

- Improved data sets- longer term monitoring

APPENDIX E

SAVANNAH HARBOR EXPANSION PROJECT & SAVANNAH HARBOR ECOSYSTEM RESTORATION STUDY APPENDIX D

OXYGEN SUPPLEMENTATION TECHNOLOGIES

Section 1. TMDL Compliance

Allowable BOD Loading

Regulations requiring that treated effluents be discharged to receiving waters at elevated D.O. concentrations are specified in some discharge permits. Conventional aeration techniques may achieve these higher concentrations but usually entail prohibitively high unit energy consumption and are limited in the D.O. levels that can be achieved. Using standard aeration equipment to increase the D.O. from 0 to 7 mg/L in water at 25^{o}C would require approximately 2700 kwhr/ton of D.O. added, which is equivalent to over $200/ton of D.O. for electricity rates of $0.08/kwhr.

An efficient oxygenation system, on the other hand, can achieve the higher D.O. requirements both more easily and more economically. Technology is now available to produce heretofore impossibly high superoxygenation levels, allowing TMDL D.O. standards to be reached in many applications without the necessity for tertiary treatment.

TMDL Requirement Solutions

Reduction of pollutant loading, water augmentation in low flow situations and aeration are the methods traditionally used to reach TMDL levels. One aspect of the TMDL process mandated for surface waters is to establish the D.O. level appropriate for the resident fishery. This then leads to designation of the allowable BOD and/or nutrient-loading rate applicable to all entities discharging to the waterway. For impounded or slow flowing rivers with attendant low reaeration rate, k_2, as found in the relatively flat terrain, the allowable pollutant loading rates are accordingly quite low, resulting in the need to achieve especially high pollutant removal rates by the contributing entities. Such advanced removals cause exponential increases in wastewater treatment costs for relatively small incremental removal of pollutants. At present secondary treatment is mandated in all states for all wastewaters, resulting in more than 90% removals commonly being realized, but tertiary removals with their attendant high cost may also be necessary to meet the TMDL levels in many cases. However tertiary treatment may no longer be necessary in most cases when using a newer method which supplements D.O. in very high concentrations sufficient to achieve TMDL standards for D.O.. However, as presented in this paper, a newer method of supplementing superoxygenation directly to the river, promises significant advantages not achievable in the past.

The rate of reaeration of a river is shown in the following equation by Thackston:

$$k_2 = 0.000025[\ 1 + 9\ \{F\}^{0.25}][(h\ S_e\ g)^{0.5}]/h$$

Where: u = velocity – ft/sec
h = depth – ft
S_e = slope – ft/ft

Fig. __ depicts the k_2 corresponding to velocity and depth combinations.

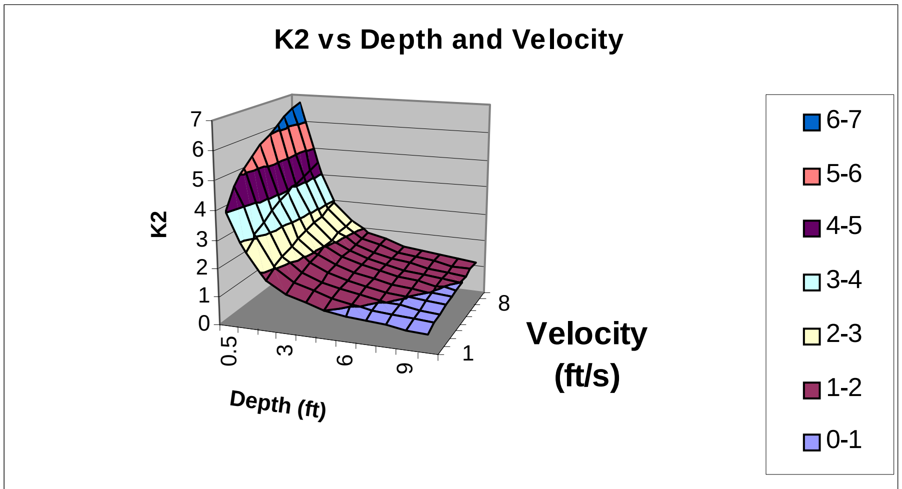
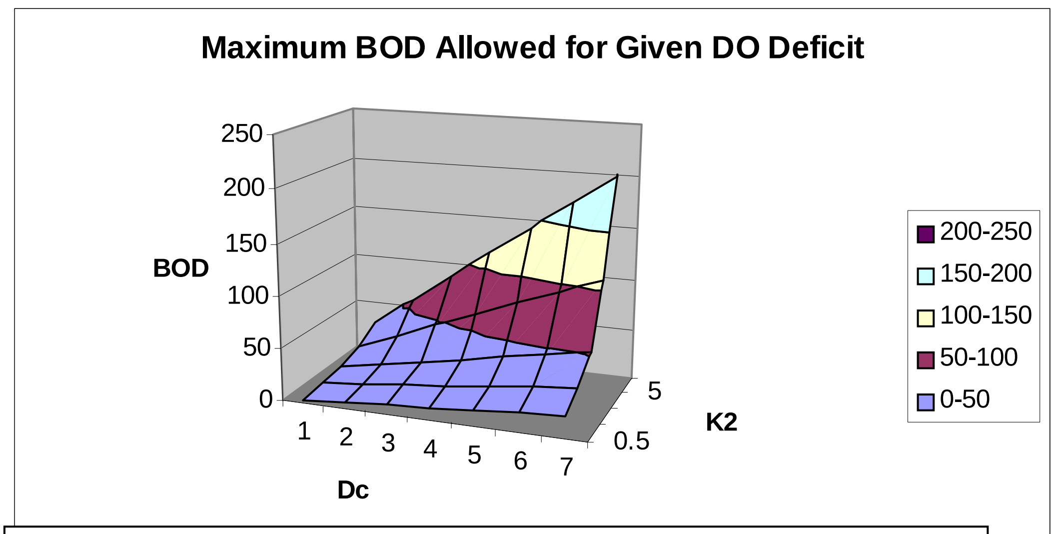


Fig. Reaeration rate vs velocity and depth



Maximum BOD Allowed for a Given D.O. Deficit at Sag Point

The allowable BOD loading in a segment of river is a function of the allowable D.O. deficit (or target D.O.) and the k_2 of that segment as shown in Fig. __

Strategy for D.O. Supplementation:

- Add D.O. equivalent to ultimate BOD in discharge so no oxygen resources in the harbor are consumed in metabolizing residual BOD.
- Higher D.O. from oxygenation station permits increased spacing between oxygenation stations.
  - This permits economy of scale.
  - Cost to bring in electrical power much reduced
  - Delivery of LOX
- Propeller pumps to assist in D.O. transport away from oxygenation station.

D.O. Supplementation Trading for Advanced BOD removal

The allowable BOD loading on a river is a function of k_r, k_d, and k_2. For example if River A has a depth of 10 ft and velocity of 1 ft/sec it will have a $k_2 = 0.65$/day while River B, with a depth of 2 ft and velocity of 4 ft/sec will have $k_2 = 2.3$/day. Thus the allowable BOD loading at 25 ^oC for a D.O. deficit of 3 mg/L and for River A is 10 mg/L. By comparison, the allowable BOD loading for River B is 28 mg/L.

Lower aeration rated rivers should not be penalized if successful reaeration rates are reached by means of superoxygenation. When water quality trading is implemented locally, then, supplemental oxygenation of the receiving water body will also be an acceptable solution for meeting TMDL standards.

On Jan 13, 2003 EPA announced a new Water Quality Trading Policy to provide guidance on how trading can occur under the Clean Water Act while implementing regulations. Water quality trading is a market-based approach that is intended to provide greater efficiency in achieving water quality goals and watersheds by allowing one source to meet its regulatory requirements by using pollutant reductions created by another source that has lower pollution control cost.

Supplemental oxygenation of a river as a trade-off for non-point source pollution control measures has been used successfully. A study performed to remediate Snake River D.O. deficiency related to TMDL (caused by non-point source phosphorous loading) established that oxygen could be supplemented directly to the river for 3 % of the cost to reduce phosphorous from non-point sources to achieve comparable D.O. standards.

Ruane has postulated how the South Fork Holston River in Tennessee point/nonpoint-source pollutant trading within a watershed might be implemented. Although several hundreds of millions of dollars were invested for waste treatment facilities in the 1970s, nevertheless D.O. levels in the South Fork Holston River dropped to 2 mg/L under low flow conditions. D.O. concentrations were even predicted to range from 0 to 1 mg/L if industrial and municipal facilities discharged to the limits of their permitted waste loads.

TVA investigators considered a number of options for improving D.O. conditions in the South Fork Holston River, including advanced waste treatment for the dischargers, turbine aeration at Fort Patrick Henry Dam, various levels of flow augmentation at the dam, and in stream aeration. The results of this exploratory analysis indicated that D.O. standards of 5 mg/L in the river could not be attained using the advanced effluent treatments that were being considered by the industrial and municipal dischargers, but a water quality trade off could meet the requirements. For example, it was predicted that state water quality standards could be met by augmenting flow releases from the dam, coupled with additional aeration by the hydroelectric project either at the dam or downstream. The annual cost of the trade off option would range from $298,000 to $395,000, compared to an estimated annual cost of $44,000,000 for the industrial and municipal dischargers to operate advanced (but insufficient) waste treatments.

Superoxygenation provides a significant advantage by increasing river D.O. without processing the entire river. Also much smaller sidestream flows and civil works are required for superoxygenation than for aeration. Compelling cost comparisons favor use of this newest type of technology to achieve TMDL standards since pure oxygen is available for only $60 to $100/ton, depending on the usage rate. Successful superoxygenation can dissolve oxygen into water with 90% oxygen absorption efficiency for a total cost of approximately $100/ton D.O. (which includes amortization of the capital cost @ $10/ton D.O., energy consumption of 400 kwhr/ton D.O. @ $0.05/kwhr = $20/ton D.O., and the cost of oxygen at $70/ton D.O.) while achieving 70 mg/L D.O. in a sidestream. When using pure oxygen vs aeration only about one tenth as much energy (300 kwhr/ton D.O.) is consumed per ton of D.O. supplemented than required for aeration yet D.O. concentrations in the river equivalent to air saturated D.O. can be easily achieved with these economies. The Chicago Canal sidestream aeration system, which moves the entire canal flow through the cascade aerators with an increase of only 1 to 3 mg/L D.O. involves energy consumption of over 3000 kwhr/ton of D.O. supplemented, which is ten times the energy requirement necessary for pure oxygen supplementation.

If the discharge has received secondary treatment there will be nil degradation of the river quality. Deep, slow moving rivers no longer need to be penalized in TMDL analyses when adopting superoxygenation technology. Advanced treatment will no longer be required.

Tertiary Removal of BOD

Tertiary treatment to lower the five-day BOD below 20 to 30 mg/L does little to improve the river habitat. The costs of tertiary treatment may exceed the cost of secondary biological treatment. If an increase in D.O. is a major need to improve the river habitat, then oxygen supplementation instead of tertiary removal of BOD should be implemented, especially with pooled rivers or harbors having very low aeration rates. For water quality limited harbors receiving secondary biologically treated industrial or domestic affluence. It is possible that an agreement could be reached with the state regulatory agency to allow oxygen to be supplemented directly to the harbor in order to maintain regulated D.O. concentrations.

As shown in the Figs. below, the health of a water body is directly correlated with the D.O. maintained therein.

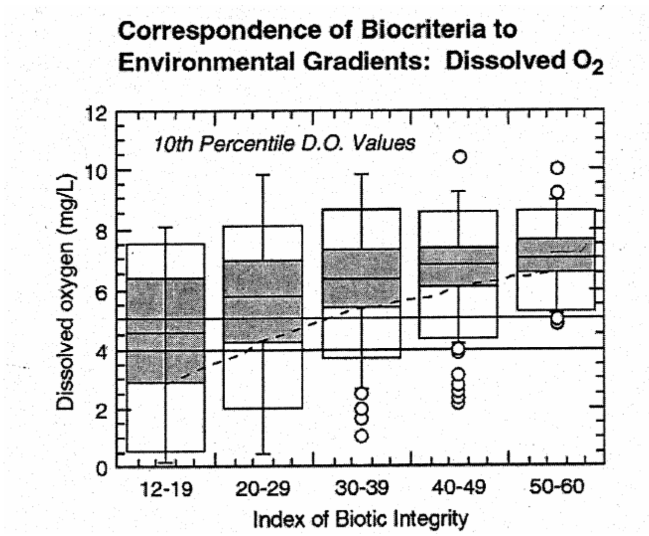
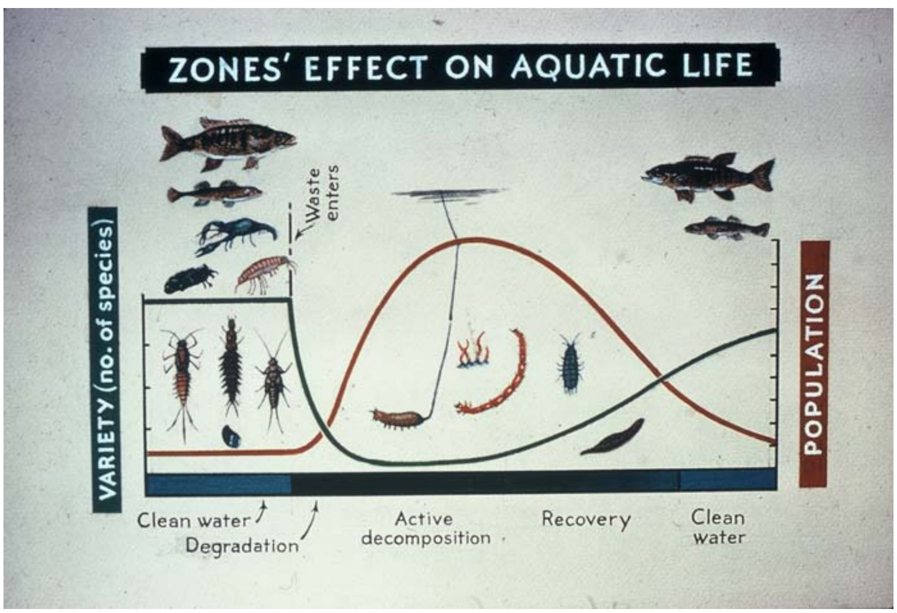
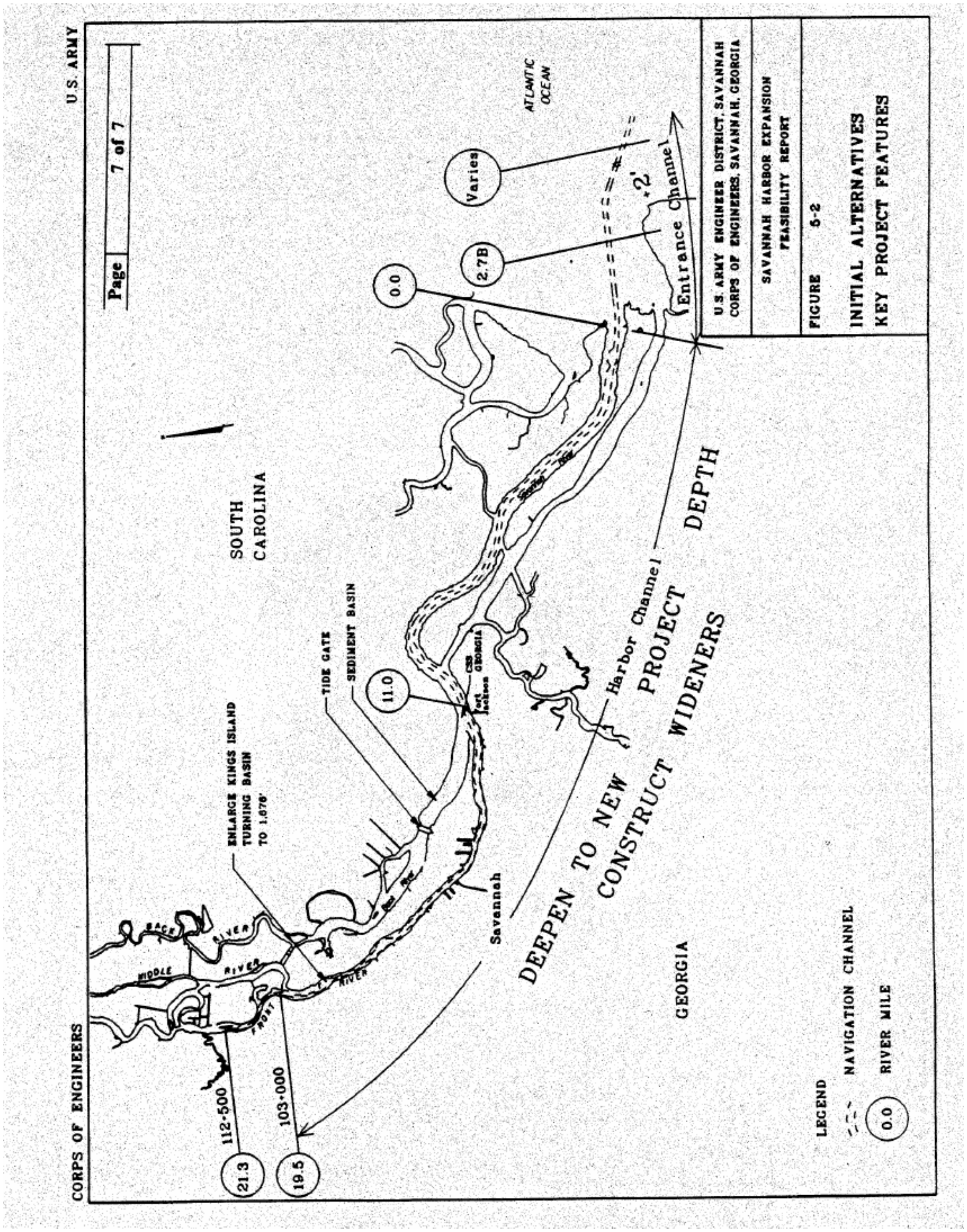
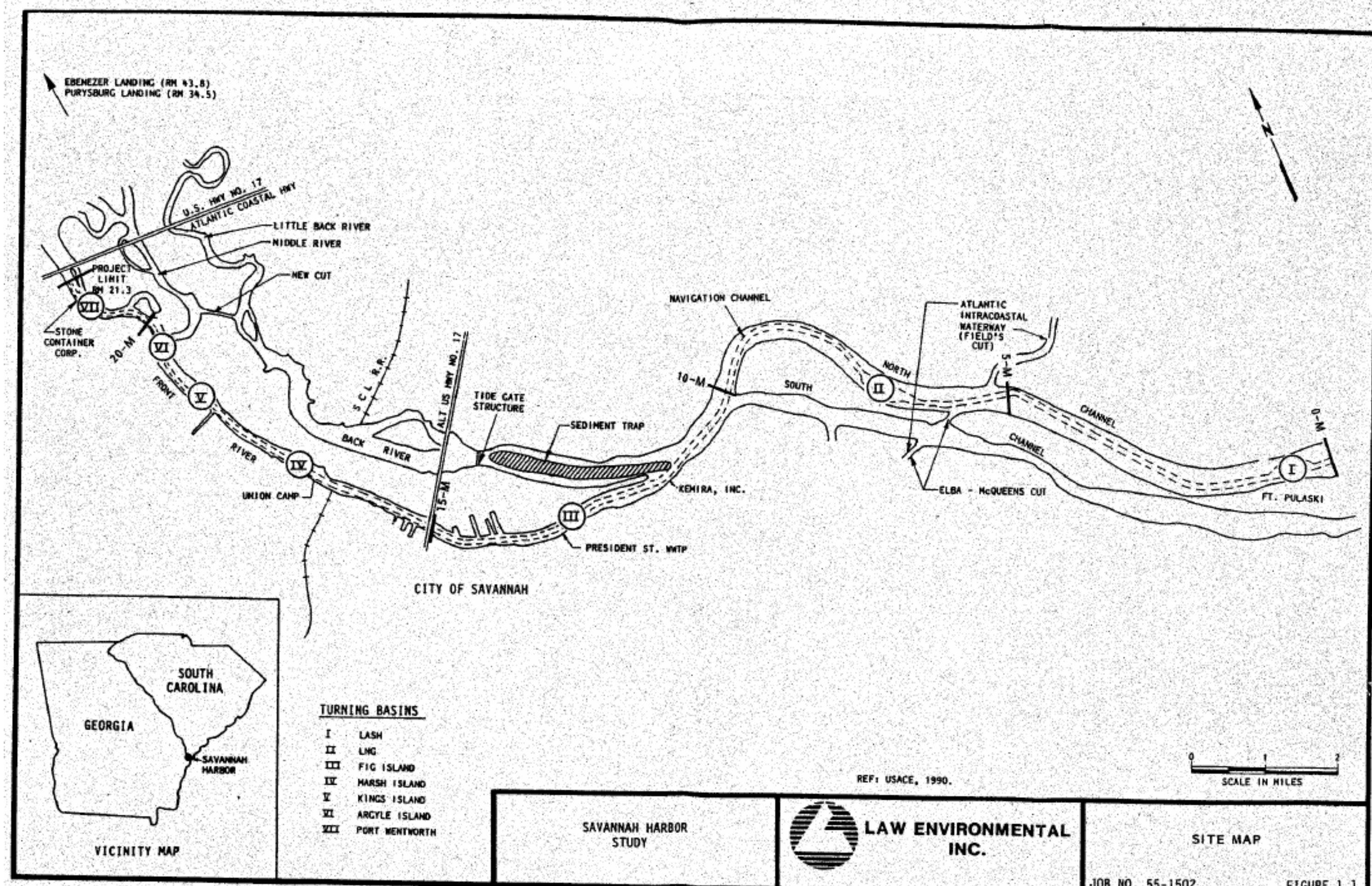


Fig. Correspondence of biocriteria to environmental gradients: dissolved oxygen



Aquatic Diversity as a Function of D.O. Recovery


CORPS OF ENGINEERS
U.S. ARMY
Page 7 of 7
SOUTH CAROLINA
ATLANTIC OCEAN
GEORGIA
BACK RIVER
MIDDLE RIVER
FRONT RIVER
Savannah
ENLARGE KINGS ISLAND TURNING BASIN TO 1,676'
TIDE GATE
SEDIMENT BASIN
CSS GEORGIA
Fort Jackson
Harbor Channel
Entrance Channel
+2'
DEEPEN TO NEW PROJECT DEPTH
CONSTRUCT WIDENERS
21.3
112+500
19.5
103+000
11.0
0.0
2.7B
Varies
LEGEND
NAVIGATION CHANNEL
0.0 RIVER MILE
U.S. ARMY ENGINEER DISTRICT, SAVANNAH
CORPS OF ENGINEERS, SAVANNAH, GEORGIA
SAVANNAH HARBOR EXPANSION
FEASIBILITY REPORT
FIGURE 5-2
INITIAL ALTERNATIVES
KEY PROJECT FEATURES


EBENEZER LANDING (RM 43.8)
PURYSBURG LANDING (RM 34.5)
U.S. HWY NO. 17
ATLANTIC COASTAL HWY
LITTLE BACK RIVER
MIDDLE RIVER
NEW CUT
PROJECT LIMIT RM 21.3
STONE CONTAINER CORP.
20-M
FRONT
RIVER
BACK RIVER
S C L R.R.
ALT US HWY NO. 17
15-M
UNION CAMP
TIDE GATE STRUCTURE
SEDIMENT TRAP
KEMIRA, INC.
PRESIDENT ST. WWTP
CITY OF SAVANNAH
NAVIGATION CHANNEL
10-M
SOUTH
NORTH
ATLANTIC INTRACOASTAL WATERWAY (FIELD'S CUT)
5-M
CHANNEL
CHANNEL
ELBA - McQUEENS CUT
0-M
FT. PULASKI
N
SOUTH CAROLINA
GEORGIA
SAVANNAH HARBOR
VICINITY MAP
TURNING BASINS
I LASH
II LNG
III FIG ISLAND
IV MARSH ISLAND
V KINGS ISLAND
VI ARGYLE ISLAND
VII PORT WENTWORTH
REF: USACE, 1990.
0 1 2
SCALE IN MILES
SAVANNAH HARBOR STUDY
LAW ENVIRONMENTAL INC.
SITE MAP
JOB NO. 55-1502
FIGURE 1.1

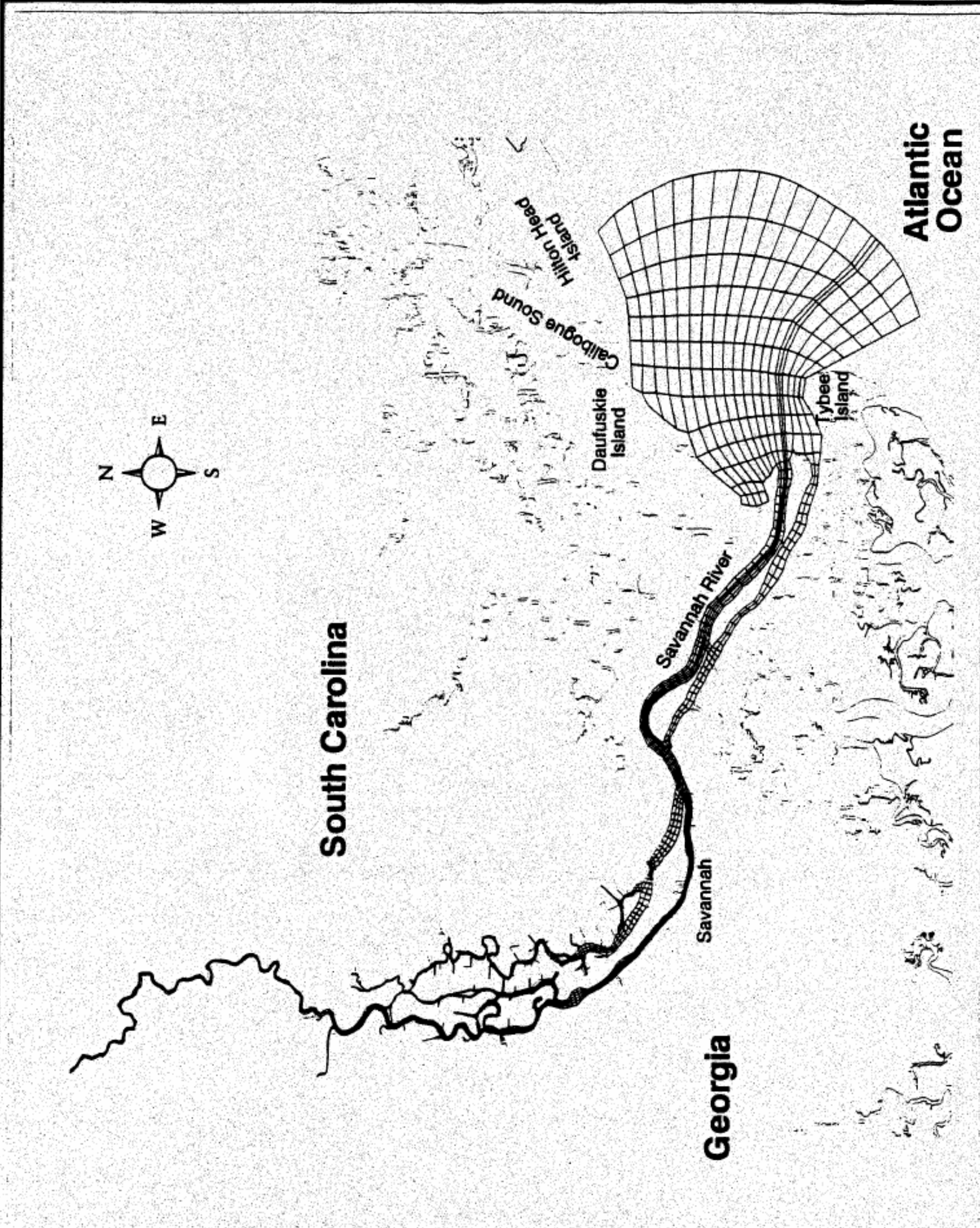


Figure 3-1
Model Grid

ATM
APPLIED TECHNOLOGY & MANAGEMENT, INC.

Section 2. Worldwide Applications of Oxygen Supplementation to Rives, Lakes and Harbors

2. Existing Oxygenation System Installations.

I. Background.

Some of the world's most beautiful harbors and lagoons and its most heavily trafficked seaports face severe flooding problems during storm tide seasons. But remedial steps to minimize flood damage may in turn cause other water quality dilemmas, which must also be addressed at the same time.

Venice's magnificent architecture is being threatened by each successive flood season, yet its historic lagoon would also experience serious oxygen depletion if isolated by tidal gates. The busy Thames River's innovative tidal gates are successfully holding back potentially damaging flood tides at this time, but are accompanied by mobile oxygenation barges which alleviate consequent D.O. deficiencies.

Other oxygen poor harbors on the other hand, such as Shanghai Harbor, sustain serious pollution damage during dry seasons and the serious malodorous conditions which have plagued the city's inhabitants for decades have also caused the fish and shrimp to die until rehabilitation efforts were undertaken in 1988, and in 2001 when an oxygenation barge was deployed there with good results.

Savannah Harbor's main pollution source is decaying vegetation from the surrounding marshes. The Stockton, California Deepwater Ship Channel also must address constant new nutrient enrichment problems along with combined sewer overflows. Manchester Ship Canal in England has excessive algae growth, caused by heavy nutrient load and accumulation of sludges on the bottom, with consequent fish kills.

Ship traffic restricts equipment location, which precludes some types of aeration equipment. However, modern oxygenation designs using pure oxygen to raise the D.O. levels show great promise in solving worldwide harbor water quality dilemmas as well as those of rivers, lakes and bays.

II. Descriptions of oxygenation systems and specific equipment site data

Described below in approximate chronological order according to installation dates, are successfully operating installations which use HPO technology to achieve regulatory compliance and enhance resident fisheries.

Richard B. Russell Reservoir Georgia
Newman Lake Washington
Camanche Reservoir California
Thames River England

Tombigbee River Alabama
Logan Martin Dam Alabama
Emscher River Germany
Hallwilersee Lake Switzerland
Patrick Henry Reservoir Tennessee
Douglas Reservoir Tennessee
Fontana Reservoir Tennessee
Androscoggin River Maine
Cardiff Bay Barrage England
Amsterdam Canals, Netherlands
Suzhou Creek, Shanghai Harbor

Richard B. Russell Dam, Georgia, Diffuser Systems

Richard B. Russell Dam is located on the Savannah River above Augusta Georgia. At Richard B. Russell Dam a first ever solution to D. O. depletion using fine bubble diffusers placed along the bottom of the 140 foot deep impoundment at approximately 1 mile in front of the dam. Oxygen supplementation was implemented within the hypolimnion from which layer the turbines withdraw water for power production and then discharge it downstream. Oxygen supplementation is practiced for approximately 7 months out of the year in order to maintain a downstream D. O. concentration of >6 mg/L for enhancement of the fishery therein.

During maximum power generation the dam release is over 60,000 $ft.^3$ per second. Like all deep lakes in the Southeast, Russell Lake stratifies during summers. Warm light waters sit on a colder dense layer in the bottom. Only the top 30 feet, which is the epilimnion is circulated by wind action. With no means to replenish D. O. consumed in biological and chemical activity the D. O. levels in the depths of the lake, namely the hypolimnion layer, are gradually exhausted after stratification sets in. The water quality standards were set at 6 mg/L of D. O. in the reservoir releases. Since Russell Dam's waters needed D. O. improvement from 1 mg/L background to 6 mg/L in the discharge a more powerful oxygen enhancement system was needed than could be achieved by turbine venting or turbine oxygen injection. Proof of concept studies were conducted in the summer of 1975, 1976 and 1977 by a Drexel University team directed by Prof. Speece.

In order to generate absorption data for mass balance and efficiency studies an experimental system was suspended at the face of the dam. Fine bubble diffuser performance were evaluated by placing the diffusers at various depths below the water surface. An 11 foot diameter bubble collection of hood was placed at the surface above the bubble plume, so that the entire off gas from the bubble plume could be captured and quantified. Various diffuser loading rates were observed. Results from Phase 1 indicated that by using low porosity diffusers and O2 loading rates of 0.5 to 2.0 feet per minute 90% of the oxygen was absorbed within a bubble rise of 100 feet. The next evaluation phase involved placing a rack of fine bubble diffusers 100 feet horizontally in front of the penstock intakes and measuring the D. O. in the discharge from those penstocks. When oxygen was injected in front of the hydropower discharge it raised the D. O. from a background level of 2 mg/L to a discharge level of 8.1 mg/L. More than 90% oxygen absorption efficiency was achieved under these conditions.

The prototype diffuser system had two 1200 foot long assemblies of fine bubble diffusers and was suspended 5 feet above the impoundment bottom and located 100 feet apart in parallel. The fine bubble ceramic diffusers had a characteristic porosity of 2 feet per minute.

The first season of oxygen injection began with the onset of lake stratification on April 3, 1985 at an O2 loading rate of 25 tons per day. A maximum oxygen loading rate of a hundred tons per day occurred in September and October of that year. Oxygenated water was shown to stay in the lower layer of the lake and a daily average of 6 mg/L was maintained. By the time injection was terminated in December, after the Fall turnover over 14,000 tons of oxygen had been injected.

In May to November of 1986. Some 10,000 tons of oxygen were injected, peaking at 90 tons per day. In 1987 only 7800 tons of oxygen were injected. Due to the natural aging of the lake the oxygen demand decreased.

This original fine, bubble system using ceramic diffusers was replaced after about 15 years by soaker hose technology.

In 2001 the original ceramic diffusers were replaced with a soaker hose diffuser design utilizing 10 - 4000 foot long lines along the old river channel upstream from the dam. High oxygen transfer efficiencies are achieved by spreading the diffuser hose over a larger area, (Mobley, Adams, Haynes and Sykes 2003).

They continued:

> The diffuser installation in the reservoir was conducted from the surface without divers. The diffusers were assembled from a temporarily closed boat ramp and floated into final position in the reservoir in sections. Floating over a mile of diffuser pipeline at a time, across the popular reservoir required seven work boats, deep anchor points. Long rope spans and patrol boats to warn public boaters. The work boats and anchor points were used to maintain the diffuser location, despite changing wind directions. Once the diffuser was satisfactorily floating above the final location, the buoyancy chamber was pumped full of water to sink the diffuser in a controlled manner to the bottom. The process can be reversed to retrieve the diffuser for maintenance or repositioning.
>
> The diffuser installation was completed with some preliminary testing in September 2001. Results indicated some disparity and individual diffuser line flows and difficulty in attaining full system design flow during test conditions that included temporary piping and flow control.
>
> During 2002 the existing liquid oxygen supply facility was modified to reliably achieve the maximum design flow capacity, a new

oxygen flow control system was installed, and several diffuser lines were modified to provide better flow capacity. Start up testing was completed in August 2002 including operation of the system at over 200 tons of oxygen per day. The oxygen system was operated successfully for the remainder of the 2002 season.

Newman Lake, Washington, Speece Cone Oxygenation

Quoted from Barry C. Moore, Washington State University "Downflow Bubble Contact Aeration Technology (Speece Cone) for Sediment Oxygenation"

Internal phosphorus recycling during summer stratification has led to the accumulation of large amounts of organic sediments in the bottom of Newman Lake, which is the centerpiece of a residential area in western Washington state. The resulting anaerobic sediment water interface allows phosphorus recycling at rates several orders of magnitude greater than under aerobic conditions (Bastrom *et al*, 1988, Funk and Morris, 1988).

A 1985 - 86, study concluded that 3000 pounds of oxygen per day would be required to meet the daily summer hypolimnetic oxygen demand, (McLean and Lean, 1986, Ashley *et al*. 1987). A Speece Cone was installed in 1992 to maintain oxic conditions with the view to eliminating unsightly algae growth visible to the residents and to restore the lake fishery.

Studies on Newman Lake conducted in 1985/1986 allowed calculation of a nutrient budget in which about half of the total net phosphorus loading was estimated to be associated with internal cycling (Funk and Moore, 1988). Therefore, intervention into processes leading to mobilization of sediment phosphorus was determined to be critical for reducing summer algae productivity and for restoring acceptable water quality. For Newman Lake, maintaining aerobic conditions during summer stratification offered the best means to reduce internal phosphorus recycling. Previous studies on sediment transport showed that, if the sediment/water interface is maintained in an aerobic state, then phosphorus solubility and mobility are greatly reduced (Bostrom et al., 1988).

Over the years, export of materials of both natural and anthropogenic origin from the watershed, combined with plant materials produced within the lake basin itself, have led to the accumulation of large volumes of organic sediments on the lake bottom. During summer stratification, microbial breakdown of these sediments exerts oxygen demand that leads to depression and depletion of oxygen in the lake hypolimnion (bottom waters). The resulting anaerobic sediment/water interface allows phosphorus to be recycled into overlying waters at rates several orders of magnitude greater than under aerobic conditions (Bostrom et al., 1988, Funk and Moore, 1988). High phosphorus concentrations in Newman Lake have been determined to be the primary cause of excessive summer algae biomass, which is major water quality problem (Funk and Moore, 1988).

TABLE 1. System specifications for the Newman Lake Speece Cone.

Cone volume	11.1 m^3 (315 ft^3)
Cone height	4.6 m (15 ft)
Oxygen delivery	1,360 kg/day (3,000 lbs/day)
Dual Air/Sep O_2 generators	680 kg/day (1,500 lbs/day) each
Dual rotary screw compressors	50 hp each
In-lake water pump	40 hp @ .73 m^3/sec (21 ft^3/sec)
Distribution manifold	100 ft (31 m) w/ 2" ports @ 2 ft spacing

In 1992, a Downflow Bubble Contact Aerator (DCBA) system, known as a Speece Cone, was installed in Newman Lake, Washington, USA. The principal purpose of the system is to provide sufficient oxygen to prevent hypolimnetic oxygen depletion and to maintain an aerobic sediment/water interface and is the first use of Speece Cone technology for lake restoration application. This later function was targeted to reduce recycling of nutrient compared to flux rates under anaerobic interfacial conditions. The system also contains other significant innovations, including pressure-swing molecular sieve technology for on-site oxygen generation, and a multi-ported exhaust manifold to reduce water velocities and prevent sediment entrainment. Compared to other available technologies, the system also represents significant savings in capital and operating costs. An evaluation of the Speece cone performance using a 17-year data set was made. When operated as designed, the system has been able to maintain elevated dissolved oxygen in the summer hypolimnion. Variations in operational and environmental parameters have provided a wealth of information on the Speece Cone, demonstrating that this is a economic and efficient technology that should receive wider application. Probably most significant are data that support the reality of a phenomenon known as induced oxygen demand, in which post-oxygenation O_2 demand rates exceed those observed prior to implementation.

Moore concludes his study with several recommendations for consideration of sediment oxygenation.

A recent review has concluded that improved water quality can be realized by hypolimnetic oxygenation, and that the method deserves more widespread application (Beutel and Horne 1999). In conclusion, it should be noted that the Speece Cone is an appropriate technology for delivering oxygen in water and sediment oxygenation applications. Methods that account for induced sediment oxygen demand are essential for predicting post-treatment oxygen requirements. Proper sizing of the system to meet that demand is crucial in order to realize environmental oxygenation goals.

When data on the range of environmental variability is limited, it should be understood that the associated high degree of uncertainty necessitates application of liberal safety factors to reduce risk of system under-sizing. For such situations, an economic analysis that balances risk versus cost of increasing system capacity may be an appropriate decision-making tool.

Camanche Reservoir, California, Speece Cone Oxygenation

Horizontal discharge of a super oxygenated sidestream is an important feature of the Speece Cone technology designed for Camanche Reservoir located in the foot hills of California, as may be seen in the photo (Figs -- --). During drought seasons the water depth, which usually varies up 135 feet, drops to only 25 feet. A yearly D.O. pattern of the hypolimnion is depicted in Fig. ---.

This reservoir discharges through a bottom pen stock during most of the stratification season and feeds a coldwater salmon fishery as well as a salmon hatchery immediately downstream from the dam. The discharge of 400 to 800 $ft.^3$ per second during the stratification season is also used to generate power before discharge as the sole headwater of the Mokolumne River, which is a salmon habitat.

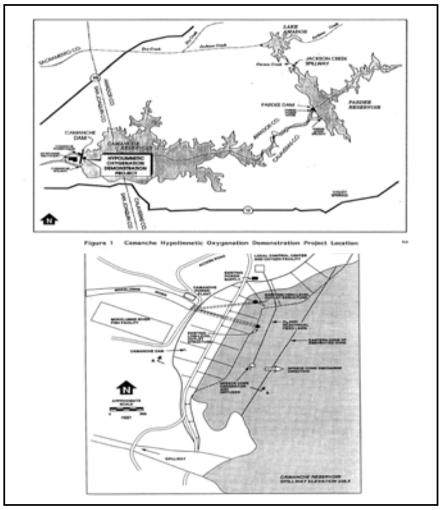
The river and hatchery require a coldwater discharge from the reservoir hypolimnion, so stratification must be carefully maintained. By mid June, the D.O. in the hypolimnion discharge is below 7 mg/L, which is the regulated D.O. for rivers in California classified for salmon. Therefore, at this time the hydropower generation must be bypassed and the water discharged through a Howell Bunger valve for aeration. Such cessation of electricity generation results in revenue losses of approximately $5,000 per day per 400 $ft.^3$ per second by-passing the generators.

By late June or early July anaerobic conditions are established in the bottom of the hypolimnion, where the discharge is located, causing iron and manganese to be solubilized and hydrogen sulfide to be produced. Hydrogen sulfide is toxic to the fish, corrosive to electrical connections in the vicinity of the Howell Bunger valve where it is stripped during aeration, and eventually is offensive to personnel and visitors to the river below the dam.

In 1996, a Speece Cone hypolimnion oxygenator with horizontally induced flow, which dissolves 18,000 pounds of oxygen per day to the sidestream discharge from the oxygenation system back into 100 foot long diffuser, was installed on the bottom of the reservoir at the toe of the dam.

When the water is 100 foot deep, the oxygenated sidestream has a dissolved oxygen concentration of about 100 mg/L. A D.O. increase of 4 mg/L was observed in the hypolimnion 10,000 feet from the diffuser two weeks after the oxygen supplementation commenced operation.

Oxygen supplementation of the hypolimnion allows power to be generated, prevents hydrogen sulfide production, and meets river and hatchery D.O. criteria for the State of California. An additional advantage is that the equipment is hidden from public view at the bottom of the reservoir.



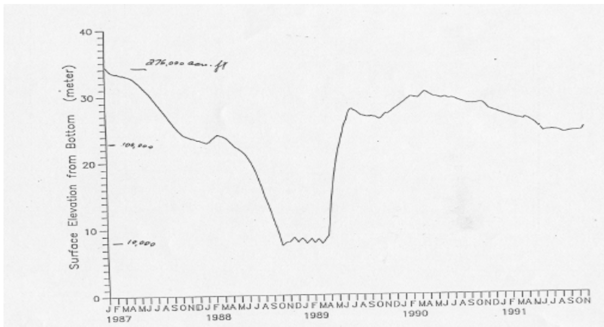


Figure 3. Reservoir Surface Elevation for 1987 to 1991 (bottom at 30.3 meters (100 ft) above sea level)

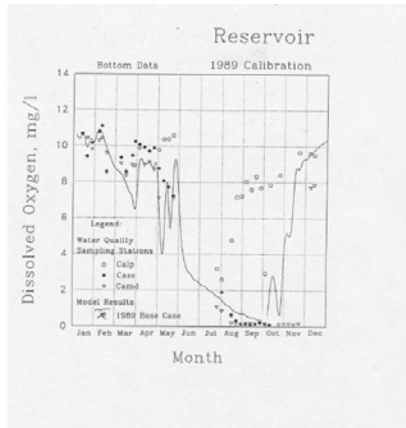


FIGURE 10
DISSOLVED OXYGEN (BOTTOM)
RESERVOIR
CALIBRATION 1989

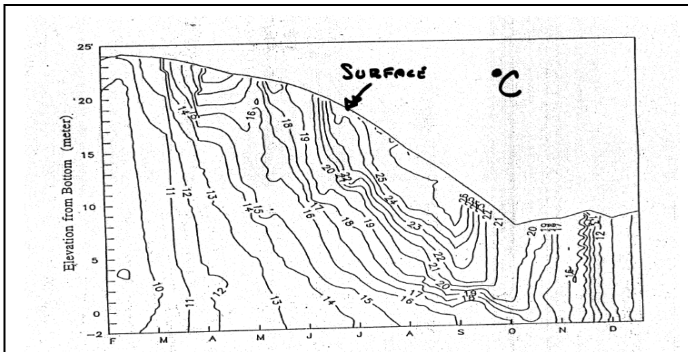


Figure 7. 1988 Reservoir Temperature Isopleths (Celsius)

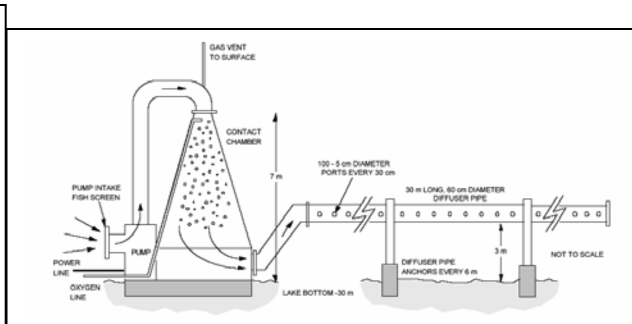


Figure 2 - Schematic of submerged contact chamber oxygenation system used in Camanche Reservoir, California and Newman Lake, Washington.

Thames River, England, Mobile Oxygenation Barge

An early network for the London sewer system was built in the 1850s with various catchments for drainage and pumping stations. Originally the design target was to intercept the dirty water coming down the river and divert it to London's east side, to minimize the pollution for the main part of the city. Both surface runoff and foul sewage enter the Thames. Two London areas, Becton and Crossness on the Eastside and Modem at the top of the tidal stretch of the river are the locations of the main sewage works. (Health and Public Services Committee, September 14, 2004 transcript).

During heavy rains, the system channels excess water back into the Thames. To avoid flooding in the city, according to the report cited above, the networks in London are so convoluted with its legacy that the normal rules do not apply. Therefore you need to have a rather individual approach to try to cure the problem.

The London sewage works are some of the largest in Europe, but when storm flows rise, untreated sewage as well as surface runoff are discharged into the Thames. Storm tank storage is limited so excessive flows cannot be contained. In order to avoid basement and house flooding, the sewage system must release storm runoff as frequently as 50 to 60 times a year, resulting in fish kills nearly every 10 to 16 weeks in the tideway,(*loc. Cit.* 2004).


Thames Bubbler

A Thames Bubbler barge and a Thames Vitality barge authorized by the National Rivers Authority and the British government, containing venturi jets to diffuse the oxygen produced on board, have been deployed to prevent fish kills during storm tides. But even with these and the addition of hydrogen peroxide at the treatment works effluent, these oxygenation systems on the river failed to prevent fish kills in August and September of 2004. About 30 tons per day of oxygen are generated by each barge. Oxygen transfer efficiency is estimated to be about 65% from the venturi jets.

According to the report, it has always been recognized that the Bubbler barges were a temporary solution until something more permanent comes along.

Tombigbee River Alabama, U-Tube Oxygenation

During periods of drought, the normally sufficient D.O. levels in the Tombigbee River, located near two paper mills in Alabama, dropped below minimum state standards. In times of prolonged drought after the 30 day treated effluent storage capacity of each mill becomes full, mill production capacity had to be curtailed to maintain river D.O. levels, negatively impacting mill profits.

Both mills discharge efficiently treated waste water, so an agreement was reached with Alabama state authorities to add D.O. directly to the Tombigbee River. Since the Gulf States mill is located about 35 miles upstream from the James River mill, both mills impact the D.O. concentration downstream of the James River mill discharge. It was therefore a mutual benefit to design one common oxygen supplementation strategy. A D.O. water quality model of the river had demonstrated this oxygen supplementation strategy would allow both mills to operate at full capacity under the most critical low flow and high temperature conditions in the Tombigbee River.

The mutually beneficial agreement between the Gulf States and James River paper mills was reached on a solution for maintenance of the regulated D.O. concentrations in the Tombigbee River to minimize the fraction of river flow which must be moved through the oxygenation system. Therefore the D.O. concentration achieved had to be maximized.

The agreement allows 12,000 pounds per day of D.O. to be added to the James River mill effluent and 40,000 pounds per day of D.O. to be added 35 miles down river. One stipulation is that the D.O. in the river can never exceed 100% of air oxygen saturation, namely 7.9 mg/L at 28° centigrade, which is a typical hot summer river temperature during drought flows.

The James River effluent storage pond is located about 30 feet above the river level and flows by gravity through a U-Tube oxygenation device, where it is superoxygenated to 50 mg/L, and then passes into a diffuser on the bottom of the river. At the second location, called McCarty's Landing, 125 MGD of water must be pumped from the river through the U-Tube oxygenation device and back into a diffuser on the bottom of the river. Here again the D.O. is raised to 50 mg/L for discharge into the river diffuser.

A number of oxygenation systems and oxygen sources were evaluated. Air as an oxygen source was rejected because of the low potential D.O. concentration saturation and also potential dissolved nitrogen supersaturation problems in the river. Conventional surface aerators were rejected because of the excessive energy consumption per ton of D.O. supplemented to maintain the D.O. at 5 mg/L under summertime temperatures. Logistics due to barge traffic and policy considerations would not allow an oxygenation system to be located on the surface of the river, where it would obstruct barge traffic. Diffused aeration was rejected because of the low potential D.O. saturation, which would require pumping the entire river through the diffused aeration basin. Dissolved nitrogen gas supersaturation would result, possibly impairing the health of fish in the river. Again, excessive energy consumption per ton of D.O. supplemented was required to maintain a target D.O. of 5 mg/L.

Pressurized sidestream pipe reactor oxygenation was rejected because of excessive energy consumption per ton of D.O. supplemented and potential effervescent loss of supersaturated D.O. due to turbulence at the throttling valve used to maintain pressure in the reactor. Costs were considerable to supply 1000 feet of stainless steel pipe required to provide the required bubble contact time of over 100 seconds at the 10 fps water velocity necessary to maintain two-phase flow.

The overwhelming economical and practical advantages of using commercial oxygen emerged in the selection process, narrowing the search to two systems, the U-Tube and the Speece Cone technologies. Excessive cost to excavate deeply enough to withstand water levels in the 100 year flood disqualified the Speece Cone. The U-Tube oxygenation system was selected for its energy efficiency and capacity to produce very high D.O. concentrations of 50 mg/L with associated high oxygen absorption efficiency.

The U-Tube oxygenation system incorporates prolonged contact of the oxygen bubbles with the water as well as hydrostatic pressurization of the bubble water mixture as it passes down through the U-Tube. Oxygen transfer is enhanced by the turbulence and extended contact time, but mainly by the hydrostatic pressurization as the water goes down the depth of the U-Tube and back up out the discharge. A depth of 175 feet was selected as the design depth for the U-Tube.

U-Tube oxygenation was selected for both of the two locations on the Tombigbee River. The U-Tube with oxygen injection produced an affluent D.O. of 50 mg/L at 28°C with an oxygen absorption efficiency of 80 to 90% for a unit energy consumption and 94 kWh per ton of D.O. The oxygenation capacity was 5400 mg/L of D.O. per cubic feet per hour and the head loss across the 175 foot deep U-Tube was 5 feet.

A bubble harvester was incorporated to harvest any undissolved bubbles and recycle them back to the influent of the U-Tube. By discharging a highly elevated D.O. sidestream into the river through a diffuser in the bottom, advantage was taken in the hydrostatic head to prevent effervescent loss of D.O. and a high D.O. discharge was mixed throughout the river cross-section within a short distance downstream.

A schematic diagram shown in (Figs. ___) of both a gravity fed U-Tube which puts in 12,000 pounds of D.O. per day, as well as a schematic of the U-Tube where 125 MGD of water is pumped from the river through the U-Tube and then discharged back into the river with 50 mg/L of supersaturated D.O. concentration, resulting in 40,000 pounds per day of D.O. supplementation.

1.6 INTRODUCTION

CUTAWAY DIAGRAM

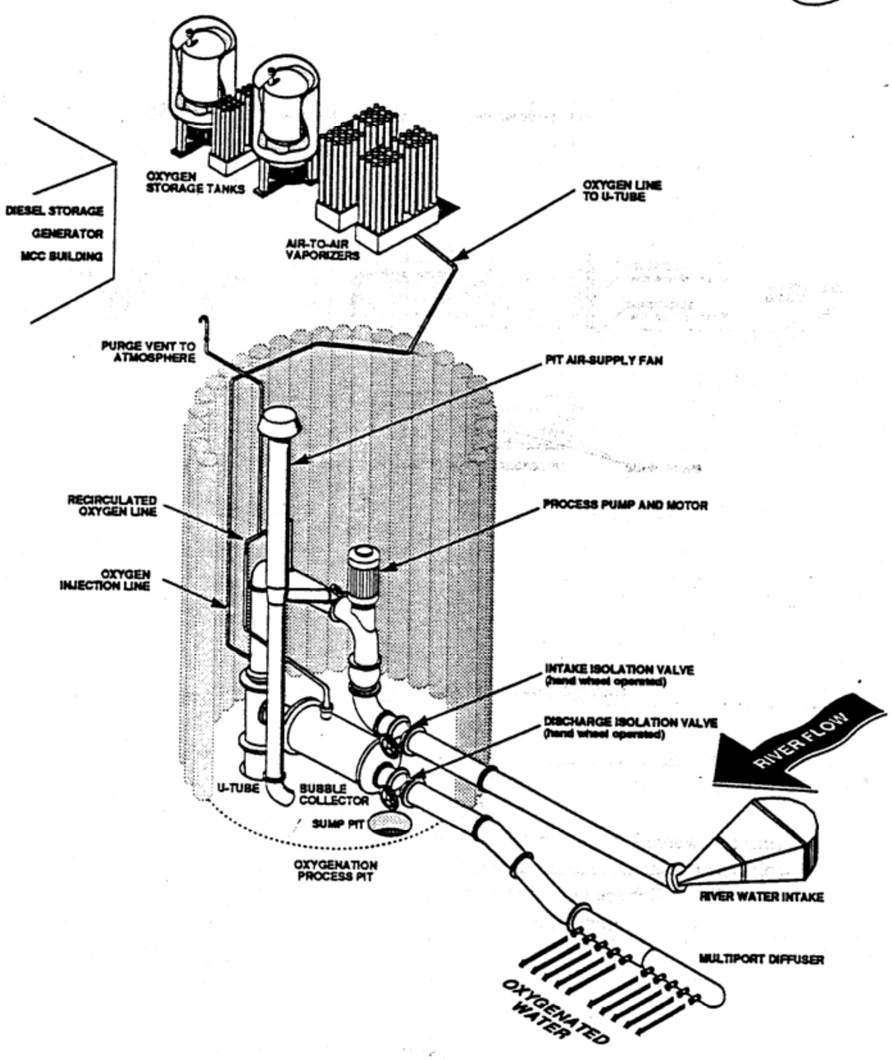


Figure 1.4 *River Oxygenation Equipment Diagram*

CUTAWAY DIAGRAM

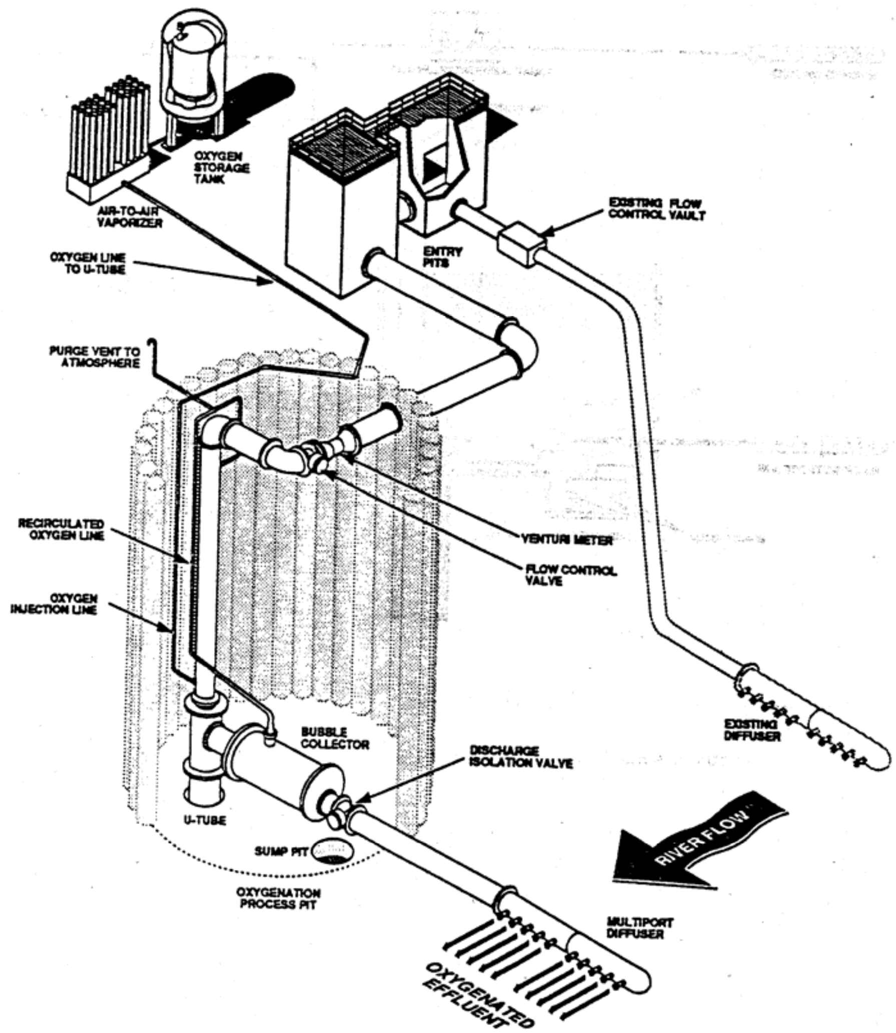


Figure 1.4 *River Oxygenation Equipment Diagram*

Field testing of the oxygenation system performance of the U-Tube installation which oxygenated the treated James River Mill effluent on the Tombigbee River yielded the following data:

- up to 50 mg/L discharge D.O. at 25°C in the water
- 5.3 foot head differential across the U-Tube
- up to 18,000 pounds of D.O. per day oxygen transfer
- 80 to 90% oxygen absorption efficiency