University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 344

EXPERIMENTAL ANALYSIS OF SEDIMENTARY OXYGEN DEMAND IN LAKES: DEPENDENCE ON NEAR–BOTTOM FLOW VELOCITIES AND IMPLICATIONS FOR AERATOR DESIGN

by

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Prepared for

LEGISLATIVE COMMISSION ON MINNESOTA RESOURCES
St. Paul, Minnesota

June 1993

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ABSTRACT

Aeration technology is applied in hundreds of Minnesota lakes and reservoirs for at least three purposes: (a) to prevent winterkill of fish in shallow lakes under ice cover, (b) to reduce nutrient release rates from the sediments and (c) in aquaculture to provide aerated water to high–density fish populations. A major uncertainty in the design, selection and application of aeration systems is the often observed increase in oxygen demand after aeration systems are installed and operated. As a result, the improvement in dissolved oxygen is often less than anticipated, even zero.

In this study we have investigated this problem through a series of carefully designed experiments. We have shown that sedimentary oxygen demand (SOD), frequently the major oxygen consumer in lakes, increases proportionally to the velocity with which the water above the sediments moves. Aeration devices often and intentionally increase water velocity above the sediments and thereby increase oxygen consumption in the lake. The results given in this report allow a more realistic estimation of oxygen demand in lakes for aerator selection. Recommendations for aerator placement are also given.

ACKNOWLEDGEMENT

Funding for this project was approved by the Minnesota Legislature (ML 1991, chapter 254, Art 1, Sec. 14, Subd. 4k, Development and Application of Aeration Technologies) as recommended by the Legislative Commission on Minnesota Resources from the Minnesota Future Resources Fund.

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I. DISSOLVED OXYGEN UPTAKE OF LAKES AND AERATION

Aeration technology is applied in hundreds of Minnesota lakes and reservoirs for at least three purposes: (a) to prevent winterkill of fish in shallow lakes under ice cover, (b) to reduce nutrient release rates from the sediments, and (c) in aquaculture to provide aerated water to high–density fish populations. A major uncertainty in the design, selection and application of aeration systems is the often observed increase in oxygen demand after aeration systems are installed and operated. As a result, the improvement in dissolved oxygen is often less than anticipated, even zero.

This study addresses this problem and makes recommendations for more reliable estimation of sedimentary oxygen demand and placement of aerators to minimize interference with the water boundary layer above the sediments.

The literature review by Ellis and Stefan (1989) clearly points out that biochemical decomposition of organic materials in the lake sediments makes a major, if not the largest demand on dissolved oxygen in winterkill lakes, i.e. ice–covered lakes with little inflow and outflow, in which fish die for lack of oxygen. Dissolved oxygen depletion or anoxia is also observed in summer in the hypolimnion of biologically very productive (eutrophic) lakes if they are deep enough to thermally stratify. In these lakes downward dispersion of dissolved oxygen from reaeration and photosynthesis of the surface layers is not at sufficient rates to compensate for sedimentary oxygen uptake. Release of phosphorus, a primary nutrient for algae, is a secondary, and usually undesirable effect, of dissolved oxygen depletion near the sediments (Mortimer, 1971, Chapra and Canale, 1991; Furnmai and Ohgaki, 1989).

Sedimentary oxygen demand (SOD) can be determined in two fundamentally different ways, each with its own advantages and disadvantages. In one method, SOD is determined as the residual of a hypolimnetic (summer) or total (winter) dissolved oxygen budget of a lake. The total net loss (or gain) of dissolved oxygen from the lake water can be determined from measurements of dissolved oxygen concentrations over depth at several times throughout the period of interest. Oxygen demand rates other than SOD need to be measured or estimated and subtracted from the net oxygen loss rate of a lake to determine SOD. These may include biochemical oxygen demand (BOD) of detritus particles in the water column, photosynthesis and respiration of plants in the hypolimnion (summer) or under the ice (winter), and dispersive transport from above.

A second method uses domelike chambers of various sizes, placed on the lake sediments, with a collar penetrating into the lake sediments. The DO in the water volume isolated in the dome is measured repeatedly and from its decrease the SOD is calculated. A discussion of these methods is given in other literature, e.g. by Cerco et al. (1992).

There is considerable evidence that water velocities, even small ones, have a strong effect on SOD. The evidence is fourfold.

(1) It has often been observed that artificial aeration devices and air bubble plumes designed to compensate for measured SOD values, sometimes fail to fulfill expectations. It is postulated that these installations increase the water circulation in the lake and hence SOD, indicating that these devices are underdesigned.

(2) SOD values measured in chambers increase considerably with necessary and appropriate mixing inside the chamber, but what is "appropriate" has not been quantified (Cerco et al., 1992).

(3) There exist some measurements which show an increase of SOD with flow rate (Belanger, 1981; Boynton et al., 1981).

(4) One can show theoretically, using mass transfer through laminar and turbulent boundary layers, that SOD should increase with flow velocity over the sediments (Nakamura and Stefan, 1992).

Increases in SOD start at very low velocities (order of cm/s) which occur naturally in lakes. Increases of SOD by an order of magnitude, i.e. tenfold increases, have been reported at velocities below 10 cm/s (Cerco et al. 1992). Typical SOD values are from 0.5 g $m^{-2}d^{-1}$ for sandy bottoms to 10 g $m^{-2}d^{-1}$ for very organic sediments. Values above 20 g $m^{-2}d^{-1}$ are found in very productive tropical water indicating a strong temperature dependence as well (Veenstra and Nolen, 1991).

Because the dependence of SOD on flow velocity has only been theoretically quantified (Nakamura and Stefan, 1992), laboratory experiments were undertaken to establish that relationship.

Current numerical models of SOD describe chemical and biological kinetics at the sediment/water interface by zero or first order kinetics (e.g. DiToro et al., 1990) but do not recognize or include the velocity dependent diffusive flow through the water boundary layer, although it can be the rate limiting process.

II. OBJECTIVE OF STUDY

The goal of the study described herein is to measure the effect of water velocity on sediment oxygen demand (SOD) under well–controlled conditions in a laboratory experiment. Decaying plant and animal matter, and bacteria in the sediments, draw dissolved oxygen (DO) out of overlying water. In calm water a steep gradient in the DO concentrations can be set up above the sediment (Fig. II–1). Very low currents can disturb this boundary layer and cause a substantial increase in the rate of SOD. The goal of this study is to measure the magnitude of this increase at varying velocities of current. A relationship between SOD ($g\ m^{-2}d^{-1}$) and flow velocity (cm/s) above the bed will be obtained. The water boundary layer will be characterized by its thickness and shear velocity which will also be related to SOD. An experimental confirmation, or disagreement with theoretical relationships, (Nakamura and Stefan, 1992) is sought.

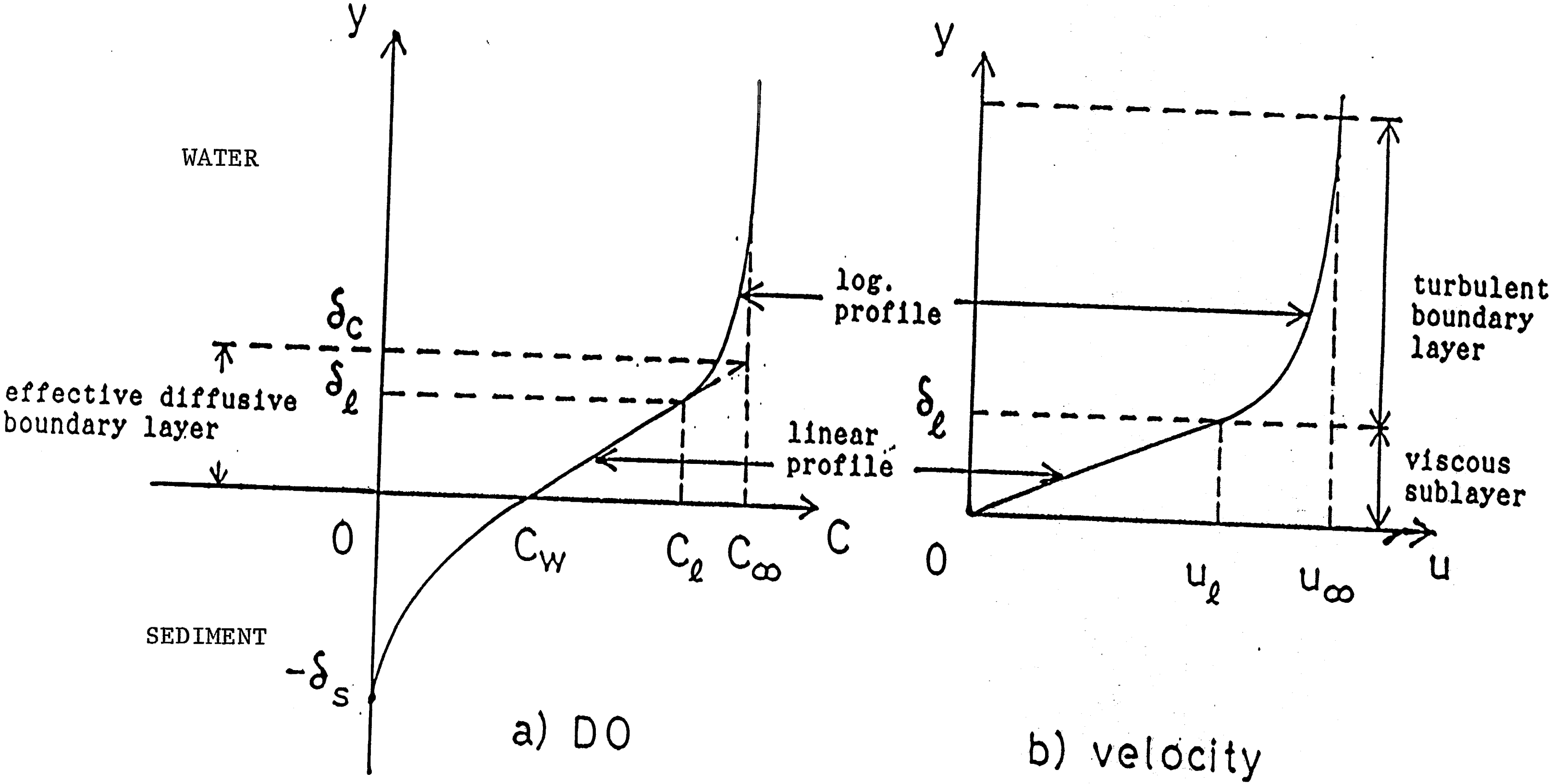

Figure II–1 Schematic distribution of dissolved oxygen concentration (a) and flow velocity (b) in the boundary layer above a sediment bed.

III. EXPERIMENTAL METHOD FOR MEASUREMENT OF SEDIMENTARY OXYGEN DEMAND RATES

1. Design and Construction of Experimental Channel

A recirculating channel with hydraulic (water) residence times of several hours was required for this experiment to measure oxygen uptake rates of 0 to 10 g $m^{-2}d^{-1}$ by the bulk oxygen budget method. To simulate natural conditions in lakes, the boundary layer of the flow in the experimental channel had to be fully developed while passing over the sediment. A wide channel was desirable to reduce boundary effects from the channel walls. Two different concepts for the geometric layout of the channel were considered. The first was a circular flume with a continuous annular flow. The second was a recirculating flow in a straight glass–walled laboratory flume

In the circular design, a jet pump would keep the water moving around continuously. The organic sediment could be placed all the way around the bottom of the circular flume. The jet pumps would most likely disturb the flow locally, and secondary flow patterns may develop due to the curvature of the streamlines. Therefore, the velocity profiles in a channel cross–section may not be symmetrical on either side of the channel axis making the data analysis difficult.

The second design option required recirculation of the water around or within the laboratory channel and redevelopment of the boundary on each pass through the channel. Velocities from 0 to 30 cm/s (0–1 ft/s) were needed to represent lake bottom conditions. The second option was chosen and a 15 m (50 ft) long laboratory channel, 60 cm (24 inches) wide and 40 cm (16 inches) high, was reconstructed for the experiments. A divider wall (Fig. III–1) was placed horizontally near mid–depth in the channel to let the water recirculate above the divider.

A pump in the by–pass loop was provided to add momentum to the flow in order to overcome friction head losses. Intake and discharge manifolds were installed in the return portion of the flow and connected to the pump. The manifolds were placed in the upper–return duct just after the water returned from the bottom to maximize the distance from the multiport jets to the sediment bed in order to dissipate turbulent net energy.

Calculations and minimization of headloss and head requirements led to the selection of a 17.5 cm (7 inch) height for the flow over the sediment bed and a 12.5 cm (5 inch) height for the return flow. With larger height differences, the velocity in the return flow becomes too high, increasing friction losses and making control difficult. The divider and false bottom were constructed of galvanized steel. A top cover was needed to prevent

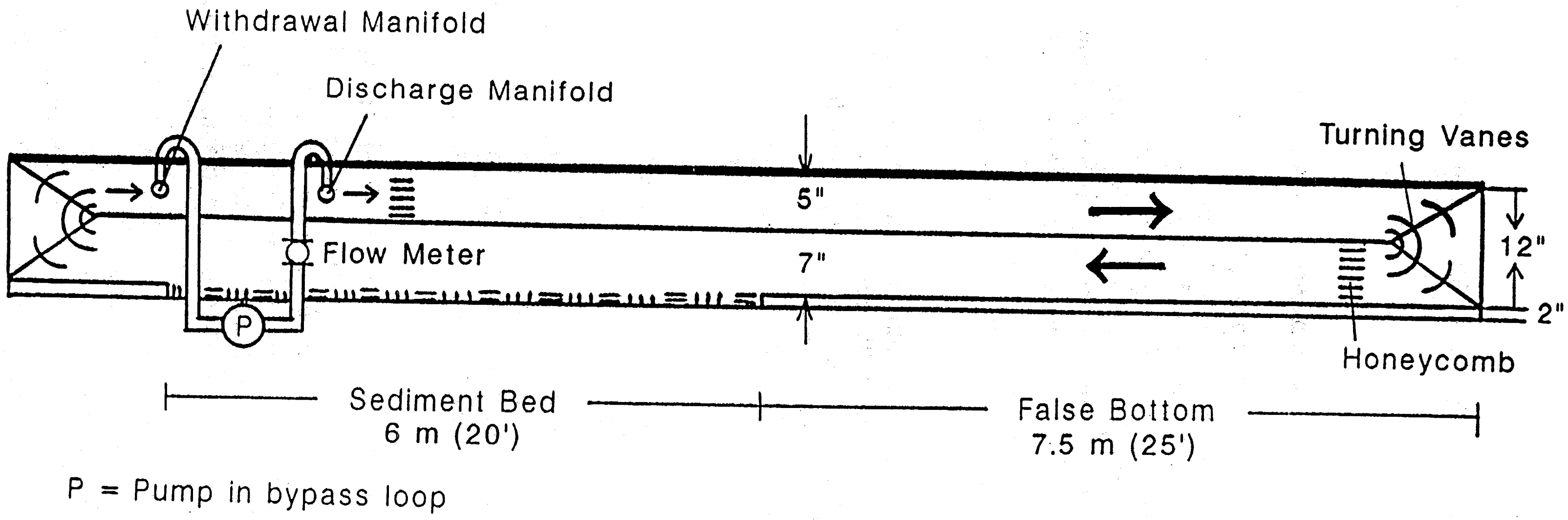

Figure III–1 Experimental Channel, 15m (50ft) long oxygen transfer from the air. One inch thick styrofoam was cut to fit in the channel without gaps. To maintain a uniform flow and to avoid flow separation, turning vanes were installed at both channel ends. Honeycombs were installed downstream from the vanes for further flow straightening and turbulent energy dissipation.

Volumetric flow meters were installed in the discharge line downstream from the pump. Although these meters did not measure the total flow in the duct, they could be used to reset known flow rates in the channel after calibration as described later.

Figures III–2 to III–5 give details of the installation.

Design flow Reynolds numbers based on water at room temperature and a hydraulic diameter for the duct equal to $D_h = 4A/P = (4)(24)(7)/(48+14) = 7 \times 1.55 = 10.85$ inches $= 27.6$ cm, indicated that the flow would be laminar ($Re < 2400$) at mean flow velocities below approximately 1 cm/s and turbulent above that value. The velocity profile in turbulent pipe flow can be considered fully developed in 50 diameters conservatively, or 20 diameters effectively. The distance from the turning vanes at the upstream end of the duct to the beginning of the sediment layer is 7.5 m (25 ft) or approximately 28 hydraulic diameters, hence sufficient to develop the velocity profile fully in turbulent flow (Fig. III–6). Laminar flow takes a longer distance to develop, but even then, the laminar velocity profile was anticipated to be well developed at the entrance to the test section with the sediment bottom.

The flow in the channel and over the sediment canal can be approximated as a flat plate boundary layer flow. In that case the distance x to develop a fully developed boundary layer thickness, δ, of 8.7 cm above the sediment bed, can be estimated from

$$\frac{\delta}{x} = \frac{5.0}{(Re_x)^{1/2}} \text{ for laminar flow} \qquad \text{(III–1)}$$

and

$$\frac{\delta}{x} = \frac{0.37}{(Re_x)^{1/5}} \text{ for turbulent flow} \qquad \text{(III–2)}$$

where $Re_x = V_c x/\nu$.

V_c = Maximum velocity

ν = Kinematic viscosity

2. Velocity Measurements

Velocity profiles were measured to determine the average velocity, maximum velocity, boundary layer thickness and average shear stress (shear velocity) on the bed. Measurement of the velocity profiles proved to be difficult. Measurements were made with an electro–magnetic Marsh–McBirnie model 523 current meter (EMCM). This instrument was very sensitive and delicate. The probe consists of a 1/2" diameter sphere with 1/8" diameter electrodes sticking out in four directions. The probe is shown mounted on a point gate and carriage over the channel in Figure III–7. This velocity meter

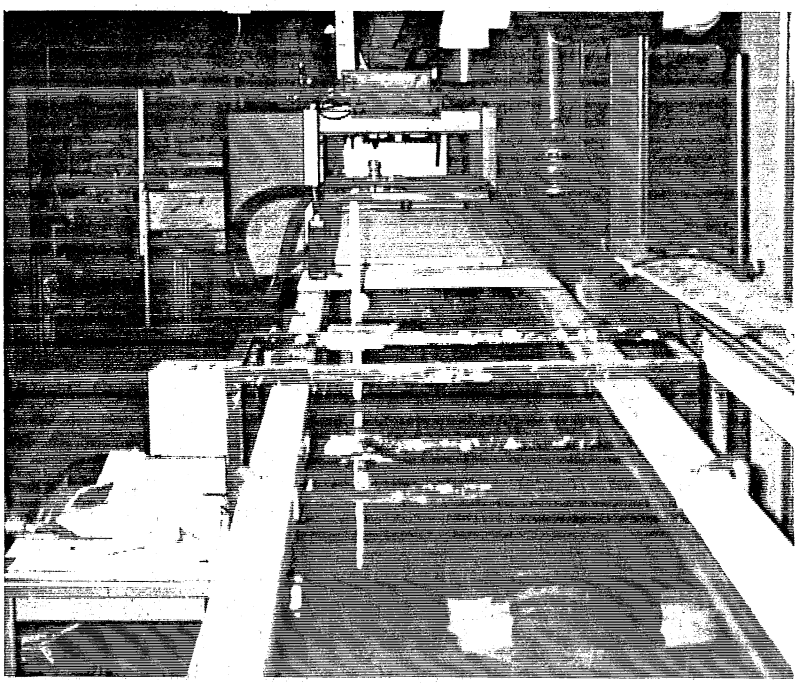

Figure III–2 Upstream portion of experimental channel seen from above. Data collection system on table next to channel

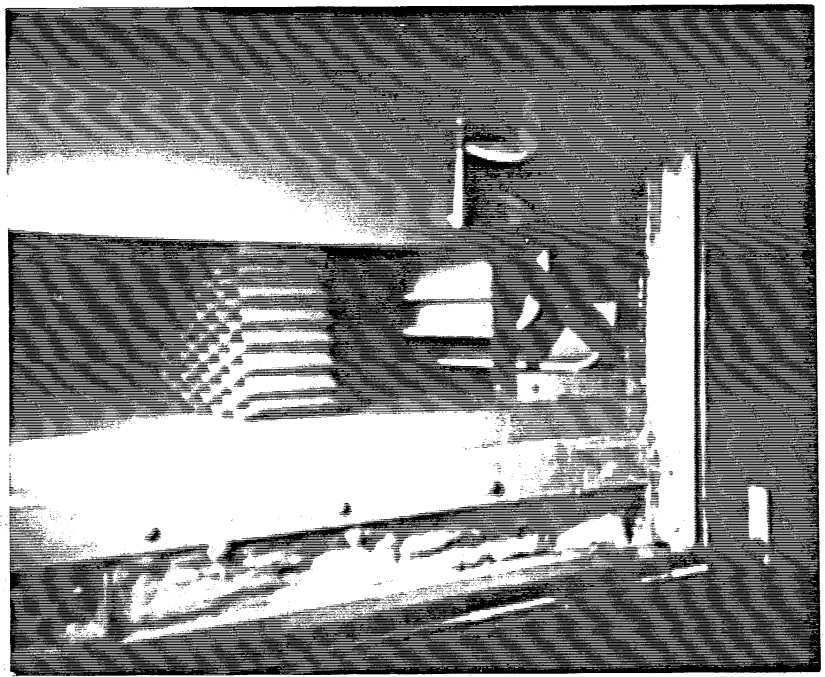

Figure III–3 Turning vanes and honeycomb at the upstream end of the channel.

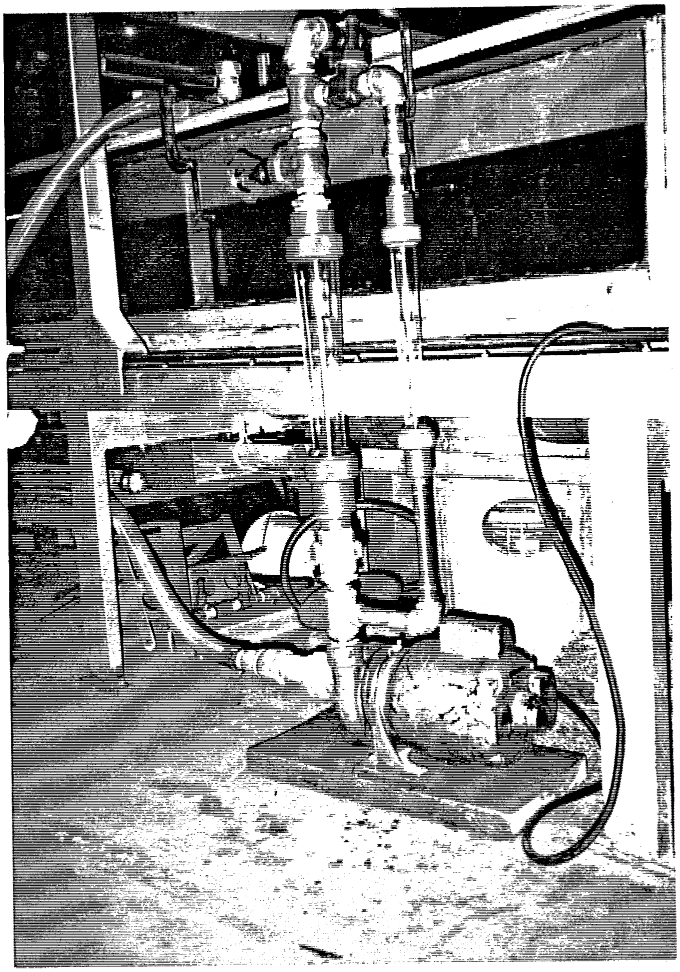

Figure III–4 Experimental flume with glass walls, rotary flow meters and pump.

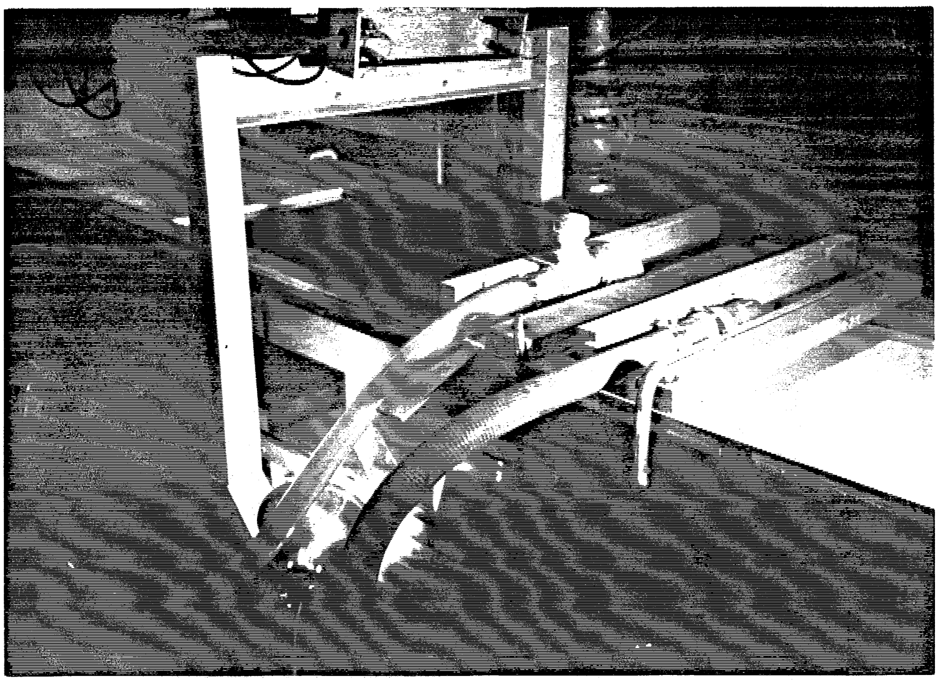

Figure III–5 Pipe connections to withdrawal manifold and the discharge manifold.

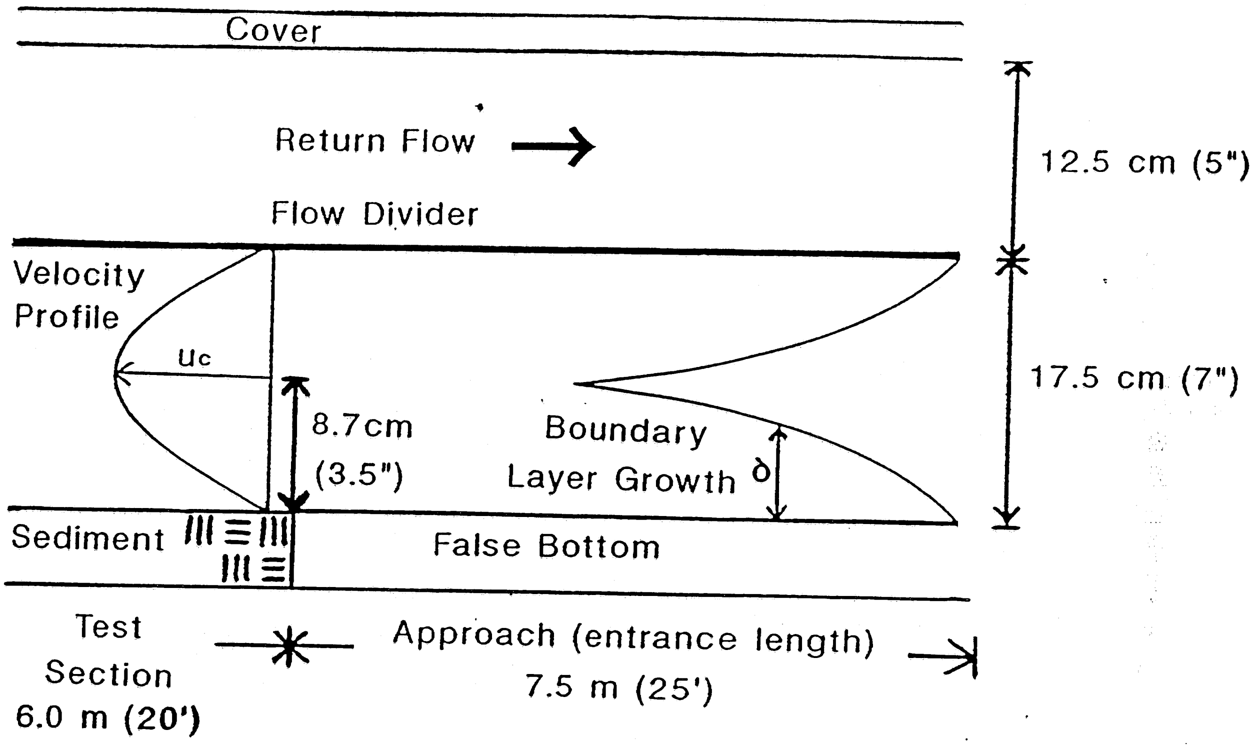

Figure III–6 Experimental approach flow towards test section showing boundary layer growth (schematic).

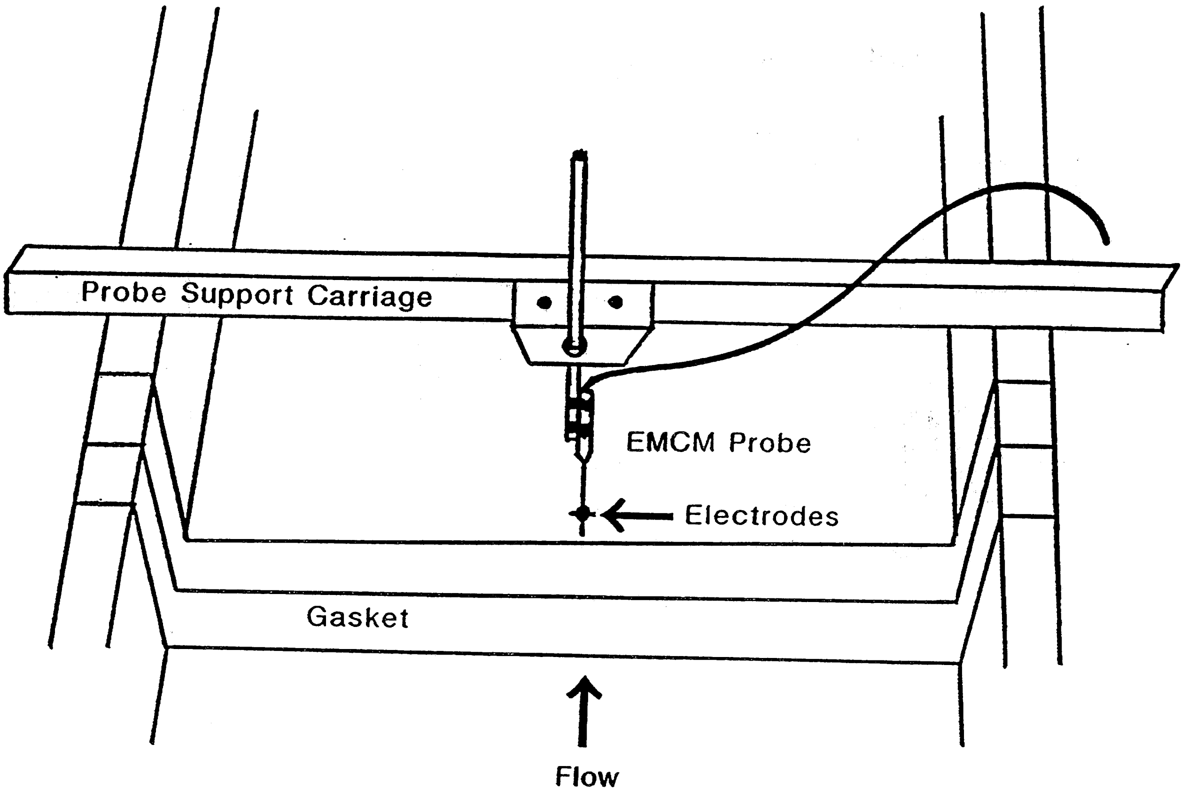

Figure III–7 Electro–magnetic current meter probe mounted above the channel (schematic).

integrates velocities in about a one-inch sphere around the probe. This limits the resolution of the probe near the walls and the floor of the channel.

The probe was connected to an Apple II computer which could sample nine times a second for any specified time period. Instantaneous measurements were averaged over sampling time which was varied depending on the average flow velocity.

The probe was inserted from above through a 2.5 cm (1.0 inch) gap in the horizontal divider wall. A rubber gasket was placed over the slot to minimize added turbulence and cuts were made in the gasket to aid in insertion of EMCM probe. The maximum average velocity which could be achieved in the channel was found to be 21 cm/s (0.7 ft/s).

Preliminary velocity measurements were taken to obtain optimum sampling times. Velocities were sampled at two flow rates and at four points. At each point sampling times varied from 4–240 seconds. The results were plotted as time-averaged velocity over sampling time and the necessary sampling time was taken to be the shortest time after which the average velocities showed no more systematic change (trend) (See Appendix A). At a time-averaged velocity of 3.0 cm/s (0.1 ft/s) a sampling time of 40 sec was found to be sufficient and at 18.3 cm/s (0.6 ft/s) approximately 25 sec was sufficient. For other velocities, sampling times were interpolated linearly.

Velocities below 3 cm/s (0.1 ft/s) could not be measured with the electromagnetic probe. At about 1 cm/s the flow becomes fully laminar and it was necessary to measure velocity profiles of these flows by a dye tracing technique.

Potassium permanganate and 5,5,7-Indigotrisulfonic acid crystals were used to measure the velocities in the laminar flow range. When the crystals are dropped into water they leave a clearly visible dye streak as they fall. These streaks can be photographed with a double exposure, and with the time between the exposures, velocities can be calculated. To do this, the negatives of the photographs were projected onto a grid and were traced. Successive dye traces were overlaid on each other. The distance between the traces was measured and divided by the time elapsed between the photos for the velocities. Two examples of the dye streak velocity measuring technique are shown in Figures III-8 and III-9.

To facilitate the resetting of different flow rates (gpm), two bullet type flow meters were installed in parallel downstream from the pumps. With the flow meters in place, velocity profiles at four different flow rates were measured. The electromagnetic current meter and the photographic technique were each used for two of these flow rates.

Sets of the velocity data obtained by the electromagnetic current meter (EMCM) and by the dye-tracing method are given in Appendix B. Velocity measurements were made along vertical lines at the beginning of the sediment bed at vertical distances of 0.3, 0.6, 1.2, 1.9, 2.5, 3.1, 3.8, 5.0, 7.8, 10.1 and 12.7 cm (0.125, 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 2.0, 3.0, 4.0 and 5.0 inches) above the bottom when the dye-tracing method was used. When the EMCM

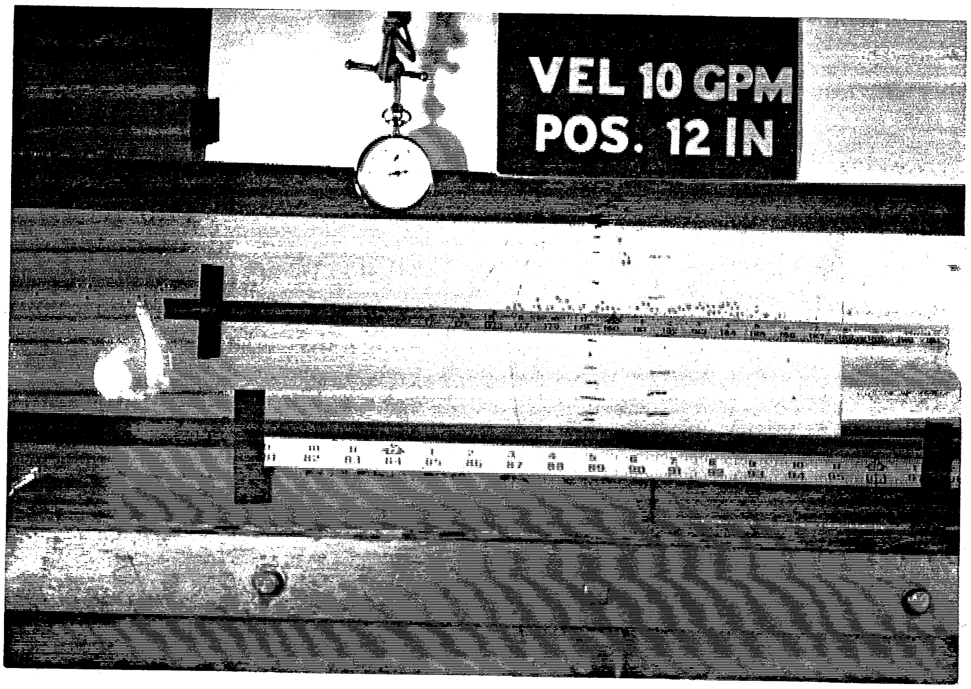

Figure III–8 Side view of test section while dye traces are used to measure velocity profiles.

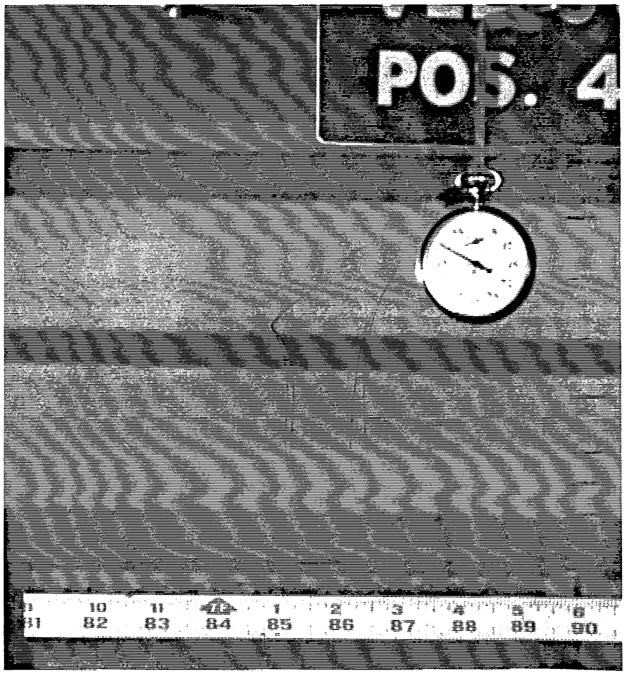

Figure III–9 Another example of the use of the dye tracing method.

was used, velocities were measured at the same distances plus 15.6, 16.9 and 17.5 cm (6.0, 6.5 and 6.75 inches). Vertical profiles were taken at 4 and 12 inches (centerline) from the sidewall when dye tracing was used and at 2.5, 5.0, 10, 20, 30, 40, 50, 55, and 57.5 cm (1, 2, 4, 8, 12, 16, 20, 22, and 23 inches) from the sidewall when the EMCM was used.

All vertical profiles were plotted in cartesian coordinates and on semi-log graphs before further analysis (Appendix B). Individual sets of velocity measurements were obtained by the dye method and were repeated up to six times. These are plotted, as well as average values, in the appendix. When the EMCM was used, the digital data acquisition permitted numerical averaging over appropriate sampling periods as discussed earlier (see Appendix A). Only the average values were plotted in Appendix B.

The semi-log plots are appropriate for turbulent velocity profiles which typically follow the relationship

$$\frac{u(y)}{u_*} = \frac{1}{\kappa} \ln y + C \qquad \text{(III-3)}$$

where $u(y)$ = velocity at distance y

u_* = shear velocity = $\sqrt{\tau_b/\rho}$

τ_b = bottom shear

ρ = density

κ = 0.41 = von Karman constant

C = constant of integration

The slope of the semi-log plot, u_*/κ, was determined by linear regression from all profiles and averaged. At 25 and 40 gpm flow rate a separate u_* was first calculated for each vertical profile and then a weighted average V_* was calculated for the total channel width (using the width for which each profile was representative as a weight factor).

$$V_* = \frac{\Sigma\, u_{*i}\, b_i}{\Sigma b_i} \qquad \text{(III-4)}$$

The resulting V_* values are given in Table III-1 for the two turbulent flows at 25 and 45 gpm.

Newton's shear law was applied to average velocity profiles at 4" and 12" from the wall for the u_* determination of the laminar flows at 6 and 10 gpm pump flow rate.

$$\tau_b = \mu \left[\frac{du}{dy} \right]_b \qquad \text{(III-5)}$$

TABLE III–1

Summary of Channel Flow Characteristics

(From analysis of individual runs for channel characterization)

	Dye Studies		EMCM Measurements	
Pump Flow Rate (gpm)	6	10	25	45
Shear Velocity, V_*(fps)	0.0027	0.00443	0.0104	0.0242
Maximum Centerline Velocity (fps)	0.0317	0.0571	0.163	0.319
Shear Stress (lb/ft^2)	1.41E–05	3.80E–05	2.10E–04	1.13E–03
Q (cfs)	0.0302	0.0585	0.161	0.310
Average Velocity (fps)	0.0259	0.0501	0.138	0.265

EMCM – Electro magnetic current meter data.

V_* from analysis of velocity vs. Ln height for turbulent flows of 25 and 45 gpm and V_* from $(\nu \times (du/dy))$^0.5 for the laminar flows of 6 and 10 gpm.

where μ = water viscosity ($\frac{N \cdot sec}{m^2}$)

$\left[\frac{du}{dy}\right]_b$ = slope of laminar flow velocity profile at bottom of flume ($\frac{1}{sec}$)

The regression was forced through u=0 at y=0.

Maximum velocities u_c were also taken from each profile at elevation y = H/2 = 3.5 inches or the nearest measurement point (usually y = 3 or 4 inches). A width–weighted average V_c is reported in Table III–1.

A total volumetric flow rate Q was calculated by integrating velocity profiles over the areas i.e. integrating first over height and then over width. These flow rates are also reported in Table III–1. An average flow velocity was then found by dividing Q by the total area of 7x24 in^2 = 1.167 ft^2. Values are in Table III–1.

The average channel flow velocity was plotted over pump flow rate (Fig. III–10) and the plot was nearly linear. This was expected because the manifold jet velocity is proportional to pump flow rate and flow entrainment velocity is proportional to jet velocity. The volumetric flow rate in the channel is essentially the flow entrained by the multiport jets. About 28% of the channel flow passes through the pump according to Fig. III–10. This figure was used to reset the desired flow rates.

The maximum flow velocity usually found at midheight of the experimental section is also linearly related to pump flow rate (Fig. III–11). Hence maximum and average flow velocities are also linearly related (Fig. III–12).

$$V_c = 1.20\ V_{avg} \tag{III–6}$$

in the range of velocities tested, i.e. $0 < V_c < 10$ cm/s and $0 < V < 8$ cm/s. Experimental shear velocity plotted against pump flow rate (Fig. III–13) shows separate linear relationships in the laminar and the turbulent ranges. Since pump flow rate is linearly related to average and maximum flow velocities, as shown earlier, shear velocity can be expressed also as (Fig. III–14).

$$V_* = 0.071\ V_{avg} = 0.059\ V_c \tag{III–7}$$

for laminar flows and as

$$V_* = 0.112\ V_{avg} = 0.093\ V_c \tag{III–8}$$

for turbulent flow.

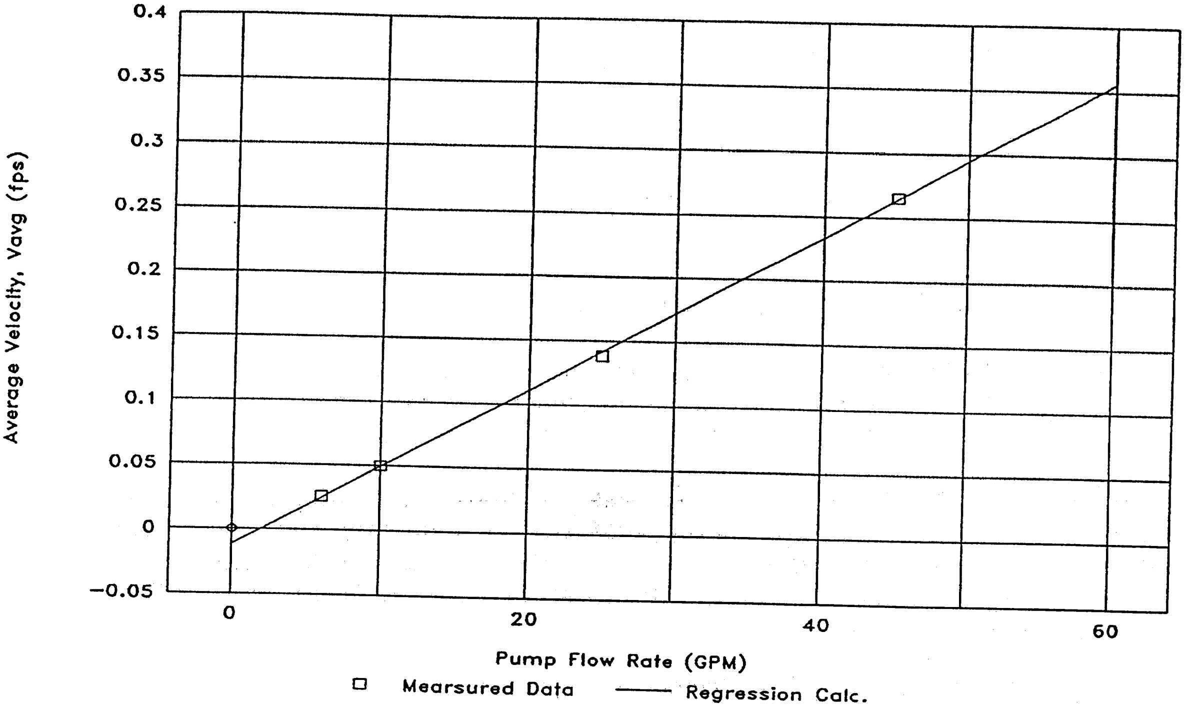

Figure III–10 Channel Summary – Pump Flow Rate vs. Average Velocity

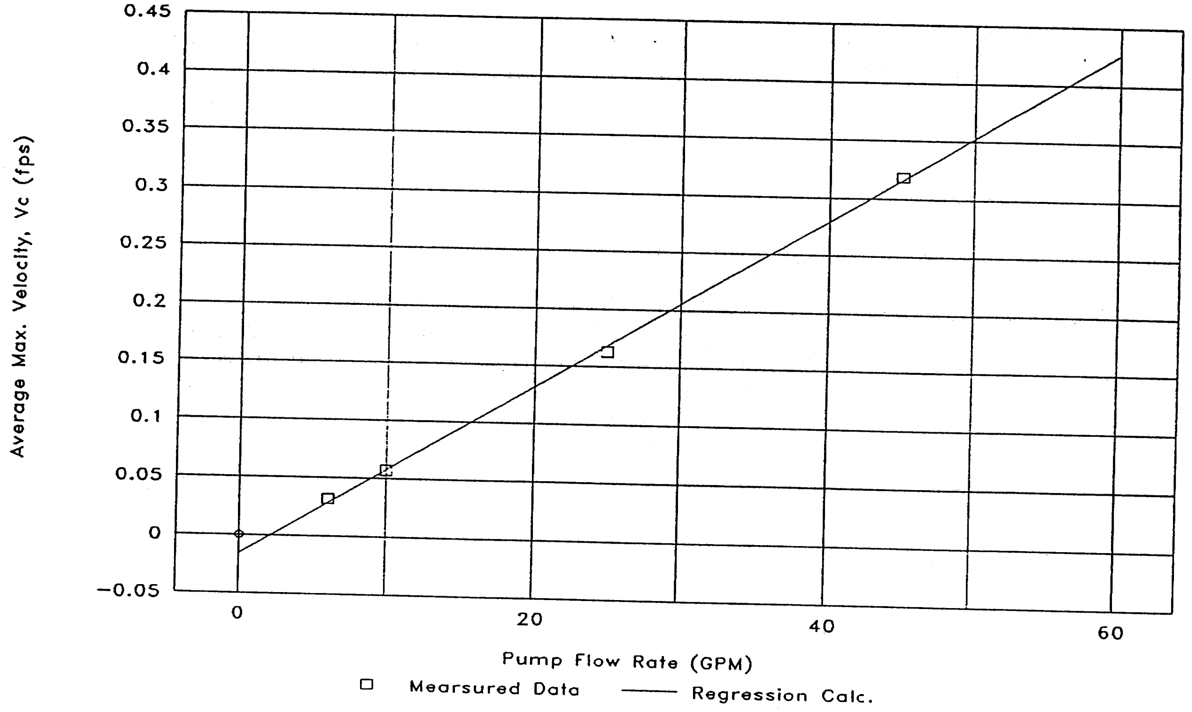

Figure III–11 Pump Flow Rate vs. Average Maximum Velocity

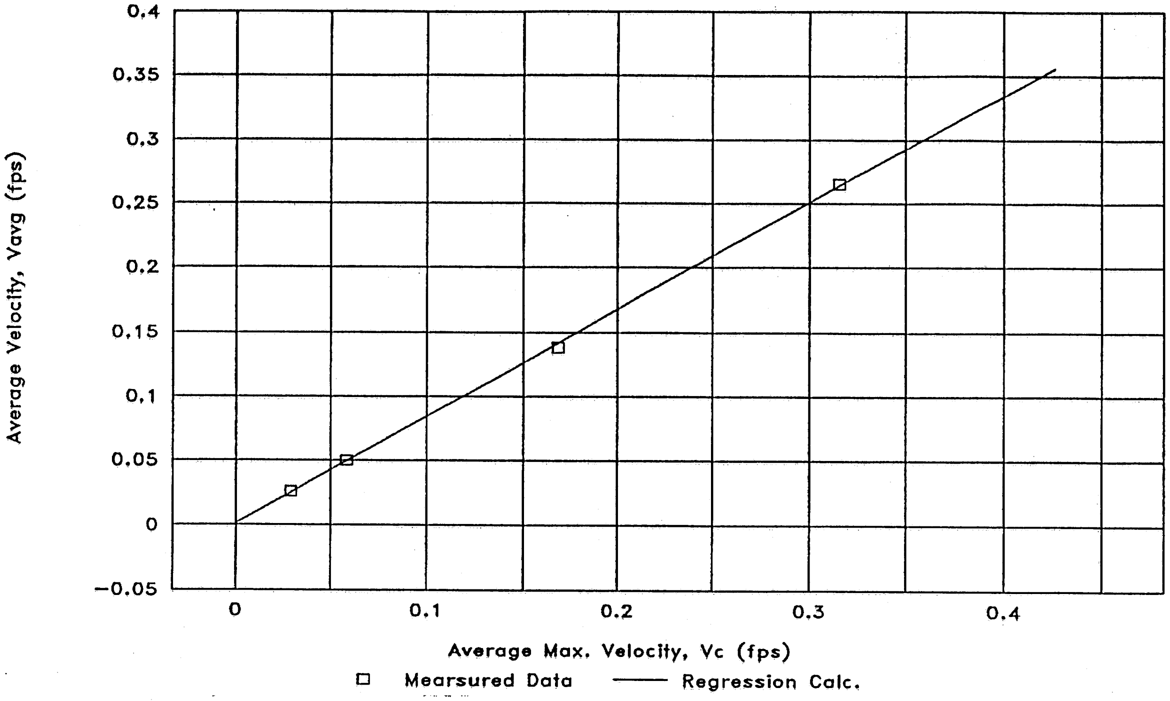

Figure III–12 Average Maximum Velocity vs. Average Velocity

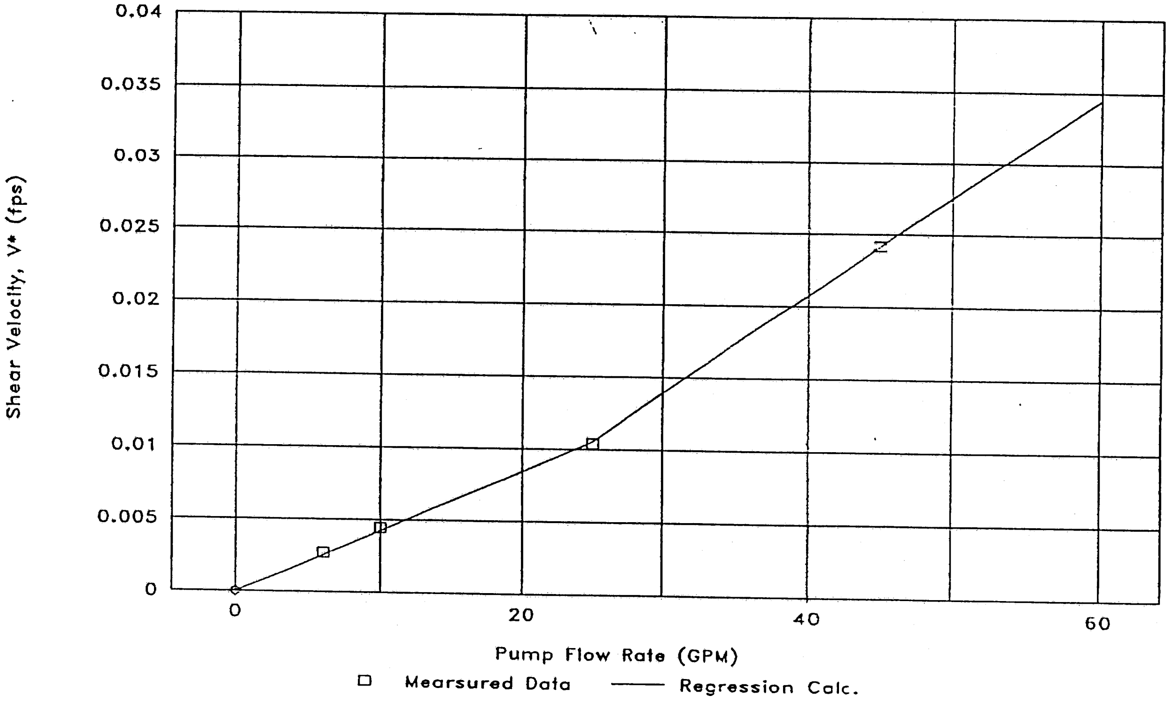

Figure III–13 Pump Flow vs. Shear Velocity

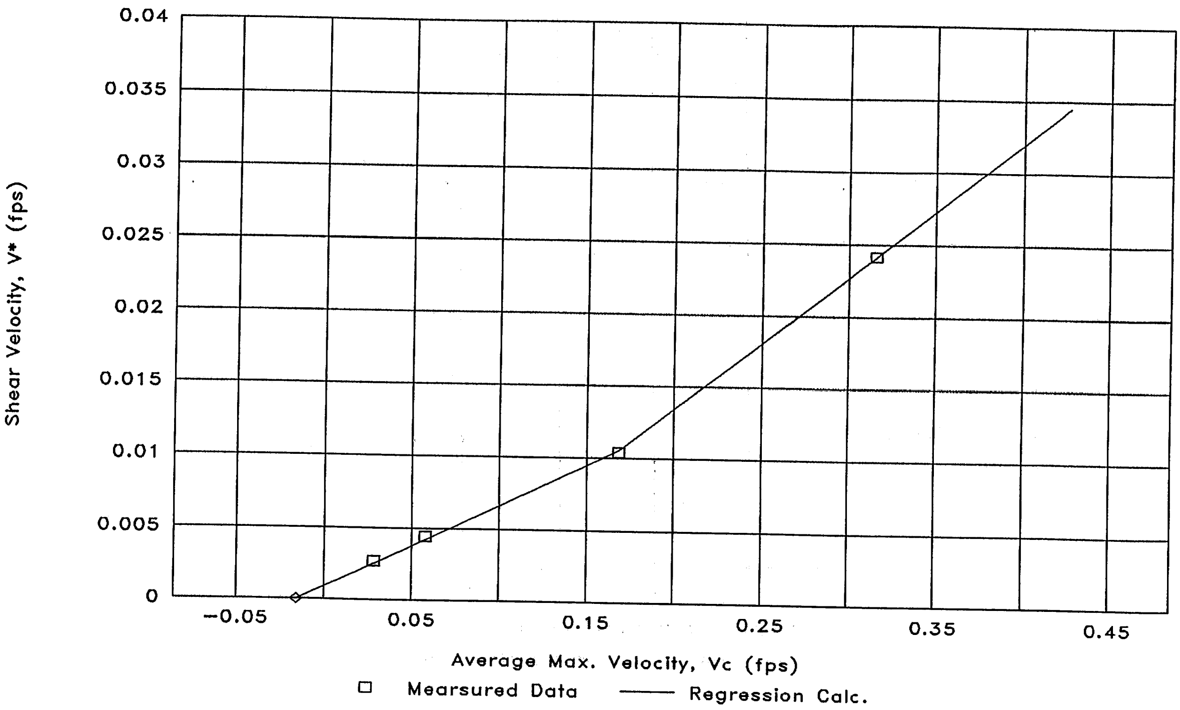

Figure III–14 Average Maximum Velocity vs. Shear Velocity

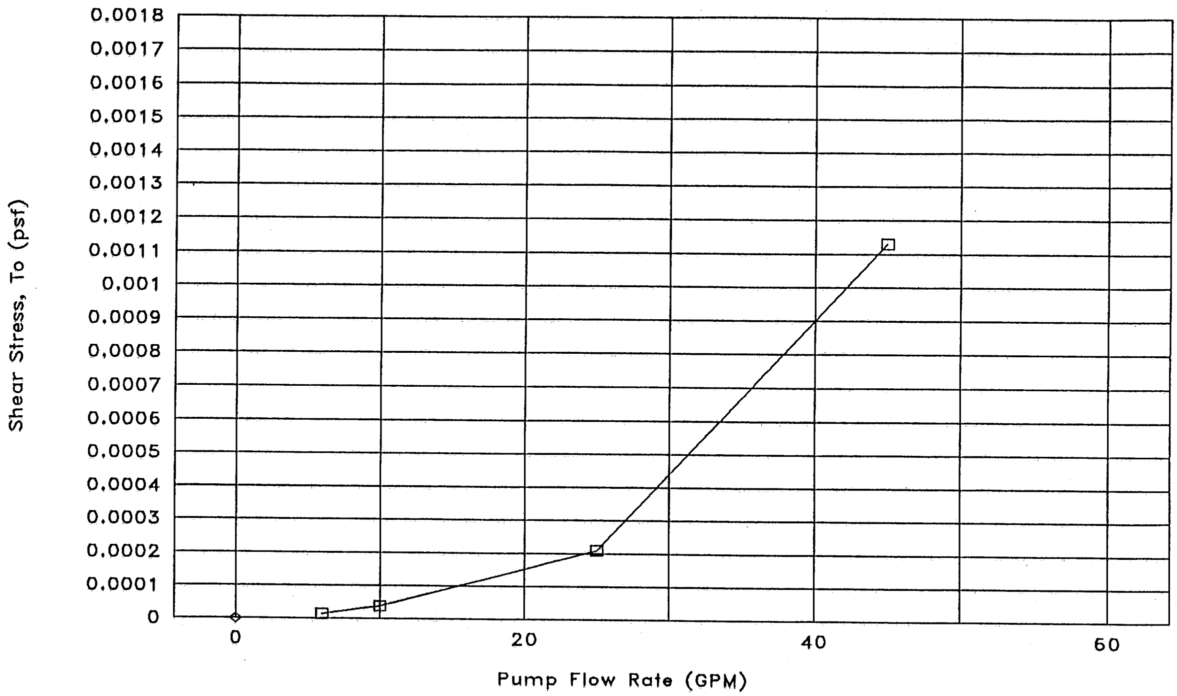

Figure III–15 Pump Flow Rate vs. Shear Stress

Laminar flow theory indicates that the relationship between shear velocity V_* and average velocity V_{avg} should be non-linear, more precisely it is V_*^2 that should be proportional to average and maximum velocity. The bed shear stress τ_b which is equal to ρV_*^2 is plotted in Fig. III–15 and shows the theoretically justified nonlinearity. The linearity in Fig. III–13 and III–14 is fortuitous because of the closeness of the two lowest data points which represent laminar flow. In fact the linearity of the low data set extends into the turbulent flow range so that Eq. III–7 is valid up to $V_{avg} < 4.3$ cm/s (0.14 ft/s) or $V_c < 5.1$ cm/s (0.17 ft/s).

The preceding plots of velocities and bed shear stress τ_b characterize the flow in the experimental channel. It was decided that the four flow rates tested adequately characterize the experimental channel and that velocity conditions at other flow rates could be obtained by interpolation between measurements and some extrapolation.

3. Determination of Sediment Type

Selection of an organic sediment was required because no obvious choice was available and time permitted the use of only one type of bed material for this report. Organic lake bottom sediment would be an obvious choice but another type of sediment might be easier to define in terms of particle size and composition, and be more easily reproducible (lake sediments vary from site to site). Some types of sediment may work more quickly, and also be cleaner and more easily obtainable. One desirable property was a rate of SOD greater than that of the lake sediment to shorten the duration of an experiment. Also, a sediment must not be washed out by the current. Cleanliness, reproducibility, accessibility, affordability, and chemical and biological stability over a period of a few weeks were other desirable properties for the sediment.

Alternative sediments were tested. Alternative sediments considered included cracked corn, silage, sawdust, and scratch (a mixture of grains used as chicken feed). The test sediments were placed under water in five gallon buckets for a period of time, then drained, and equal amounts of water were placed in the buckets before they were covered with styrofoam. The level of dissolved oxygen in each bucket was measured initially and several times during the following day or two.

The silage had a very high rate of SOD, but it did not settle well, it had an unpleasant odor and it spoiled.

The sawdust performed well at first, but over time the rate of SOD slowed. This was attributed to a washing out of the fines when the water was changed a number of times. Reaeration was tried instead of simply replacing the water with low DO. This helped considerably.

The cracked corn also had a very high rate of SOD, but it spoiled, and smelled badly. The scratch grain performed well, but it contains some cracked corn. A light film appeared on the top of the water over time. This was not nearly as bad as the cracked corn and possibly a mix with no cracked corn could work well.

Results with different sediments in bucket experiments are shown in Appendix D.

Sawdust was chosen to be the sediment material because of its cleanliness, its apparent stability of DO consumption with time, and its high rate of DO uptake. Washout was avoided by using low enough water velocities.

4. Dissolved Oxygen and BOD Measurement

Dissolved oxygen was measured in water samples by the Winkler titration method. Water samples of 300 mℓ were taken from the channel. The titration protocol is described separately by Mackenthun (1993). Dissolved oxygen measurements were made with two replicas every time. The standard error of the D.O. measurements was less than 0.02 mg/ℓ. *Standard Methods* gives a precision of 0.05 mg/ℓ for an experienced analyst using visual end-point detection.

During the initial evaluation of sediments, no attempt was made to measure the BOD of the water itself. The water above the grains was quite cloudy suggesting that BOD might be high. During later runs the BOD of the water needed to be accounted for and it was measured in samples taken at the beginning of each run. The samples were collected in 300 ml BOD bottles. As water samples were taken to measure the DO level in the main channel, BOD of the samples collected earlier could also be measured. The BOD could be subtracted from the total change in DO concentration in the channel and the residual could be attributed to SOD. The BOD samples were stored near the channel with the lip of the bottles filled with water to avoid diffusion of air along the bottle cap.

5. Experimental Protocol

Several preparations were necessary before an experiment was ready to be performed. The sawdust was placed under water in barrels for about 10 days to allow it to become water saturated. Before the sediment could be placed into the channel, the cover, the divider wall, the false floor, turning vanes, honeycombs, and manifolds were removed and the channel was cleaned with city water and a brush. The channel was then reassembled. The watersaturated sediment was placed into the test section and covered with cheese cloth to prevent it from being washed out of the bed at higher velocities. This later proved to be a problem and unnecessary. The channel was slowly filled with city water and allowed to sit for about one week to allow the sediment to settle and stabilize. During this time, aeration was provided by two dome shaped porous stone aerators placed on the bottom of one end of the channel. Also, the channel water was circulated continually to ensure a uniform distribution of oxygen and aerobic conditions.

The cheese cloth started to rise above the sediment when it trapped small air bubbles released from the sediment after the channel was filled with water. This was abated by lightly touching the cloth which allowed the air to pass through and then weighting the cheese cloth down at the edges. The last three feet of the bed was not covered to monitor for any washout problem. It was observed that there was only a small amount of resuspension of the sawdust at the highest velocities, and the cheese cloth was therefore removed after the fourth run. Resuspension was not noticed again during the remaining experiments.

The experimental procedure required disconnecting the aeration source and setting the pump to the desired flow rate. The top of the channel was then sealed and at least half an hour was allowed for the flow to reach a quasi–steady state. The water temperature was measured and several water samples were taken in 300 ml BOD bottles. These samples were collected by raising one of the styrofoam panels on top of the channel for access and then immersing the BOD bottles in the water very slowly. Bubbling was kept to a minimum to limit the potential for reaeration of the water. The lip of the BOD bottles was kept filled and the bottles were kept near the channel so that their temperature was maintained near the temperature of the channel. As many as 27 water samples were taken initially for BOD measurements so that DO in two or three bottles could be measured several times throughout the experiment.

After a few experiments had been performed, it became clear that the DO drop in the water during normal working hours was small. Therefore, the later experiments were allowed to run for about 24 hours. It was observed that the DO of the channel water dropped linearly with time, the rate of BOD and SOD seemed to be constant over the duration of each experiment. The number of times the channel was sampled could therefore be reduced to 3 or 4 times per experiment. Samples were first taken half an hour to one hour after aeration was discontinued and pump rate was set, then twice near the middle of the run and once about 24 hours after the run was begun. Two or three water samples were taken from the channel each time, and two or three BOD samples were also analyzed simultaneously. The results were then averaged and the DO level of the channel samples was subtracted from the DO level in the BOD bottles to obtain the SOD exerted on the water in the channel during the run.

The DO level in the channel usually dropped one to two mg/L during the experiment, and when the run was completed, the aeration was again begun to ensure that the channel was never allowed to become anaerobic. Since the DO level was kept near saturation and it did not drop much during each run, it is expected that there was no reaeration from air in contact with the water along the edges of the styrofoam cover. The cover was cut to fit in the channel snugly, but there were a few very small gaps. Tap water was added to the channel occasionally to replace water that was lost to either evaporation during aeration, leakage, or to the samples.

After approximately one month, it was noticed that microbiological growth colonies were appearing on the sediment bed. These were believed to be fungi. Soon the water in the channel became quite cloudy while it had previously been clear, though the rate of BOD did not seem to change much during this time. Soon after it was noticed that a film was formed on the glass walls of the channel. This lasted approximately two weeks and was followed by clearing of channel water on its own. Subsequently, only the microbiological growth remained on the sediment bed.

IV. EXPERIMENTAL RESULTS

The experimental data collected are assembled in Appendix E. The results of data analysis to compute SOD are given in Appendix F. An example of the cumulative dissolved oxygen (DO) consumption by the sediments over the duration of an experiment is shown in Fig. IV–1. A regression line is fitted through the data. The slope of this line is the SOD rate. SOD rates determined in this way are summarized in Table IV–1 for all experiments.

Cumulative DO consumption by the sediment bed is calculated from DO drop in the water over time minus the measured BOD of the water, i.e.

$$\mathrm{SOD} = \left[\frac{\Delta \mathrm{DO}}{\Delta t} - \mathrm{BOD}\right] \cdot \frac{\forall_w}{A_s} \tag{IV–1}$$

where $\Delta \mathrm{DO}/\Delta t$ = slope of the cumulative total DO consumption rate (mg $L^{-1}d^{-1}$)

BOD = biochemical oxygen demand rate mg $L^{-1}d^{-1}$) in the water

$\forall_w$ = water volume in the flume = 2.83 m^3 (100 ft^3)

A_s = surface area of sediments = 3.6 m^2 = 40 ft^2

BOD is measured in water samples incubated since the beginning of the experiment. BOD depends on oxidizable materials in suspension or in solution in the recirculated water. Because the flume is initially fitted with city water BOD depends on material leaching or being suspended from the sediments. BOD values are listed against age of the channel water in Fig. IV–2. An initial rapid increase followed by a trend towards decreasing values seems evident. The cause may be the depletion of soluble and suspendable materials from the sediments, the growth of microbes on the sediment surface, or floatation removal of the suspended organics due to aeration.

SOD is temperature adjusted to 20°C by the equation

$$\mathrm{SOD}\ (20^\circ\mathrm{C}) = \mathrm{SOD}(T)\theta^{T-20} \tag{VI–2}$$

where $\theta = 1.065$ is used. SOD is plotted in Fig. IV–3 against maximum flow velocity, i.e velocity outside the boundary layer, as it would occur in a lake. SOD is plotted versus average velocity in Fig IV–4. A fairly linear relationship is apparent between flow velocity and SOD as predicted by theory (Wakamura and Stefan, 1992) for low flow velocities. There is, however, a significant change in SOD rates over time. This correlates with the development of microorganisms on the surface of the sediments in the channel. The organisms are believed to be fungi.

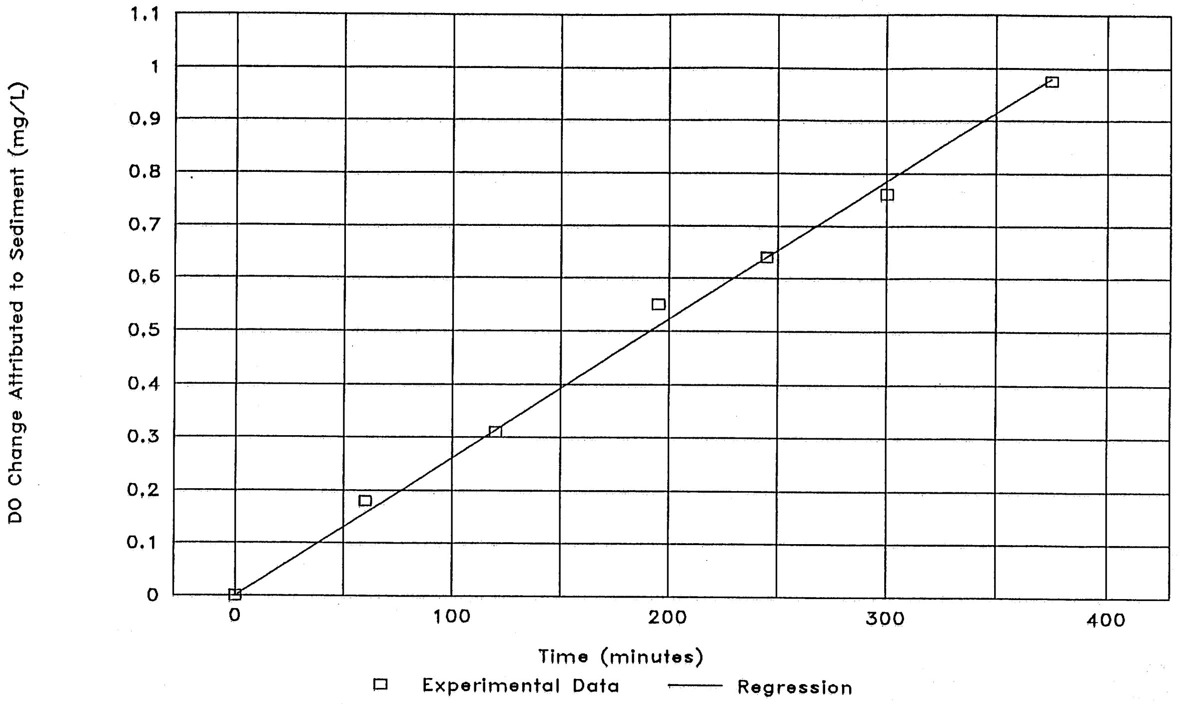

Figure IV–1 Example of Sediment Oxygen Utilization, 3rd Experiment, 45 gpm Pump Flow

TABLE IV–1

Summary of Experiments

Day from 1st run	Run No.	Pump Flow (gpm)	Avg. Vel. (cm/s)	Slope of DO vs. time (mg/ℓ*min)	SOD (g/m^2*d)	Temp. (F)	Temp. Corr. SOD* (g/m^2*d)	Rate of BOD (mg/1*min)	BOD Rate (mg/L*d)
1	1	25	2.44	0.00065	0.893	63	1.06	0.00042	0.62
2	2	30	5.24	0.00157	2.155	63	2.57	0.00005	0.08
3	3	45	8.04	0.00261	3.583	63	4.27	0.00154	2.23
4	4	60	10.84	0.00355	4.877	63	5.81	0.00371	5.35
10	5	15	2.44	0.00105	1.444	63	1.72	0.00072	1.05
11	6	20	3.37	0.00205	2.818	63	3.36	0.00050	0.72
17	7	30	5.24	0.00192	2.641	64	3.04	0.00032	0.46
19	8	10	1.51	0.00091	1.251	63	1.49	0.00120	1.73
22	9	5	0.57	0.00065	0.897	64	1.03	0.00036	0.38
25	10	20	3.37	0.00110	1.518	65	1.69	0.00029	0.43
29	11	15	2.44	0.00097	1.335	65	1.48	0.00019	0.28
32	12	45	8.04	0.00145	2.002	65	2.22	0.00022	0.32
33	13	60	10.84	0.00165	2.271	65	2.52	0.00028	0.40
45	14	30	5.24	0.00088	1.207	64.5	1.36	0.00018	0.26
46	15	5	0.57	0.00047	0.652	64.5	0.74	0.00022	0.32
47	16	10	1.51	0.00054	0.751	64	0.86	0.00022	0.33
48	17	15	2.44	0.00056	0.778	64	0.89	0.00017	0.25
51	18	20	3.37	0.00071	0.976	64	1.12	0.00016	0.24
52	20	45	8.04	0.00127	1.746	65	1.94	0.00009	0.14

*SOD(20) = SOD.*1.065^(20–T) T(° Celsius)

TABLE IV–1 (Cont'd)

Summary of Velocities and Bed Shear Stresses Used for the Analysis

Run No.	Pump Flow (gpm)	Avg. Vel. (cm/s)	Avg. Vel. (fps)	Max. Vel. (cm/s)	Max. Vel. (fps)	Shear Vel. (cm/s)	Shear Vel (fps)	Shear Stress (kg/m*s)
1	15	2.44	0.080	2.89	0.095	0.20	0.006	0.0039
2	30	5.24	0.172	6.26	0.205	0.41	0.013	0.0169
3	45	8.04	0.264	9.63	0.316	0.73	0.024	0.0539
4	60	10.84	0.356	13.00	0.426	1.06	0.034	0.1118
5	15	2.44	0.080	2.89	0.095	0.20	0.006	0.0039
6	20	3.37	0.111	4.01	0.132	0.26	0.008	0.0065
7	30	5.24	0.172	6.26	0.205	0.41	0.013	0.0169
8	10	1.51	0.049	1.76	0.058	0.14	0.004	0.0018
9	5	0.57	0.019	0.64	0.021	0.07	0.002	0.0005
10	20	3.37	0.111	4.01	0.132	0.26	0.008	0.0065
11	15	2.44	0.080	2.89	0.095	0.20	0.006	0.0039
12	45	10.84	0.264	13.00	0.426	1.06	0.034	0.1118
14	30	5.24	0.356	6.26	0.205	0.41	0.013	0.0169
15	5	0.57	0.172	0.64	0.021	0.07	0.002	0.0005
16	10	1.51	0.019	1.76	0.058	0.14	0.004	0.0018
17	15	2.44	0.049	2.89	0.095	0.20	0.006	0.0039
18	20	3.37	0.080	4.01	0.132	0.26	0.008	0.0065
19	30	5.24	0.111	6.26	0.205	0.41	0.013	0.0169
20	45	8.04	0.264	9.63	0.316	0.73	0.024	0.0539

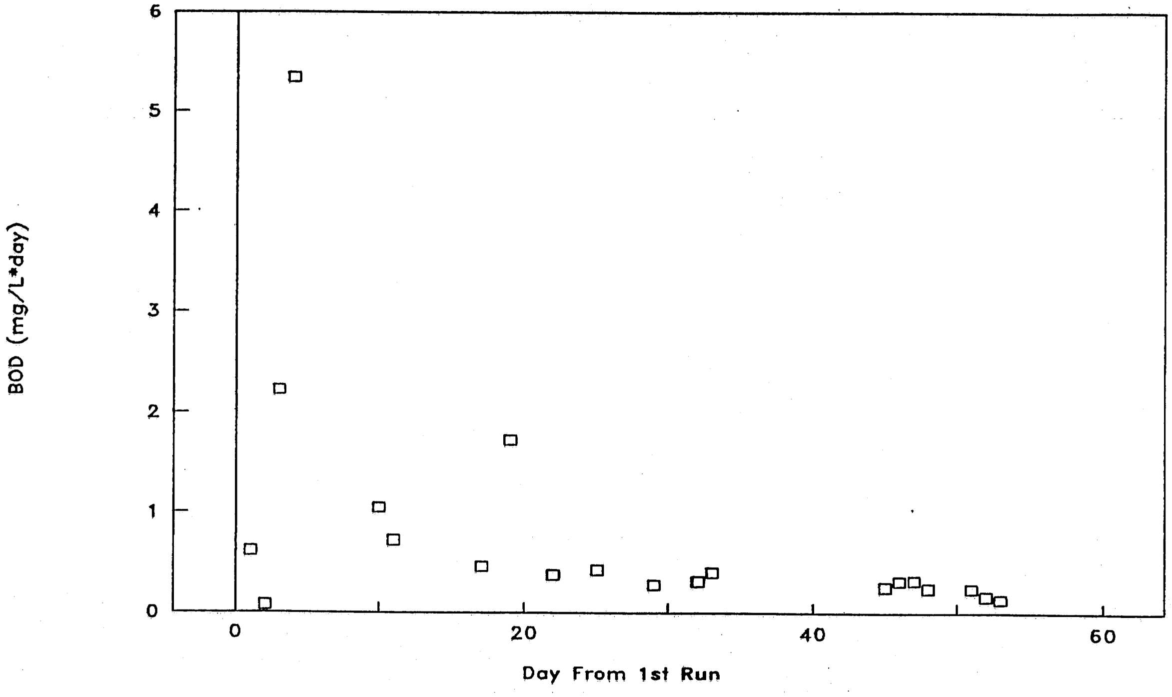

Figure IV–2 BOD vs. Time.

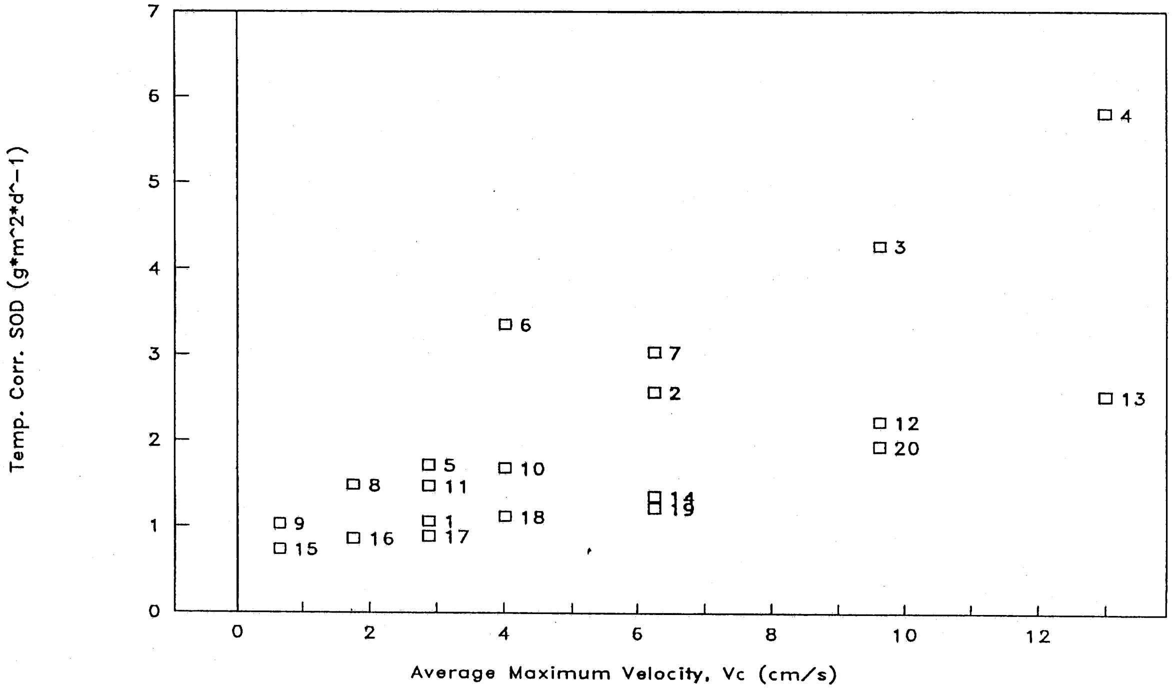

Figure IV–3 Average Maximum Velocity vs. SOD (all data).

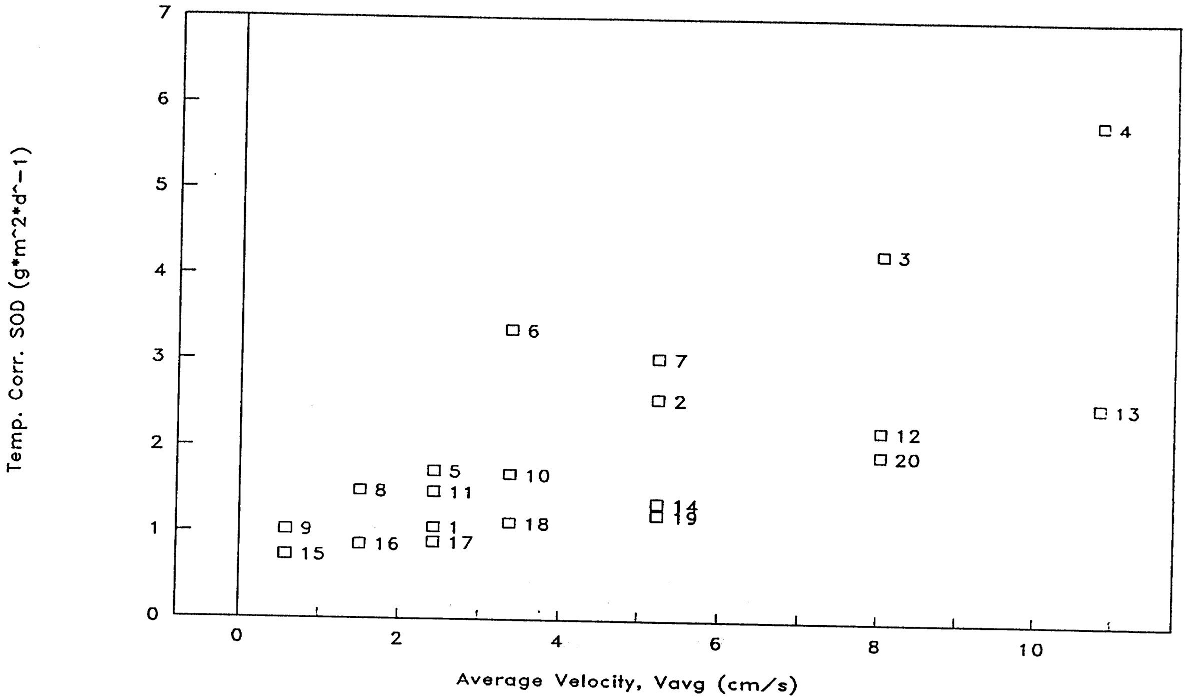

Figure IV–4 Average Velocity vs. SOD (all data).

It is therefore appropriate to divide the SOD data into several sets:

Set 1: Experiments 1 to 4 were conducted with fresh sediment covered by cheese cloth, which was removed after experiment 4. This set was completed within 3 days from the beginning of the experiment. The sediment had been submerged in city water for at least 19 days prior to the start of the experiment. There was no inoculation of the water with bacterial colonies.

Set 2: Experiments 5 to 11 were started 6 days after the end of Set 1 and were completed 19 days later. Over this extended period, some transformations in the properties of the sediment appear to have occurred. SOD results are widely scattered.

Set 3: Experiments 12 to 20 began 31 days after the first experiment (Run 1 and lasted 23 days. Microbes in the form of clusters and mats which had grown during Set 2 were much in evidence.

The total SOD data from the three sets of experiments have been plotted in Fig. IV–5 against average velocity V_{avg}, in Fig. IV–6 against maximum velocity, V_c and in Fig. IV–7 against shear velocity, V_*. Although the rate coefficients are substantially different in each set, the linear dependence on flow velocities is very much evident.

The regression equations which fit the data are:

Set 1 $$\text{SOD}(20^\circ\text{C}) = 0.54\, V_{avg} \qquad \text{(IV–3a)}$$
with $R^2 = 0.01$

Set 2 $$\text{SOD}(20^\circ\text{C}) = 0.70 + 0.470\, V_{avg} \qquad \text{(IV–3b)}$$
with $R^2 = 0.16$

Set 3 $$\text{SOD}(20^\circ\text{C}) = 0.54 + 0.186\, V_{avg} \qquad \text{(IV–3c)}$$
with $R^2 = 0.013$

where

SOD (20° C) = sedimentary oxygen demand ($g\ m^{-2}d^{-1}$) at 20° C

V_{avg} = average water velocity (cm/s) in the boundary layer ($\delta = 8.7$ cm)

If maximum velocity V_c at the edge of the boundary layer of 8.7 cm thickness is used, the SOD equations are

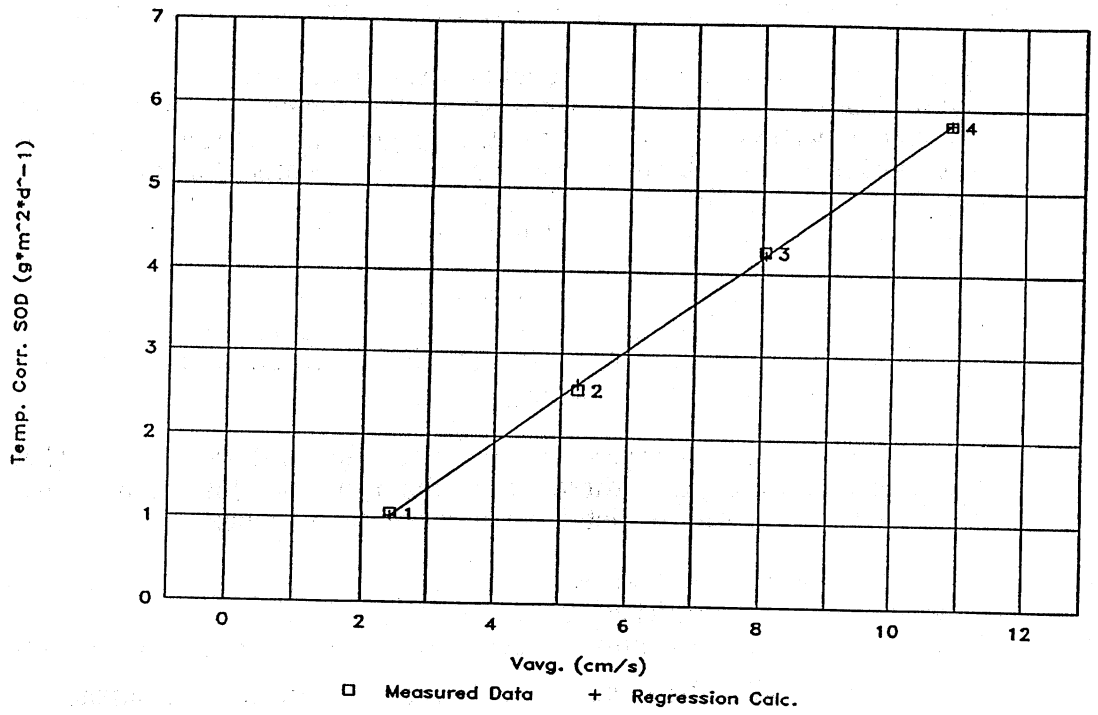

Figure IV–5(a) Average Velocity vs. SOD, Set 1

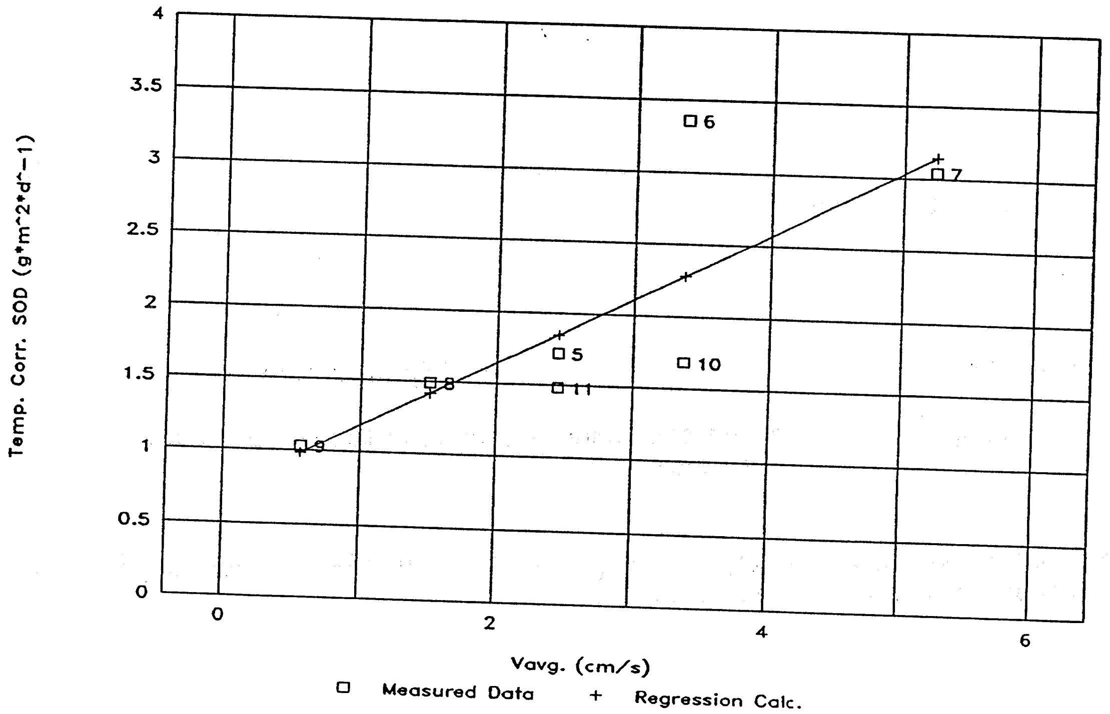

Figure IV–5(b) Average Velocity vs. SOD, Set 2

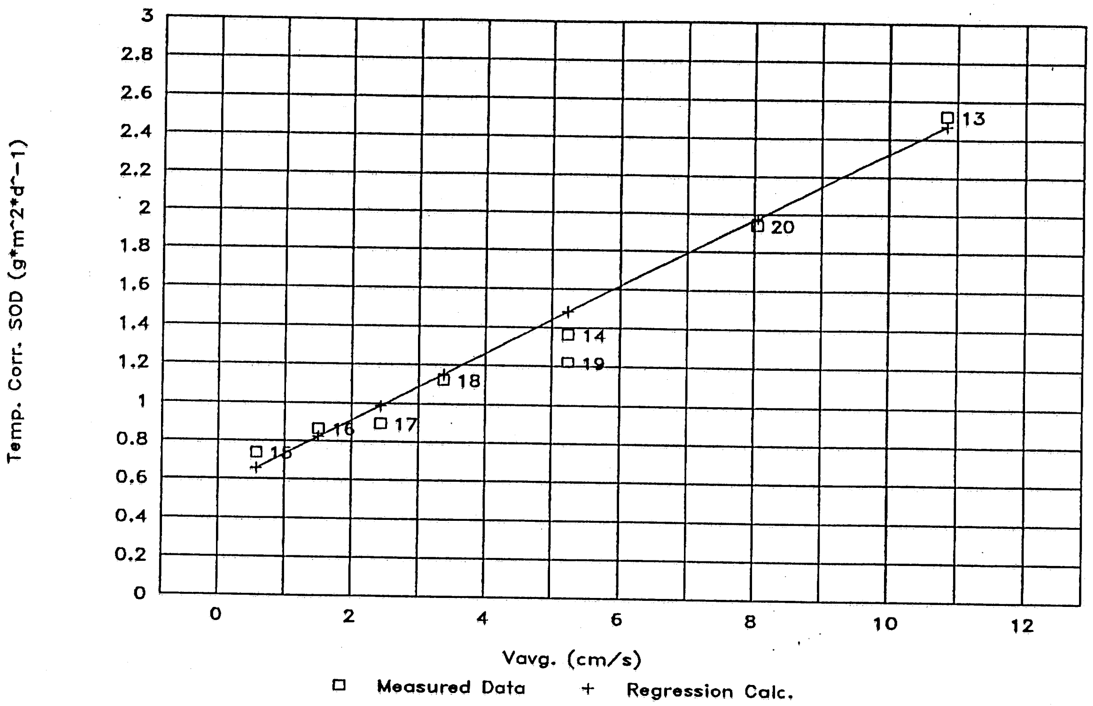

Figure IV–5(c) Average Velocity vs. SOD, Set 3

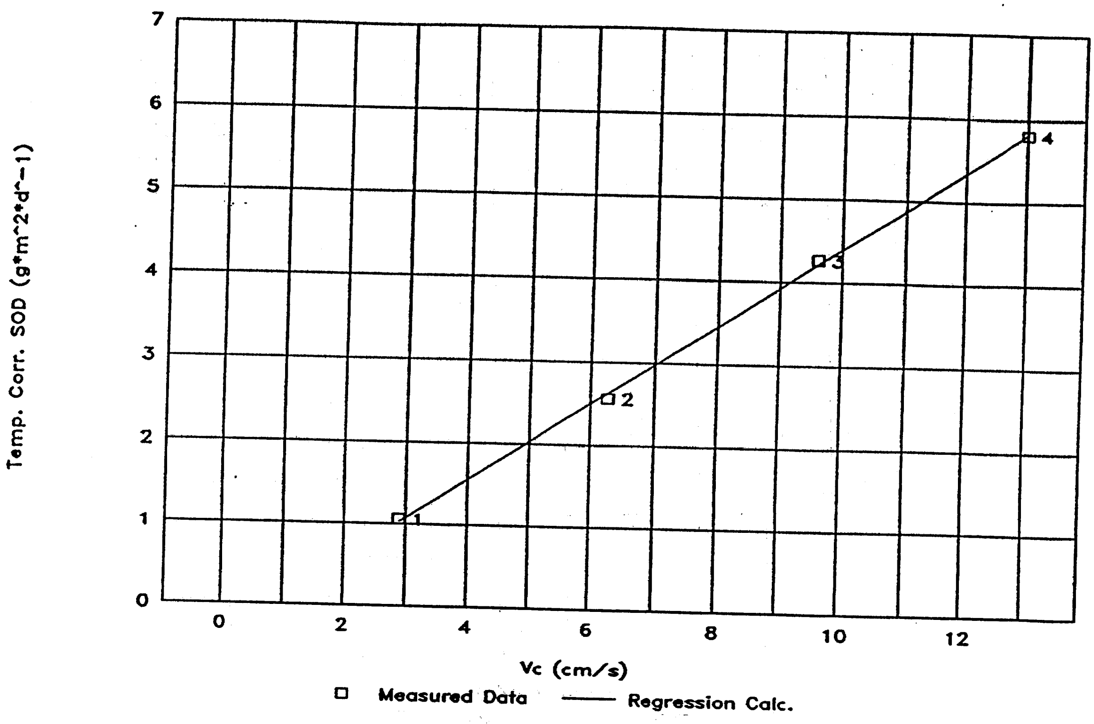

Figure IV–6(a) Average Maximum Velocity vs. SOD, Set 1

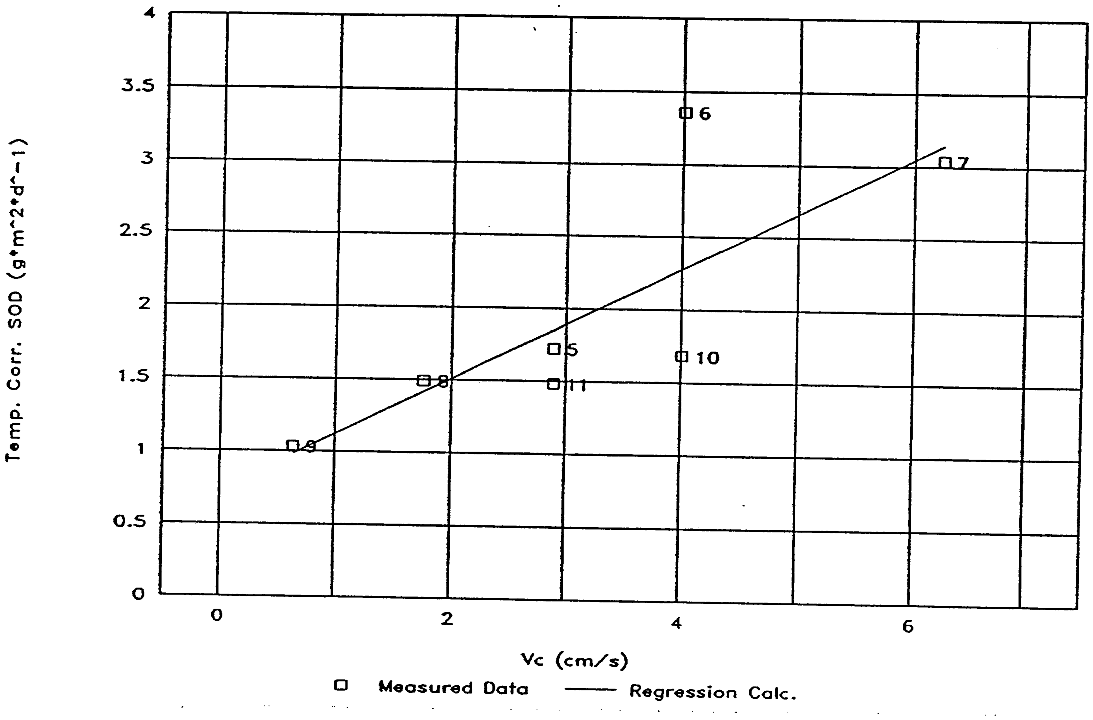

Figure IV–6(b) Average Maximum Velocity vs. SOD, Set 2

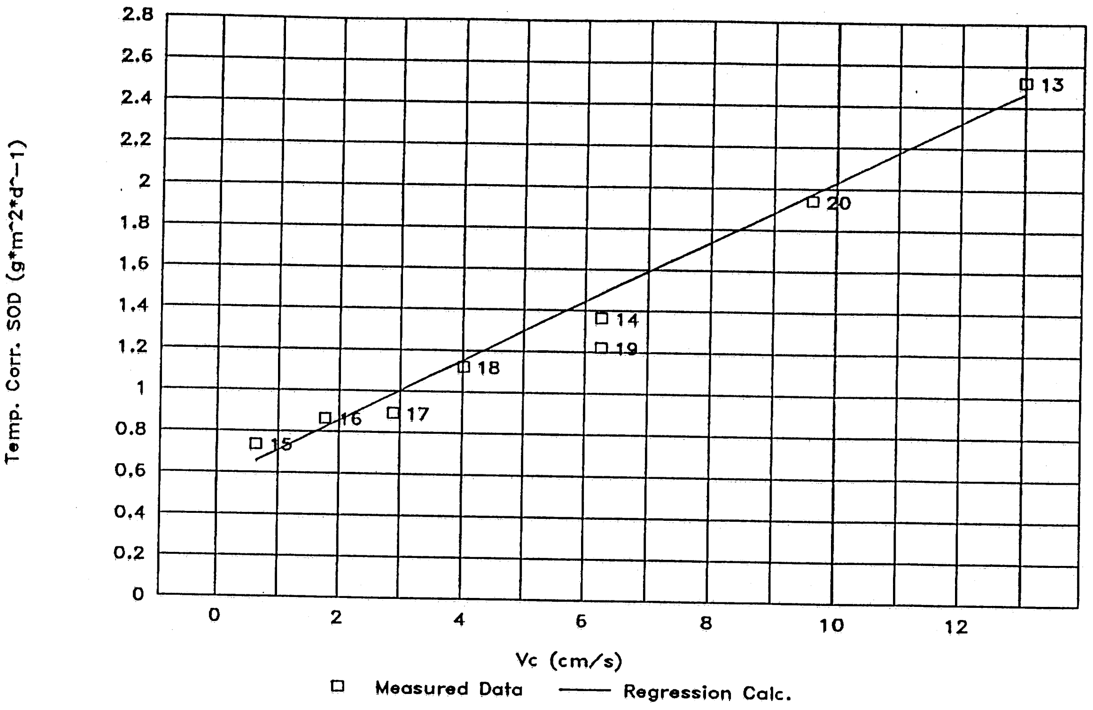

Figure IV–6(c) Average Maximum Velocity vs. SOD, Set 3

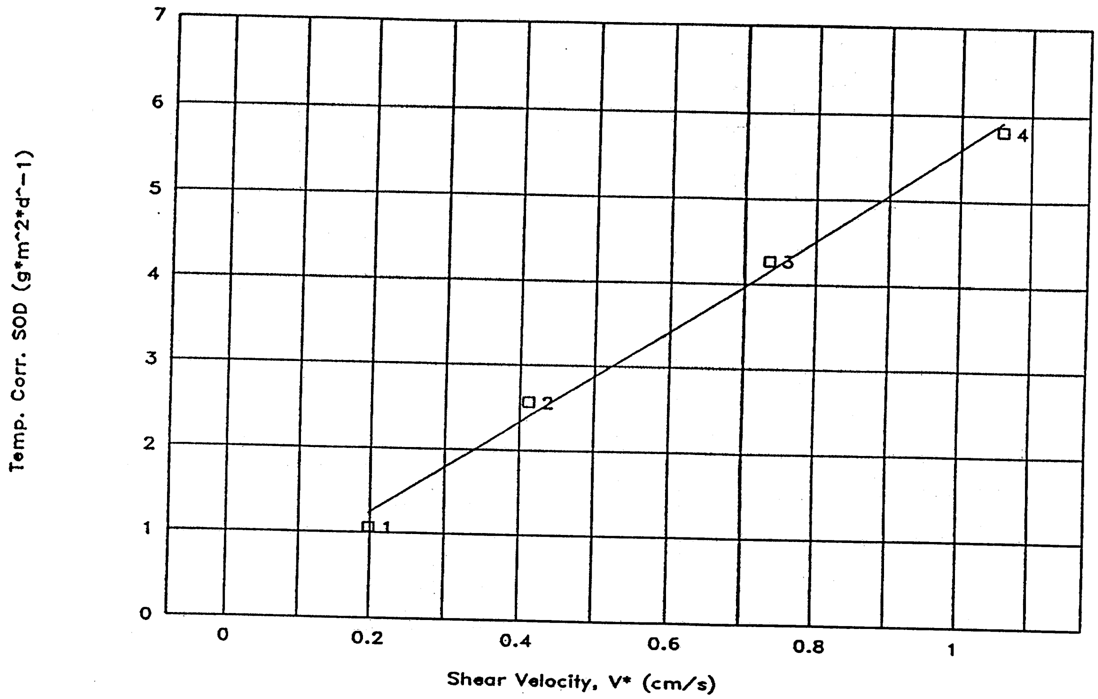

Figure IV–7(a) Shear Velocity vs. SOD, Set 1

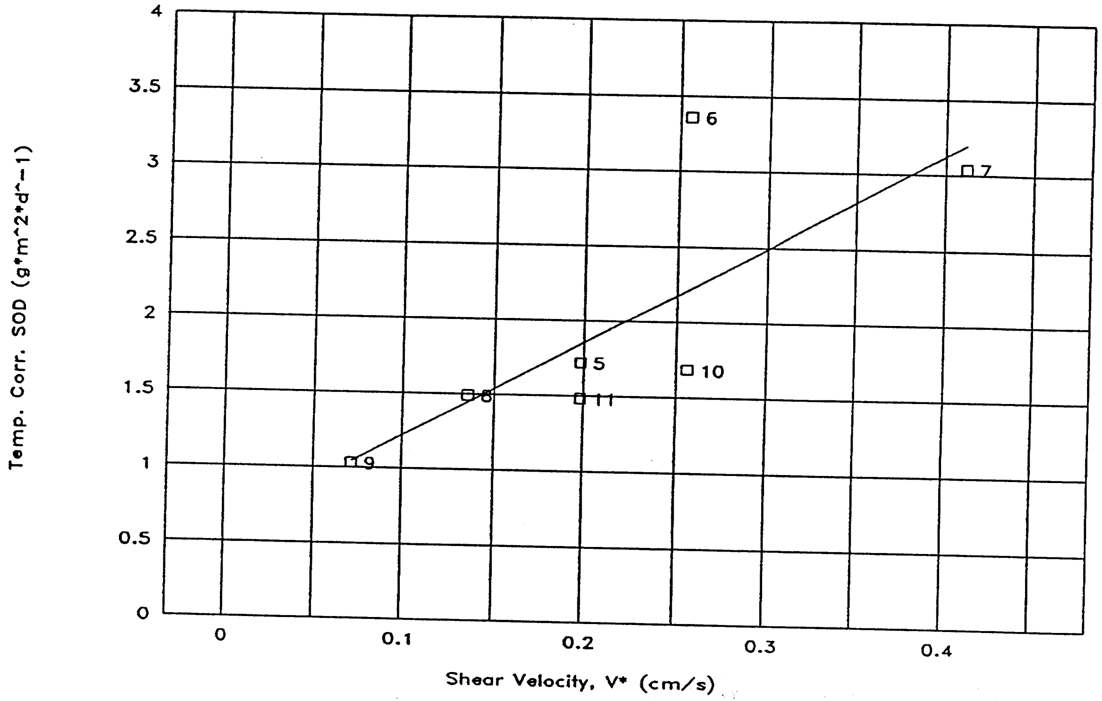

Figure IV–7(b) Shear Velocity vs. SOD, Set 2

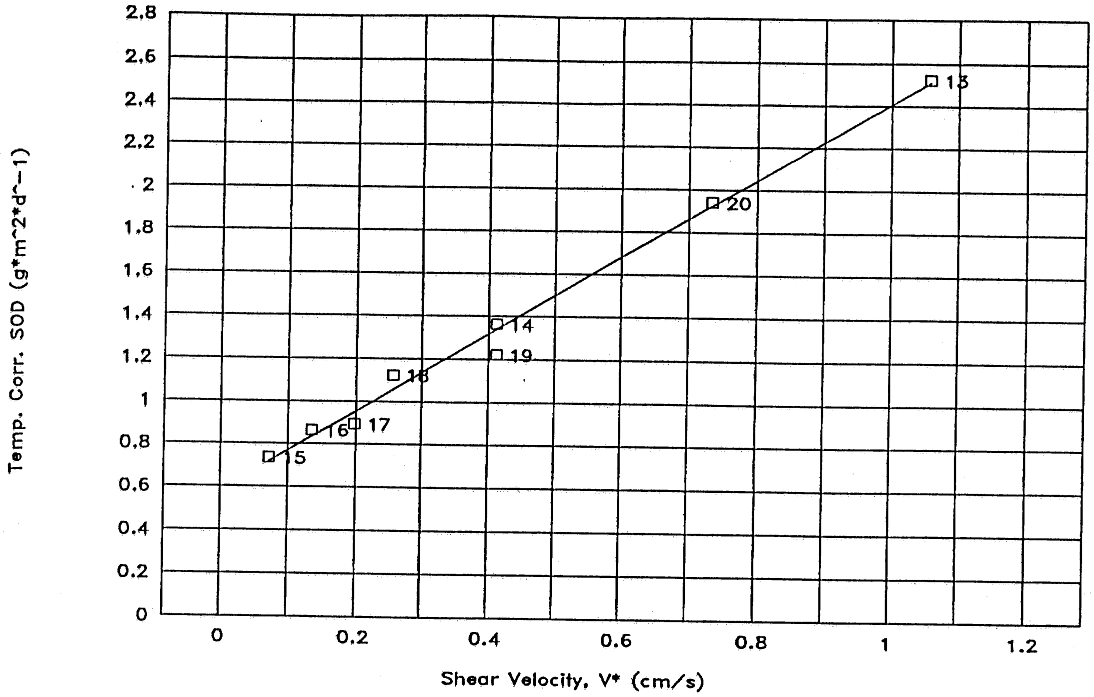

Figure IV–7(c) Shear Velocity vs. SOD, Set 3

Set 1 $\text{SOD (20°C)} = 0.44\ V_c$ (IV–4a)
with $R^2 = 0.008$

Set 2 $\text{SOD (20°C)} = 0.70 + 0.391\ V_c$ (IV–4b)
with $R^2 = 0.13$

Set 3 $\text{SOD (20°C)} = 0.54 + 0.150\ V_c$ (IV–4c)
with $R^2 = 0.011$

If shear velocity V_* is used, the SOD equations are

Set 1 $\text{SOD (20°C)} = 5.65\ V_*$ (IV–5a)
with $R^2 = 0.31$

Set 2 $\text{SOD (20°C)} = 0.70 + 6.02\ V_*$ (IV–5b)
with $R^2 = 2.25$

Set 3 $\text{SOD (20°C)} = 0.54 + 1.85\ V_*$ (IV–5c)
with $R^2 = 0.07$

The empirical equations IV–3, IV–4, and IV–5 apply only to the range of velocities used in the experiments, i.e. $V_{avg} < 11$ cm/s, $V_c < 13$ cm/s and $V_* < 1$ and should not be applied to velocities beyond this range. The nature of the sediments and the condition of the sediment surface influence the coefficients in the equations strongly. The linearity of the relationship is universal and applies to any sediment when water velocities are low as shown in the theoretical analysis by Nakamura and Stefan (1992).

In a natural environment, e.g. a lake or bay, the coefficients a and b in the equation

$$\text{SOD (g m}^{-2}\text{d}^{-1}) = a + b \times \text{velocity (cm/s)} \qquad \text{(IV–6)}$$

can be measured if domed enclosures are used and velocities are measured at the same time as SOD. In Minnesota, lake environment long–term averages of SOD are expected to be in the range from 0.5 to 3 g $m^{-2}d^{-1}$ (Fang and Stefan, 1993). Tests with various types of sediment are yet to be conducted, but for the present, a=0.5 and b=1.0 are estimated to give reasonably high estimates of SOD (20°C) values for lake sediments rich in organic materials, if the velocity used is the average velocity in the boundary layer. These are recommended for aerator capacity selection at this time until experimental evidence with other sediments is obtained.

V. SUMMARY

(1) This study has shown that the sedimentary oxygen demand increases linearly with water velocity, i.e. it can increase ten fold, e.g. from 0.5 to 5 g $m^{-2}d^{-1}$ when the water velocity over the sediment increases from 1 cm/s to 10 cm/s.

(2) The measured increase of SOD per cm/s velocity increase expressed mathematically as the gradient (SOD)/ΔV is summarized in Table V–1.

TABLE V–1. Rate of increase in SOD with velocity ($g\ m^{-2}d^{-1}$)($cm\ s^{-1}$)

	$\frac{\Delta SOD}{\Delta V_{avg}}$	$\frac{\Delta SOD}{\Delta V_c}$	$\frac{\Delta SOD}{\Delta V_*}$
Set 1	0.54	0.44	5.5
Set 2	0.47	0.39	6.3
Set 3	0.19	0.15	1.8

$V_{avg} < 11$ cm/s, $V_c < 13$ cm/s, $V_* < 1$ cm/s

(3) Typical long–term average SOD (20°C) values in quiescent lake water in Minnesota are on the order of 0.5 to 2.0 g $m^{-2}d^{-1}$ (Fang and Stefan, 1993). Thus the SOD can double if flow velocity on the lake bottom is increased by as little as 1 cm/s.

(4) To transfer the laboratory SOD values to real lakes, shear velocity V_* is probably the most appropriate, but unfortunately, also the least convenient velocity indicator because it is a measure of the bottom shear and incorporates the effect of flow velocity outside the boundary layer as well as boundary layer thickness. The latter is fixed in the laboratory experiments but variable in a lake.

(5) Twenty experimental runs have been completed. The data and results match the linear increase in SOD with water velocity predicted by theory (Nakamura and Stefan, 1992). In addition, there is strong evidence in the experimental data that SOD can be changing in time because of microbial growth and fine sediment washout.

VI. DESIGN IMPLICATIONS FOR LAKE AERATORS (SUMMER AND WINTER)

Lake aerators must be designed and installed to cause minimum disturbance of water adjacent to the sediments. Disturbance is defined as a change in mean flow velocity and turbulence. Disturbance increases the rate of oxygen depletion in a lake significantly. See Figure VI–1.

The above "cardinal rule" can be implemented by the following design measures:

(1) Orient all water intake and discharge pipes, e.g., of pump and baffle systems parallel to or away from the lake bottom. If an existing temperature (density) stratification in a lake can be destroyed (caution: in summer this is often not advisable because it will cause algal blooms, and in winter it may caused open water in an ice cover), direct intakes and outlets vertically upward. Use pipe elbows or pipe support systems to direct the pipes 30° to 45° upwards. If an existing temperature stratification is important, direct the discharge parallel to the surface as high above the sediment as practical (Fig. VI–2).

(2) Place intakes and discharges of aeration systems well above the lake bottom and in deep water as far as possible, e.g. to create a fish refuge.

(3) Avoid discharges into shallow (1–2 m depth) areas and over areas filled with organic materials. If this cannot be avoided, build enclosures (boxes) to dissipate the kinetic energy of the discharge from a pipe (Fig. VI–3).

(4) Use the smallest possible intake and discharge velocities, i.e. use large diameter sections for intake and discharge pipe or ducts. Reduce them to smaller diameters ten diameters away from the pipe end.

(5) In summary, in the design and placement of lake aerators strong attention should be paid to water disturbance near the sediment; otherwise aeration as a remedy for oxygen deficiency in a lake may not solve but aggravate the problem.

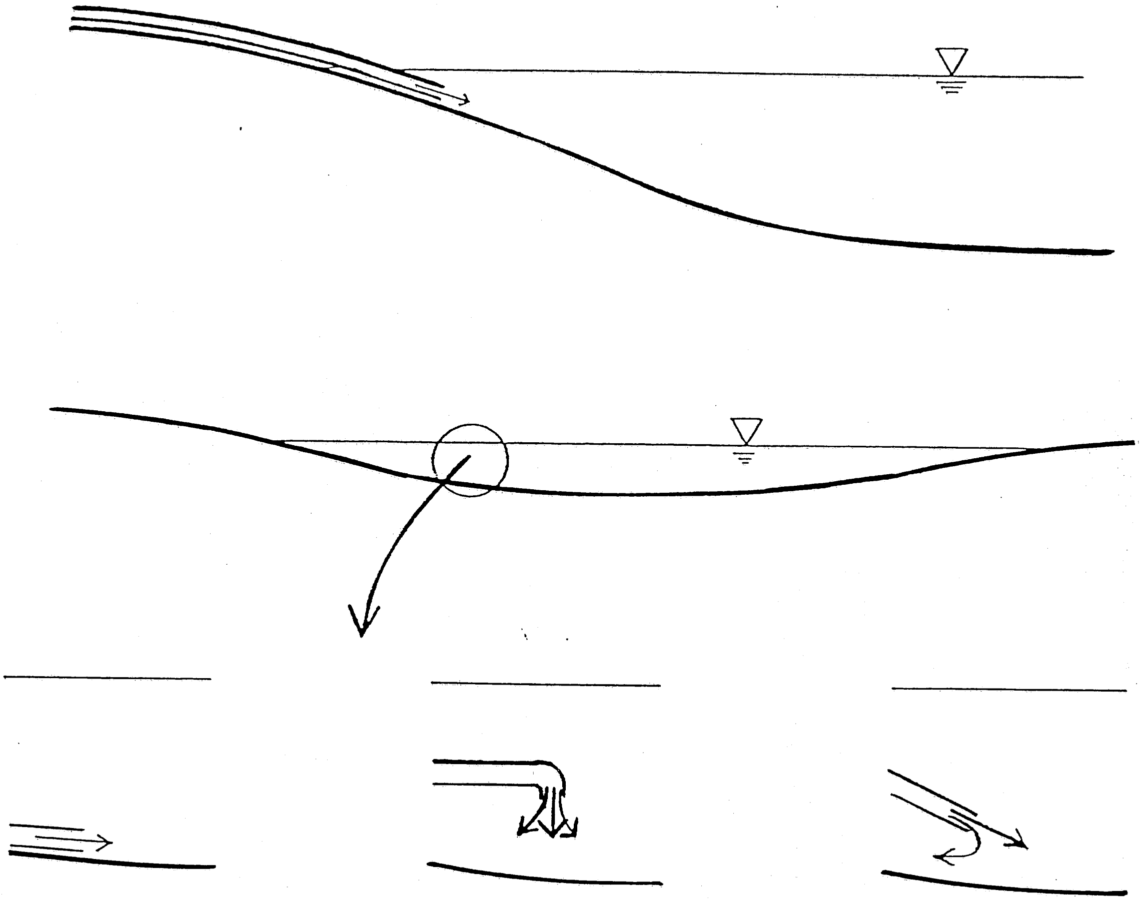

Figure VI–1 Examples of poor design orientation of inlets or outlets when the DO concentration of a body of water is of concern (schematic).

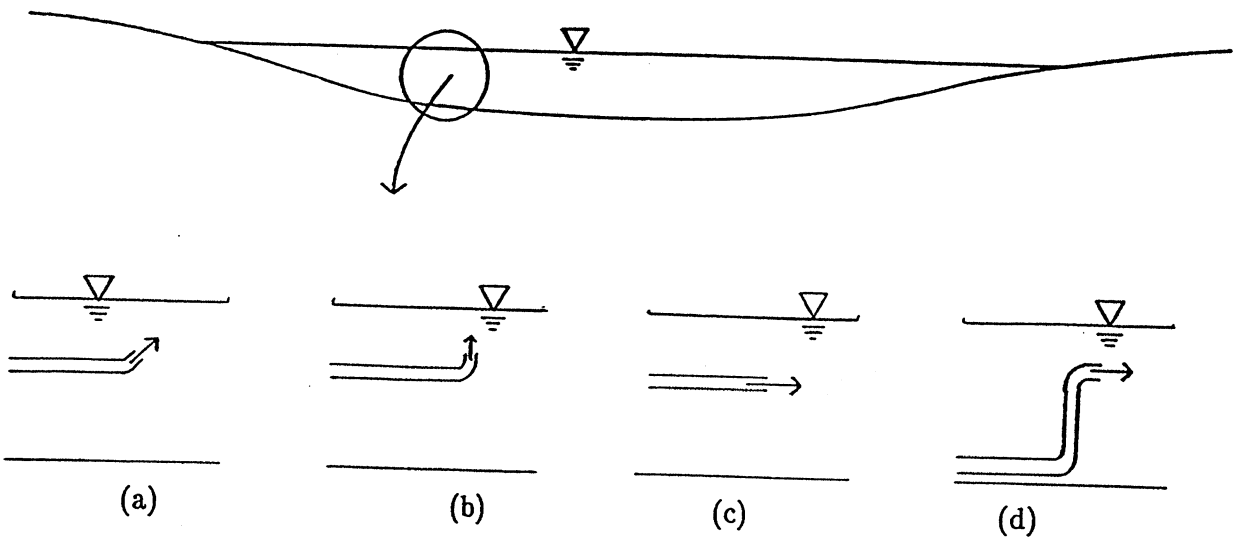

Figure VI–2 Examples of improved design configurations. a) and b) are examples of deep water outlets when temperature stratification is unimportant. c) and d) are examples which minimize temperature destratification and surface disturbance (schematic).

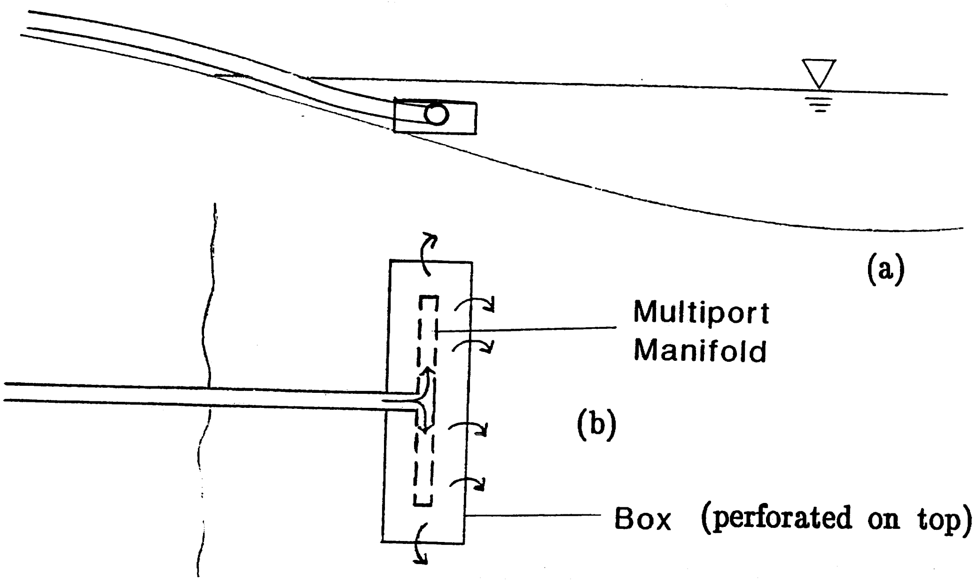

Figure VI–3 Schematic configuration of shallow water boxed energy diffuser. a) side view. b) top view.

VII. BIBLIOGRAPHY

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APPENDICES

EXPERIMENTAL ANALYSIS OF SEDIMENTARY OXYGEN DEMAND IN LAKES: DEPENDENCE ON NEAR–BOTTOM FLOW VELOCITIES AND IMPLICATIONS FOR AERATOR DESIGN

by

A.A. Mackenthun and H. G. Stefan

APPENDIX A

SAMPLING TIME ANALYSIS

Determination of Optimum Sampling Times

The purpose of this analysis was to determine the length of time and the number of samples required to obtain smooth velocity profiles despite turbulence in the channel. Velocity measurements were taken at four points in the channel at two channel flows with average velocities of approximately 0.6 and 0.1 fps (Tables A1 and A2). The data were plotted as the time averaged velocity over sampling time (see Figures A–1 and A–2). The least sampling duration that yielded a time–independent average on the graph of measured velocity over sampling time was taken to be the minimum sampling time. The resulting two points were plotted and connected by a straight line to use as a guide when selecting sampling times at other channel flows (Figure A–3).

EMCM Sampling Time Optimization

Table A-1
Approximate Velocity = 0.1 fps

Sampling Time (sec)	Approx. # of Samples	Calculated Velocities, fps			
		(2",1")	(2",3,5")	(12",1")	(12",3.5")
4	36	0.107	0.096	0.114	0.119
16	144	0.099	0.098	0.121	0.125
40	360	0.097	0.099	0.111	0.119
60	540	0.098	0.099	0.111	0.119
120	1080	0.098	0.096	0.114	0.120
240	2160	0.099	0.100	0.112	0.120
Weighted Average =		0.099	0.099	0.113	0.120

Sampling Time (sec)	Percent Deviation From Average (%)				
	(2",1")	(2",3,5")	(12",1")	(12",3.5")	Sum
4	8.43	2.81	0.66	0.94	12.83
16	0.34	0.76	7.36	4.18	12.64
40	1.56	0.46	1.54	0.80	4.35
60	0.38	0.29	1.42	0.62	2.72
120	0.55	2.64	1.17	0.08	4.43
240	0.46	1.27	0.47	0.02	2.22

Table A-2
Approximate Velocity = 0.6 fps

Sampling Time (sec)	Approx. # of Samples	Calculated Velocities			
		(2",1")	(2",3,5")	(12",1")	(12",3.5")
4	36	0.515	0.547	0.597	0.678
10	90	0.536	0.529	0.572	0.661
16	144	0.519	0.539	0.601	0.658
30	270	0.515	0.548	0.595	0.665
60	540	0.520	0.555	0.583	0.663
120	1080	0.515	0.543	0.586	0.660
Weighted Average =		0.517	0.546	0.587	0.662

Sampling Time (sec)	Percent Deviation From Average (%)				
	(2",1")	(2",3,5")	(12",1")	(12",3.5")	Sum
4	0.55	0.13	1.65	2.54	4.87
10	3.58	3.19	2.68	0.10	9.55
16	0.24	1.21	2.41	0.49	4.35
30	0.44	0.33	1.37	0.54	2.69
60	0.52	1.68	0.65	0.24	3.09
120	0.46	0.50	0.17	0.27	1.40

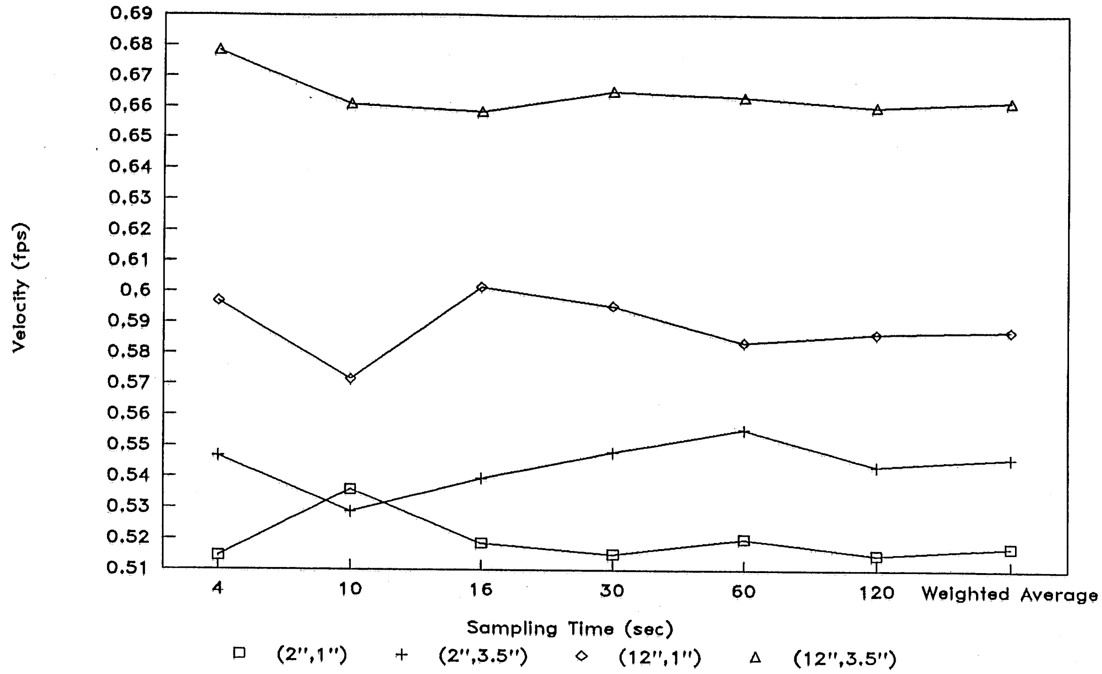

Fig. A–1 Sampling duration vs. time averaged velocity at approximately 0.6 fps average velocity.

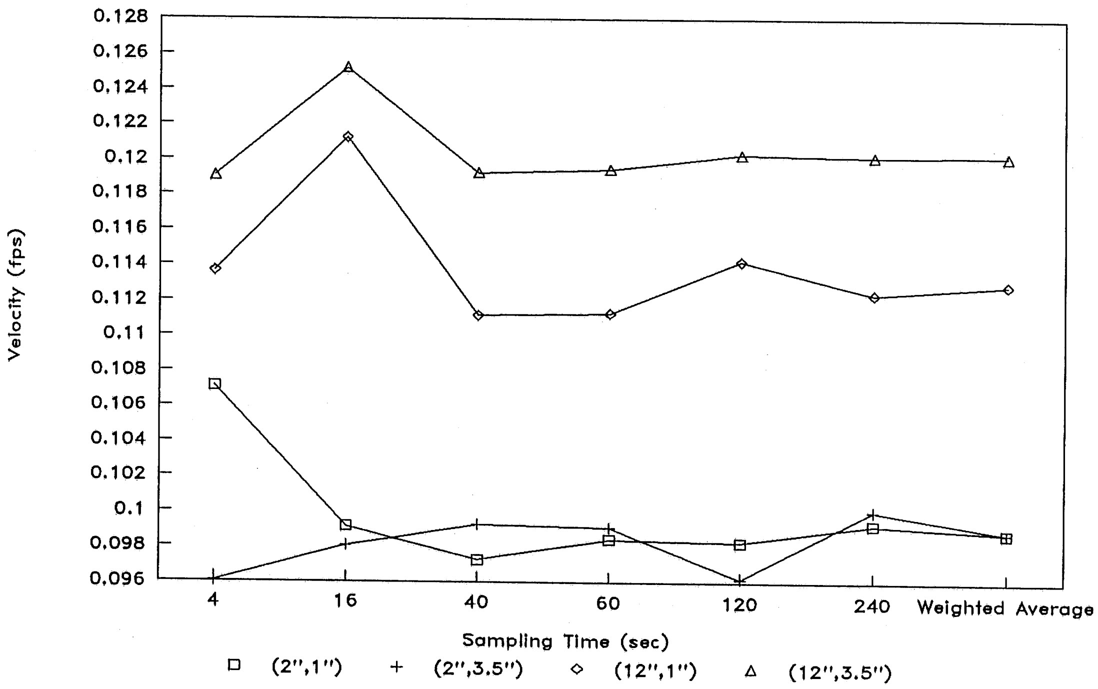

Fig. A–2 Sampling duration vs. time averaged velocity at approximately 0.1 fps average velocity.

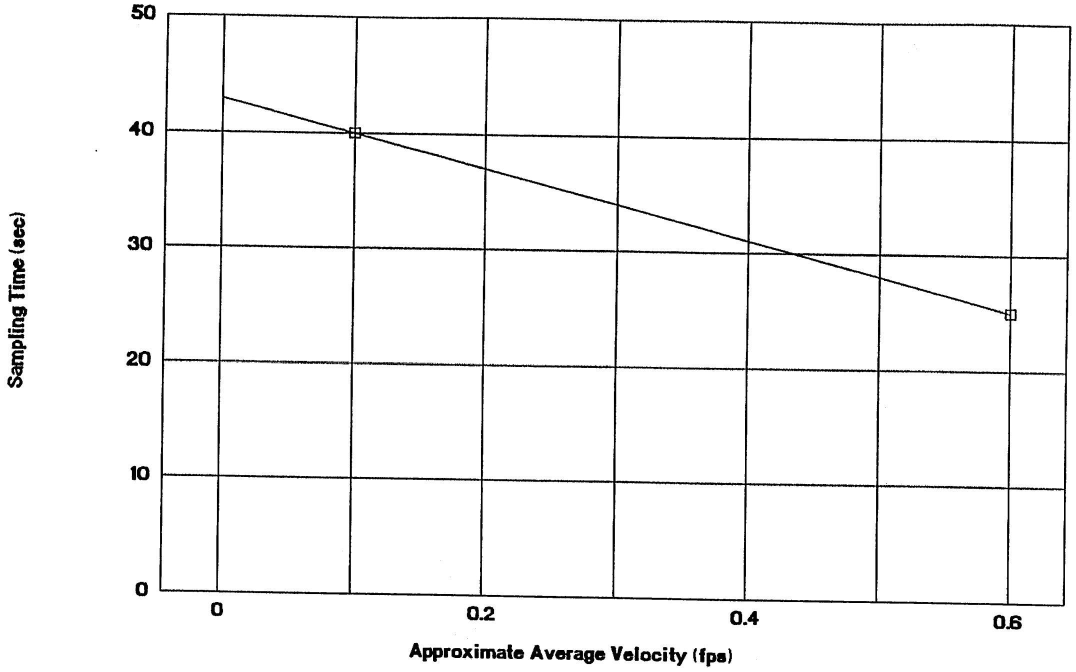

Fig. A–3 Average velocity versus optimum sampling time.

APPENDIX B

Velocity Measurements

Velocity Measurements

Velocity profiles were measured for pump flow rates of 6, 10, 25, and 45 gpm. these flows range between the upper and lower limit of the flow rates to be used in the experiment. The velocity profiles are needed to characterize the flow in the channel w.r.t. average and centerline velocity, shear velocity, boundary layer thickness, and shear stress on the test section. The measured velocity profiles and a summary of how they were obtained are given here. These profiles are analyzed in Appendix C.

The flow in the channel ranged from laminar for the 6 and 10 gpm pump flows to turbulent for 25 and 45 gpm pump flows. At 6 and 10 gpm pump flows a dye tracing method was used to measure the velocities. The velocities of the 25 and 45 gpm pump flows were measured with a Marsh McBirnie electro–magnetic current meter model 523 (EMCM).

Velocity profiles were measured at 4 and 12 inches from the channel wall when the dye tracing method was used. To allow averaging, three to four profiles were taken at each of these positions. Table B–1 contains the calculated velocities and the calculated averages for the 6 gpm pump flow. Table B–2 contains the 10 gpm pump flow data. These profiles are shown along with the calculated average profiles on Figures B–1 and B–2 for the 6 gpm pump flow and on Figures B–5 and B–6 for the 10 gpm pump flow.

The EMCM setup used for the velocity profile measurements of the 25 and 45 gpm pump flows allowed time averaging of the velocities. Therefore, numerous velocity measurements at each position were unnecessary. Velocities were measured at 1, 2, 4, 8, 12, 16, 20, 22, and 23 inches from the side wall and at 0.25, 0.5, 0.75, 1, 1.5, 2, 3, 4, 5, 6, and 6.5 inches from the bottom of the channel. Tables B–3 and B–4 contain the velocity data for the 25 and 45 gpm pump flows, respectively. Vertical velocity profiles are plotted in Figures B–9 and B–10 for the 25 gpm pump flow and in Figures B–15 and B–16 for the 45 gpm pump flow. Horizontal velocity profiles are also included for the 25 and 45 gpm pump flows as Figs. B–11 and B–12 and Figs. B–17 and B–18.

The vertical velocity profiles are also plotted over the natural log of the distance from the bottom of the channel. These are used during the analysis to compute the shear velocity. These plots are included as Figures B–3 and B–4, B–7 and B–8, B–13 and B–14, and B–19 and B–20 for the 6, 10, 25, and 45 gpm pump flows, respectively.

Table B-1, Velocity Profiles from Photographs of Dye Traces at 6 gpm Pump Flow.

	Height From Bottom (in/ft)									
	0.125	0.25	0.5	0.75	1	1.25	1.5	2	3	4
Pos. (in)	0.0104	0.0208	0.0417	0.0625	0.0833	0.1042	0.1250	0.1667	0.2500	0.3333
	Velocities (fps)									
4	0.0096	0.0154	0.0211	0.0240	0.0272	0.0299	0.0322	0.0347	0.0321	0.0275
4	0.0091	0.0124	0.0184	0.0236	0.0277	0.0296	0.0303	0.0311	0.0313	0.0274
4	0.0087	0.0141	0.0198	0.0236	0.0258	0.0279	0.0293	0.0304	0.0302	0.0294
4	0.0062	0.0119	0.0172	0.0206	0.0231	0.0249	0.0262	0.0284	0.0310	0.0321
Avg.	0.0080	0.0127	0.0184	0.0226	0.0255	0.0274	0.0286	0.0299	0.0308	0.0296
12	0.0071	0.0102	0.0142	0.0189	0.0227	0.0278	0.0306	0.0337	0.0337	
12	0.0051	0.0094	0.0150	0.0207	0.0239	0.0261	0.0280	0.0312	0.0344	0.0251
12	0.0061	0.0093	0.0155	0.0192	0.0235	0.0266	0.0294	0.0315	0.0339	0.0323
12	0.0075	0.0111	0.0160	0.0200	0.0239	0.0266	0.0276	0.0290	0.0325	0.0307
12	0.0056	0.0119	0.0206	0.0246	0.0300	0.0306	0.0307	0.0307	0.0333	0.0314
12	0.0066	0.0104	0.0156	0.0227	0.0266	0.0305	0.0310	0.0303	0.0302	0.0302
Avg.	0.0064	0.0100	0.0152	0.0197	0.0235	0.0268	0.0289	0.0314	0.0336	0.0279

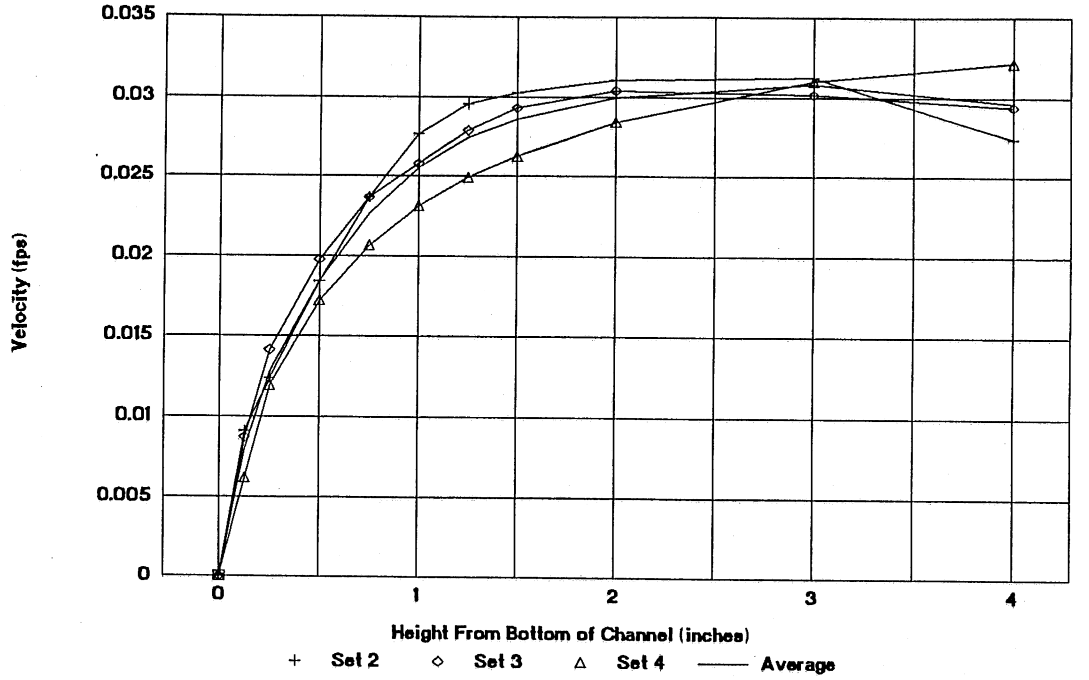

Fig. B–1 Vertical velocity profile at 6 gpm pump flow 4 inches from sidewall.

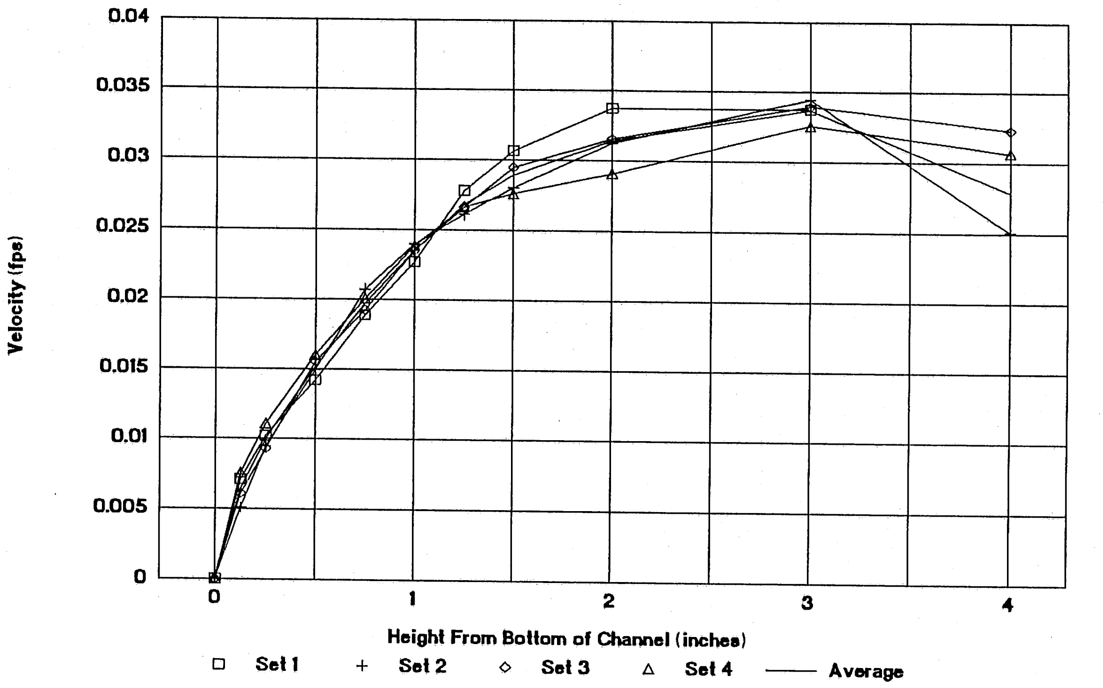

Fig. B–2 Vertical velocity profile at 6 gpm pump flow 12 inches from sidewall.

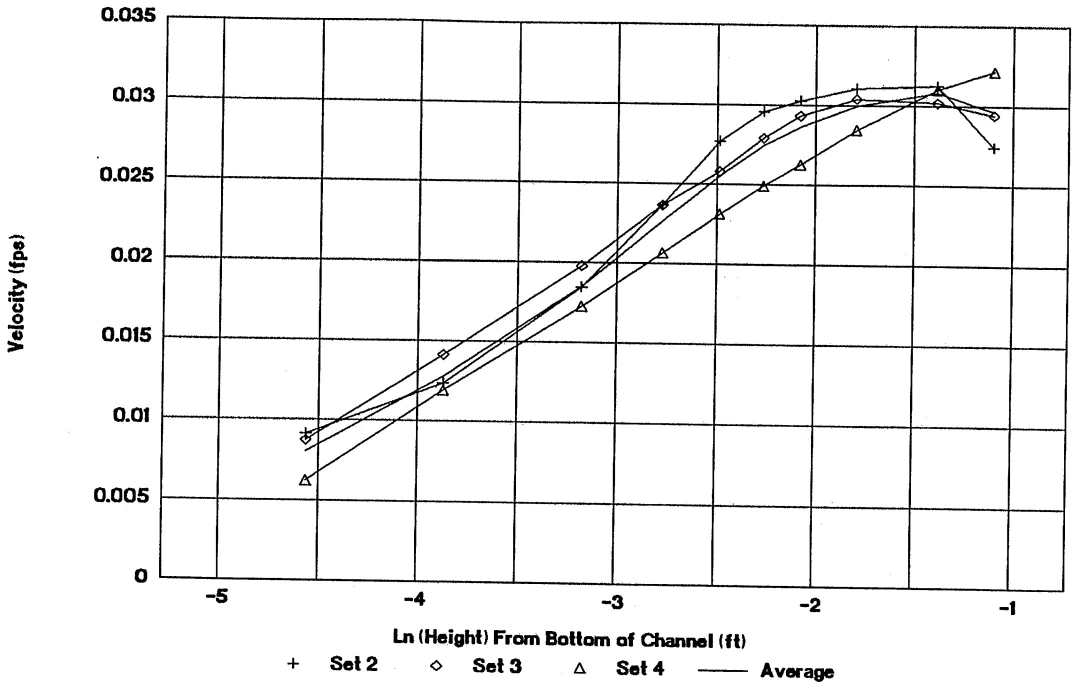

Fig. B–3 Ln (height above bottom) vs. velocity at 6 gpm pump flow 4 inches from sidewall.

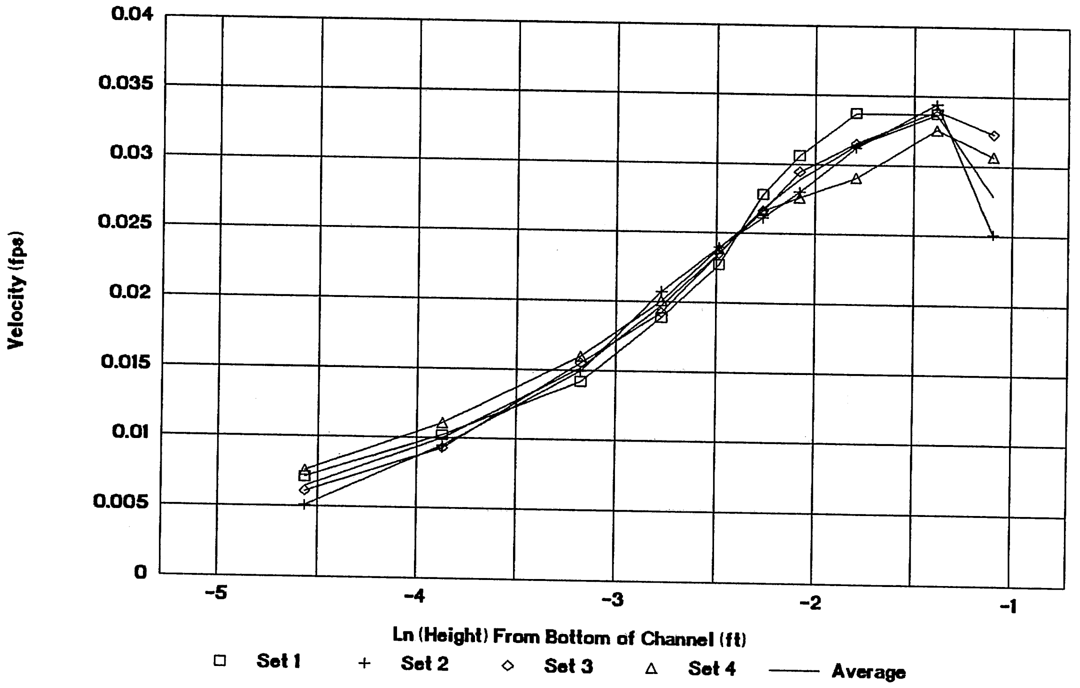

Fig. B–4 Ln (height above bottom) vs. velocity at 6 gpm pump flow 12 inches from widewall.

Table B-2, Velocity Profiles from Photographs of Dye Traces at 10 gpm Pump Flow.

	Height From Bottom (in/ft)								
	0.25	0.5	0.75	1	1.5	2	3	4	5
	0.0208	0.0417	0.0625	0.0833	0.1250	0.1667	0.2500	0.3333	0.4167
Pos. (in)	Velocities (fps)								
4	0.0303	0.0421	0.0474	0.0500	0.0540	0.0557	0.0544	0.0553	0.0536
4		0.0309	0.0324	0.0340	0.0380	0.0409	0.0494	0.0502	
4	0.0384	0.0465	0.0512	0.0560	0.0570	0.0572	0.0570	0.0556	0.0593
4	0.0344	0.0443	0.0493	0.0530	0.0555	0.0564	0.0557	0.0554	0.0565
12	0.0320	0.0507	0.0559	0.0584	0.0601	0.0604	0.0560	0.0480	0.0424
12		0.0256	0.0313	0.0364	0.0485	0.0521	0.0553	0.0494	0.0421
12		0.0391	0.0409	0.0449	0.0483	0.0539	0.0636	0.0671	0.0635
12	0.032	0.0384	0.0426	0.0465	0.0522	0.0554	0.0583	0.0548	0.0493

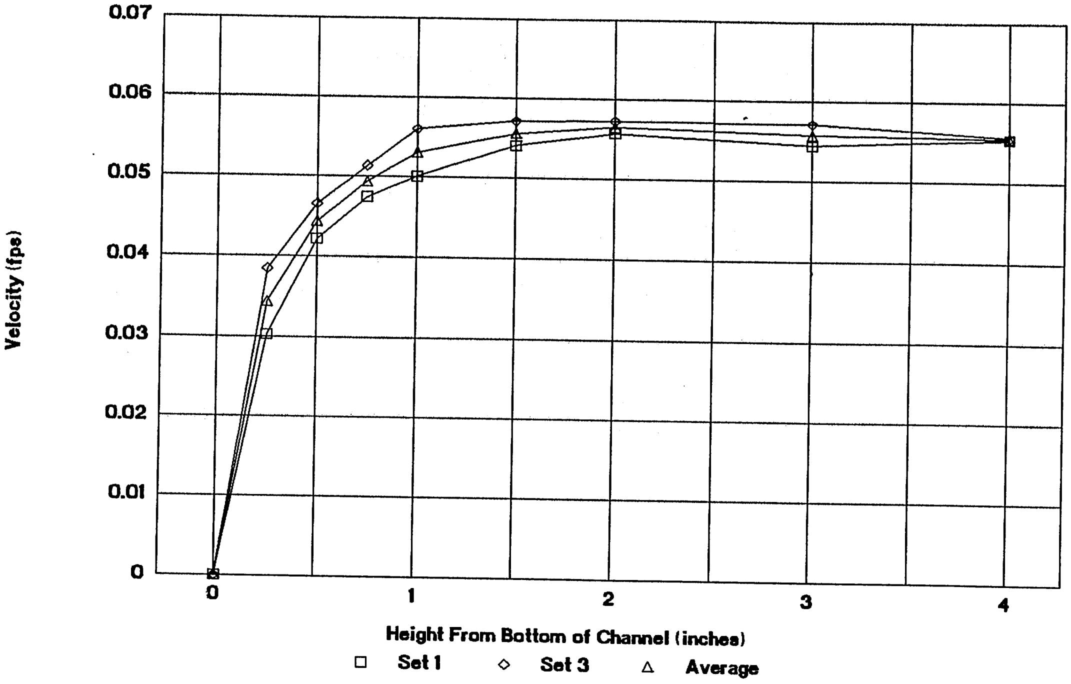

Fig. B–5 Vertical velocity profile at 10 gpm pump flow 4 inches from sidewall.

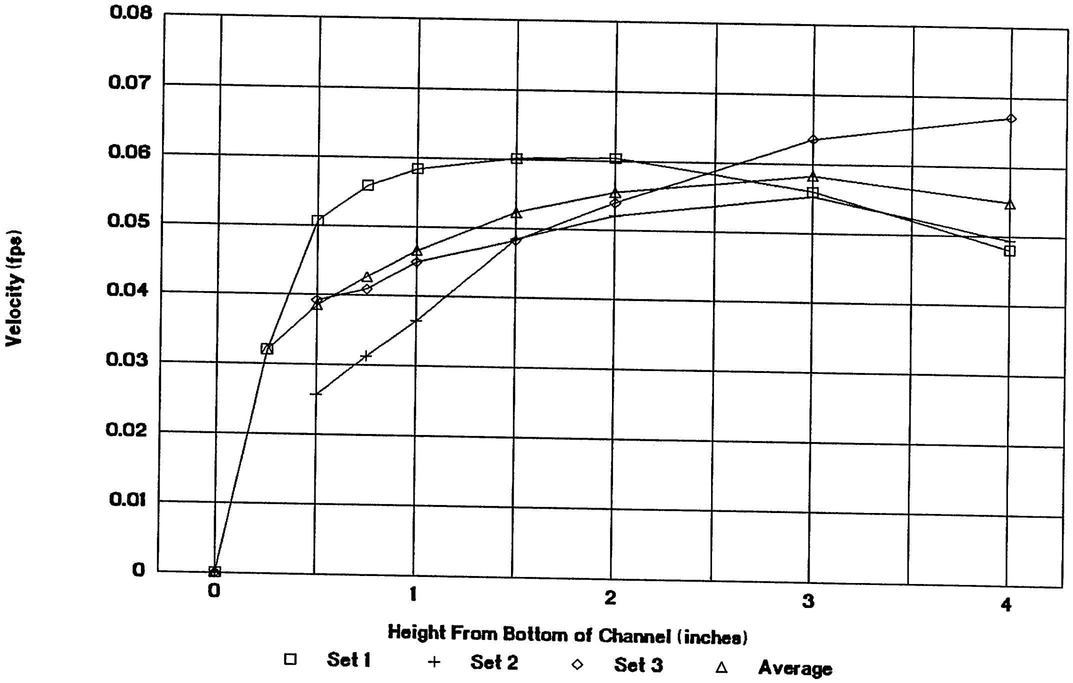

Fig. B–6 Vertical velocity profile at 10 gpm pump flow 12 inches from sidewall.

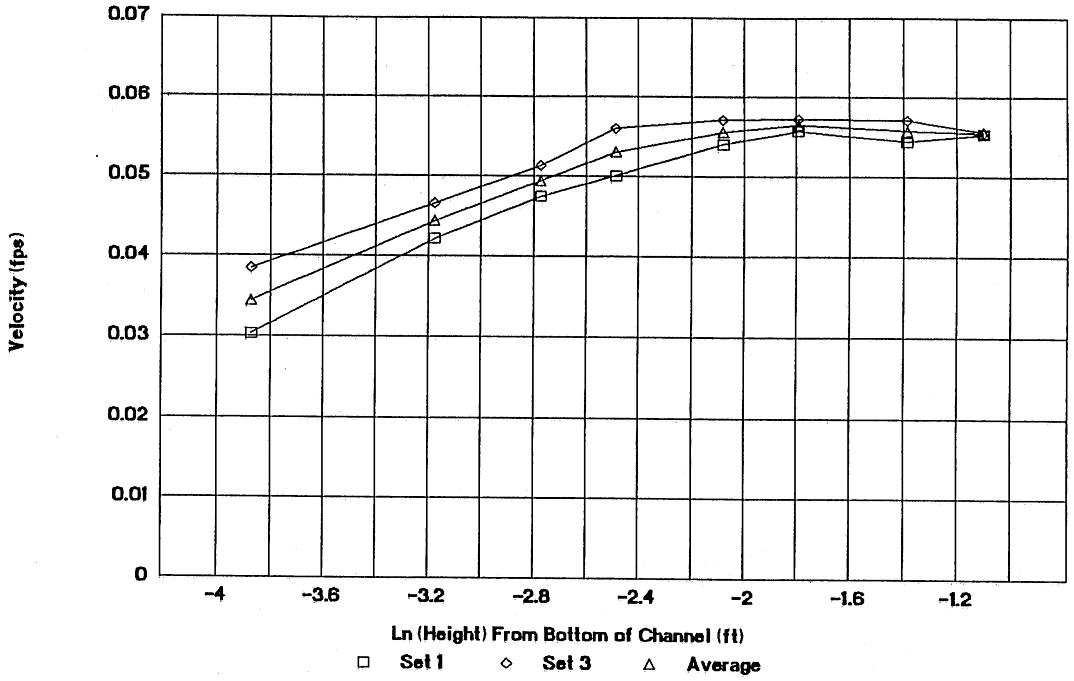

Fig. B–7 Ln (height above bottom) of channel vs. velocity at 10 gpm pump flow 4 inches from sidewall.

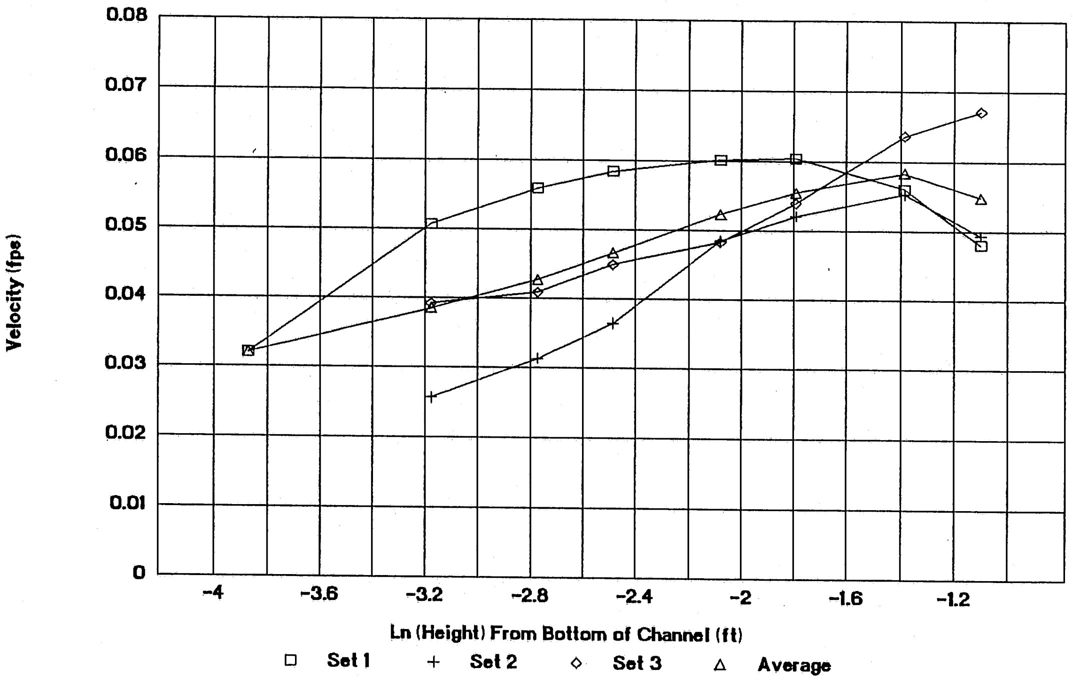

Fig. B–8 Ln (height above bottom) of channel vs. velocity at 10 gpm pump flow 12 inches from sidewall.

Table B-3, 25 gpm Pump Flow Velocity Data (From EMCM).

Distance From Side of Channel (inches/feet)

x/y Velocities (fps)

Ht. (in.)	0 0	1 0.083	2 0.167	4 0.333	8 0.667	12 1.000	16 1.333	20 1.667	22 1.833	23 1.917	24 2
7	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0.089	0.112	0.104	0.101	0.112	0.1	0.133	0.098	0.096	0
	0	0.023	0.038	0.001	0.025	0.032	0.033	0.05	0.052	0.023	0
6.5	0	0.109	0.12	0.126	0.121	0.132	0.138	0.146	0.142	0.118	0
	0	0.024	0.016	0.023	0.015	0.023	0.03	0.037	0.021	0.021	0
6	0	0.102	0.099	0.135	0.127	0.157	0.145	0.133	0.139	0.129	0
	0	0.024	0.004	0.024	0.003	0.03	0.038	0.021	0.051	0.025	0
5	0	0.104	0.127	0.138	0.155	0.16	0.157	0.16	0.13	0.127	0
	0	0.019	0.007	0.023	0.027	0.039	0.032	0.036	0.008	0.019	0
4	0	0.116	0.146	0.174	0.173	0.182	0.174	0.172	0.17	0.103	0
	0	0.018	0.005	0.02	0.044	0.043	0.044	0.046	0.097	0.014	0
3	0	0.118	0.152	0.16	0.157	0.175	0.165	0.158	0.155	0.154	0
	0	0.021	0.001	0.019	0.009	0.011	0.008	0.004	0.049	0.06	0
2	0	0.115	0.15	0.153	0.159	0.182	0.155	0.145	0.14	0.112	0
	0	0.021	0.016	0.004	0.026	0.072	0.009	0.004	0.018	0.012	0
1.5	0	0.116	0.143	0.15	0.158	0.154	0.154	0.143	0.146	0.139	0
	0	0.021	0.03	0.038	0.03	0.011	0.001	0.002	0.04	0.038	0
1	0	0.114	0.122	0.136	0.152	0.141	0.159	0.124	0.14	0.147	0
	0	0.026	0.006	0.024	0.039	0.002	0.04	0.019	0.03	0.073	0
0.75	0	0.101	0.123	0.132	0.121	0.136	0.132	0.116	0.132		0
	0	0.001	0.021	0.018	0.006	0.038	0.004	0.041	0.014		0
0.5	0	0.105	0.113	0.115	0.124	0.137	0.131	0.127	0.119		0
	0	0.029	0.016	0.013	0.022	0.032	0.008	0.042	0.017		0
0.25	0	0.077	0.08	0.097	0.112	0.125	0.123	0.11	0.108		0
	0	0.015	0.034	0.022	0.01	0.034	0.016	0.039	0.034		0
0.12	0	0.066	0.088	0.039	0.05	0.076	0.036	0.095	0.082		0
	0	0.022	0.009	0.047	0.025	0.017	0.107	0.028	0.023		0
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

Calculated Velocities (fps)

Ht. (in.)	0 0	1 0.083	2 0.167	4 0.333	8 0.667	12 1.000	16 1.333	20 1.667	22 1.833	23 1.917	24 2
7	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0.0919	0.1182	0.1040	0.1040	0.1164	0.1053	0.1420	0.1109	0.0987	0
6.5	0	0.1116	0.1210	0.1280	0.1219	0.1339	0.1412	0.1506	0.1435	0.1198	0
6	0	0.1047	0.0990	0.1371	0.1270	0.1598	0.1498	0.1346	0.1480	0.1314	0
5	0	0.1057	0.1271	0.1399	0.1573	0.1646	0.1602	0.164	0.1302	0.1284	0
4	0	0.1173	0.1460	0.1751	0.1785	0.1870	0.1794	0.1780	0.1957	0.1039	0
3	0	0.1198	0.1520	0.1611	0.1572	0.1753	0.1651	0.1580	0.1625	0.1652	0
2	0	0.1169	0.1508	0.1530	0.1611	0.1957	0.1552	0.1450	0.1411	0.1126	0
1.5	0	0.1178	0.1461	0.1547	0.1608	0.1543	0.1540	0.1430	0.1513	0.1441	0
1	0	0.1169	0.1221	0.1381	0.1569	0.1410	0.1639	0.1254	0.1431	0.1641	0
0.75	0	0.1010	0.1247	0.1332	0.1211	0.1412	0.1320	0.1230	0.1327		0
0.5	0	0.1089	0.1141	0.1157	0.1259	0.1406	0.1312	0.1337	0.1202		0
0.25	0	0.0784	0.0869	0.0994	0.1124	0.1295	0.1240	0.1167	0.1132		0
0.12	0	0.0695	0.0884	0.0610	0.0559	0.0778	0.1128	0.0990	0.0851		0
0	0	0	0	0	0	0	0	0	0	0	0

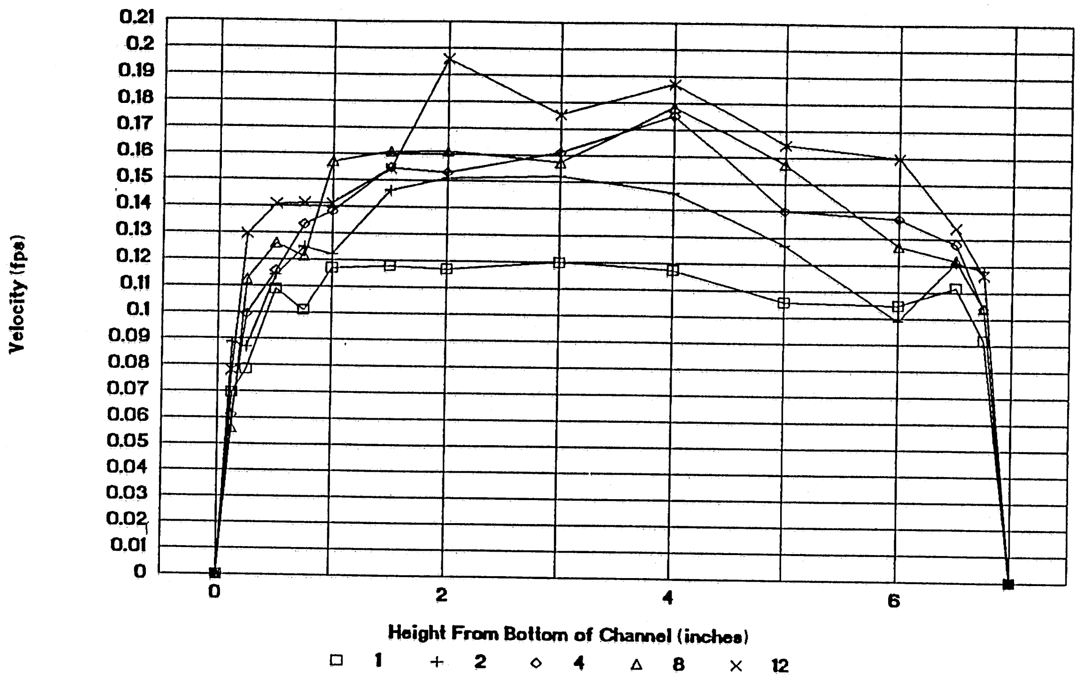

Fig. B–9 Vertical velocity profile at 25 gpm pump flow, 1–12 inches from sidewall.

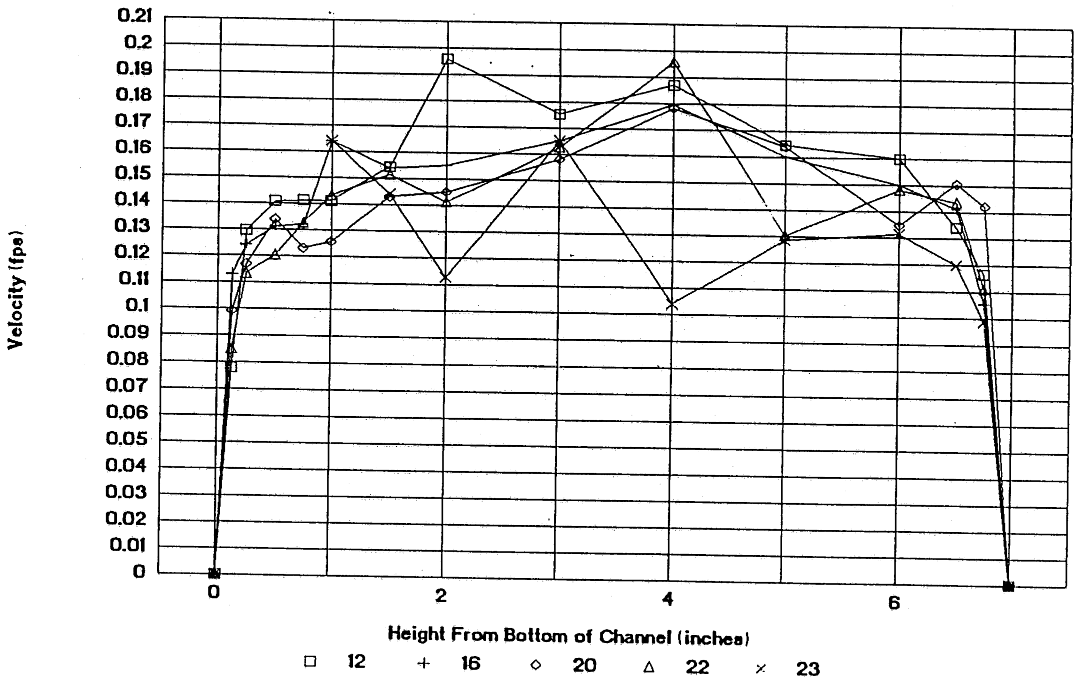

Fig. B–10 Vertical velocity profile at 25 gpm pump flow, 12–23 inches from sidewall.

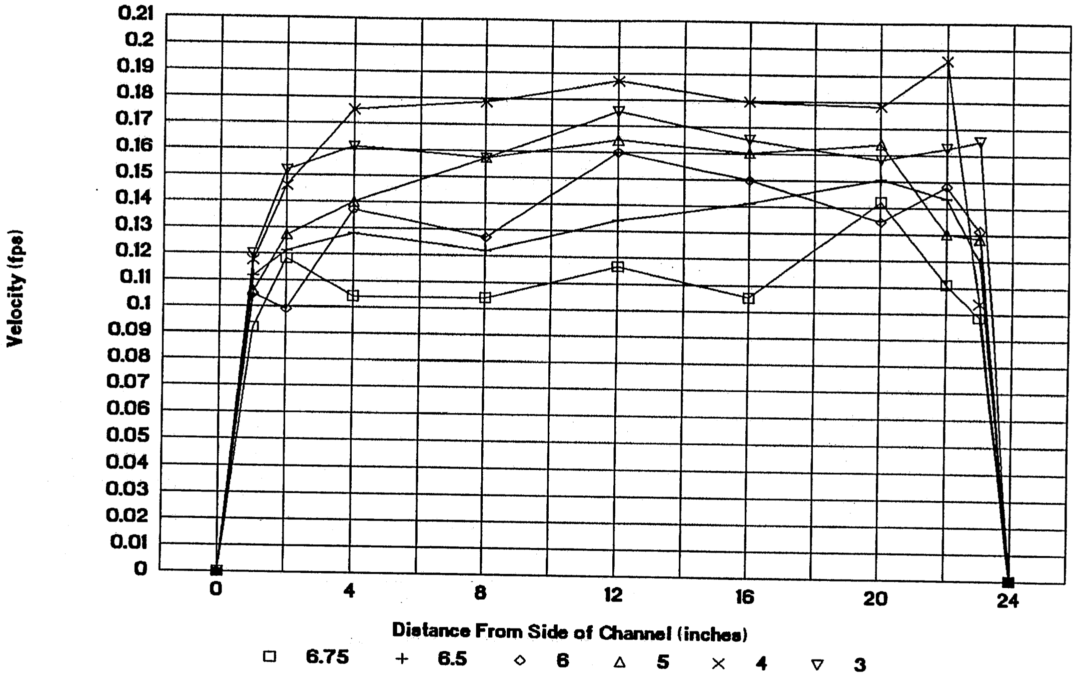

Fig. B–11 Horizontal velocity profile at 25 gpm pump flow, 6.75–3 inches from bottom of channel.

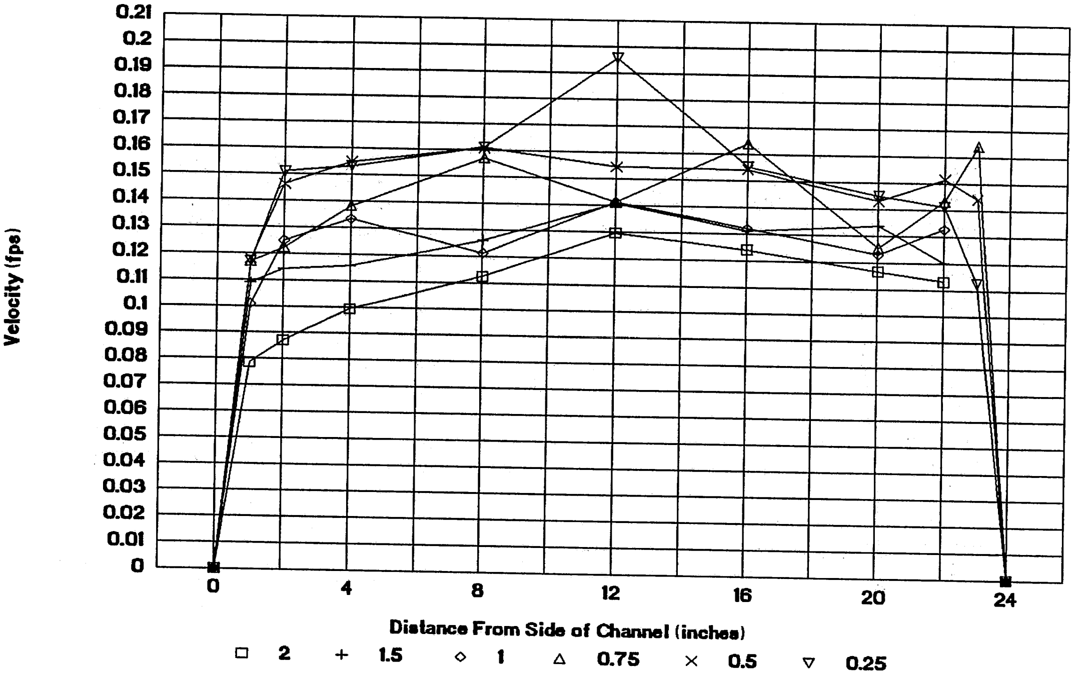

Fig. B–12 Horizontal velocity profile at 25 gpm pump flow 2–0.25 inches from bottom of channel.

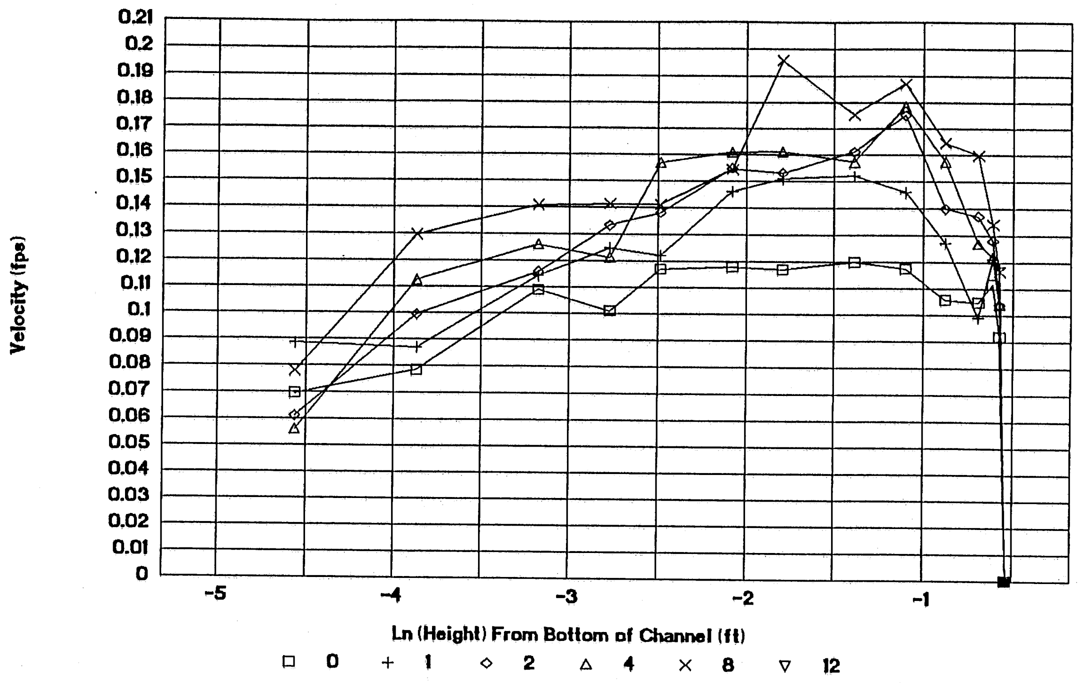

Fig. B–13 Ln (height from bottom of channel) versus velocity at 25 gpm pump flow, 1–12 inches from sidewall.

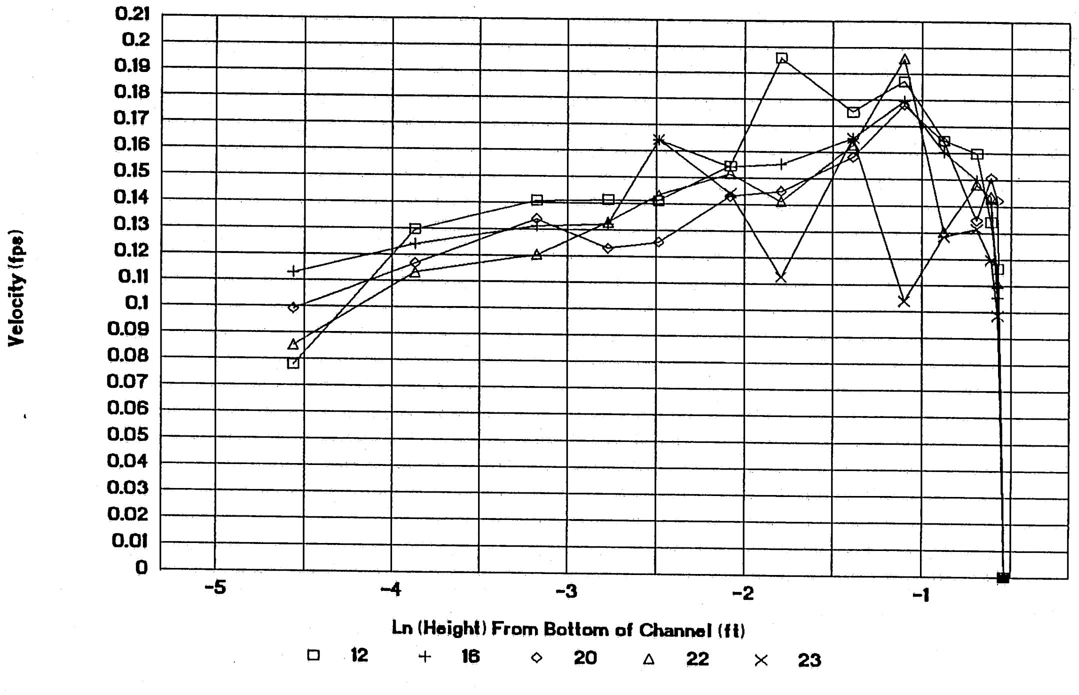

Fig. B–14 Ln (height from bottom of channel) versus velocity at 25 gpm, 12–23 inches from sidewall.

Table B-4, 45 gpm Pump Flow Velocity Data (From EMCM)

Distance From Side of Channel (inches/feet)

x/y Velocities (fps)

Ht. (in.)	0	1	2	4	8	12	16	20	22	23	24
	0	0.083	0.167	0.333	0.667	1.000	1.333	1.667	1.833	1.917	2
7	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0.501	0.082	0.108	0.127	0.147	0.106	0.097	0.114	0.066	0
	0	0.474	0.27	0.152	0.221	0.159	0.177	0.189	0.444	0.324	0
6.5	0	0.311	0.103	0.122	0.168	0.182	0.121	0.134	0.121	0.093	0
	0	0.473	0.135	0.181	0.193	0.193	0.208	0.224	0.223	0.21	0
6	0	0.125	0.145	0.157	0.187	0.205	0.14	0.139	0.123	0.113	0
	0	0.199	0.172	0.196	0.201	0.197	0.239	0.246	0.245	0.218	0
5	0	0.172	0.154	0.171	0.218	0.216	0.156	0.153	0.139	0.115	0
	0	0.195	0.191	0.226	0.221	0.228	0.266	0.294	0.26	0.233	0
4	0	0.138	0.169	0.193	0.237	0.244	0.168	0.168	0.125	0.112	0
	0	0.176	0.196	0.208	0.221	0.242	0.294	0.298	0.263	0.226	0
3	0	0.121	0.165	0.198	0.251	0.242	0.183	0.163	0.13	0.103	0
	0	0.172	0.199	0.178	0.221	0.236	0.301	0.291	0.276	0.223	0
2	0	0.154	0.177	0.224	0.217	0.229	0.166	0.145	0.13	0.118	0
	0	0.163	0.17	0.181	0.23	0.239	0.315	0.284	0.26	0.229	0
1.5	0	0.142	0.169	0.203	0.203	0.23	0.158	0.188	0.131	0.109	0
	0	0.16	0.179	0.169	0.214	0.228	0.285	0.297	0.264	0.234	0
1	0	0.152	0.157	0.201	0.194	0.21	0.159	0.13	0.122	0.109	0
	0	0.4	0.175	0.192	0.207	0.208	0.277	0.26	0.252	0.233	0
0.75	0	0.375	0.123	0.165	0.169	0.192	0.152	0.128	0.125	0.117	0
	0	0.474	0.17	0.146	0.187	0.205	0.261	0.257	0.226	0.231	0
0.5	0	0.136	0.14	0.149	0.137	0.183	0.139	0.115	0.116	0.109	0
	0	0.46	0.15	0.144	0.188	0.199	0.244	0.229	0.195	0.205	0
0.25	0	0.396	0.134	0.097	0.101	0.163	0.119	0.091	0.089	0.071	0
	0	0.474	0.118	0.122	0.14	0.171	0.204	0.183	0.173	0.154	0
0.12	0	0.336	0.092	0.185	-0.005	0.132	0.107	0.097	0.07	0.105	0
	0	0.474	0.078	0.204	0.077	0.133	0.168	0.138	0.147	0.15	0
0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0

Calculated Velocities (fps)

7	0	0	0	0	0	0	0	0	0	0	0
6.75	0			0.1864	0.2548	0.2165	0.2063	0.2124			0
6.5	0		0.1698	0.2182	0.2558	0.2652	0.2406	0.2610	0.2537	0.2296	0
6	0	0.2350	0.2249	0.2511	0.2745	0.2843	0.2769	0.2825	0.2741	0.2455	0
5	0	0.2600	0.2453	0.2834	0.3104	0.3140	0.3083	0.3314	0.2948	0.2598	0
4	0	0.2236	0.2587	0.2837	0.3240	0.3436	0.3386	0.3420	0.2911	0.2522	0
3	0	0.2102	0.2585	0.2662	0.3344	0.3380	0.3522	0.3335	0.3050	0.2456	0
2	0	0.2242	0.2454	0.2879	0.3162	0.3310	0.3560	0.3188	0.2906	0.2576	0
1.5	0	0.2139	0.2461	0.2641	0.2949	0.3238	0.3258	0.3515	0.2947	0.2581	0
1	0		0.2351	0.2779	0.2836	0.2955	0.3193	0.2906	0.2799	0.2572	0
0.75	0		0.2098	0.2203	0.2520	0.2808	0.3020	0.2871	0.2582	0.2589	0
0.5	0		0.2051	0.2072	0.2326	0.2703	0.2808	0.2562	0.2268	0.2321	0
0.25	0		0.1785	0.1558	0.1726	0.2362	0.2361	0.2043	0.1945	0.1695	0
0.12	0		0.1206		0.0771	0.1873	0.1991	0.1686	0.1628	0.1830	0
0	0	0	0	0	0	0	0	0	0	0	0

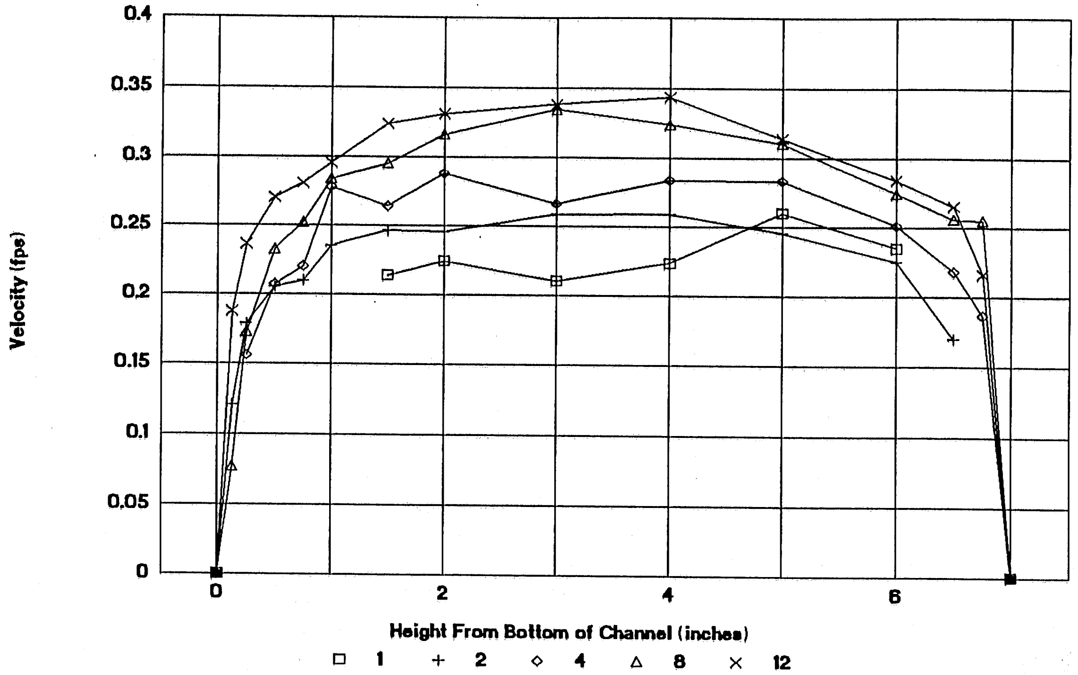

Fig. B–15 Vertical velocity profile at 45 gpm pump flow, 1–12 inches from sidewall.

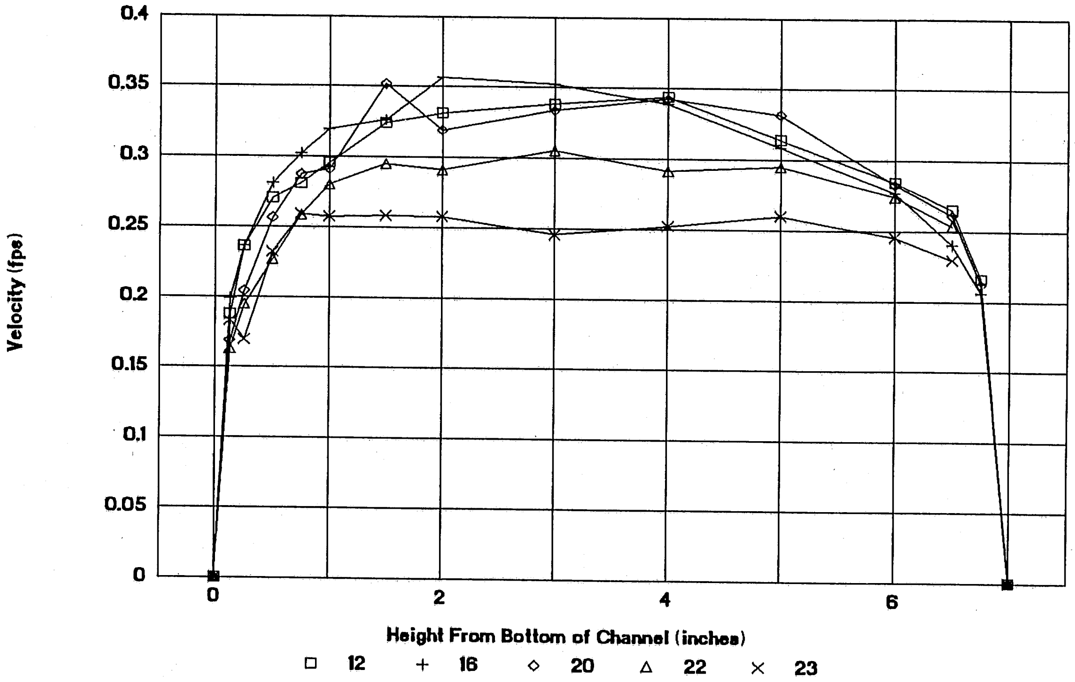

Fig. B–16 Vertical velocity profile at 45 gpm pump flow, 12–23 inches from sidewall.

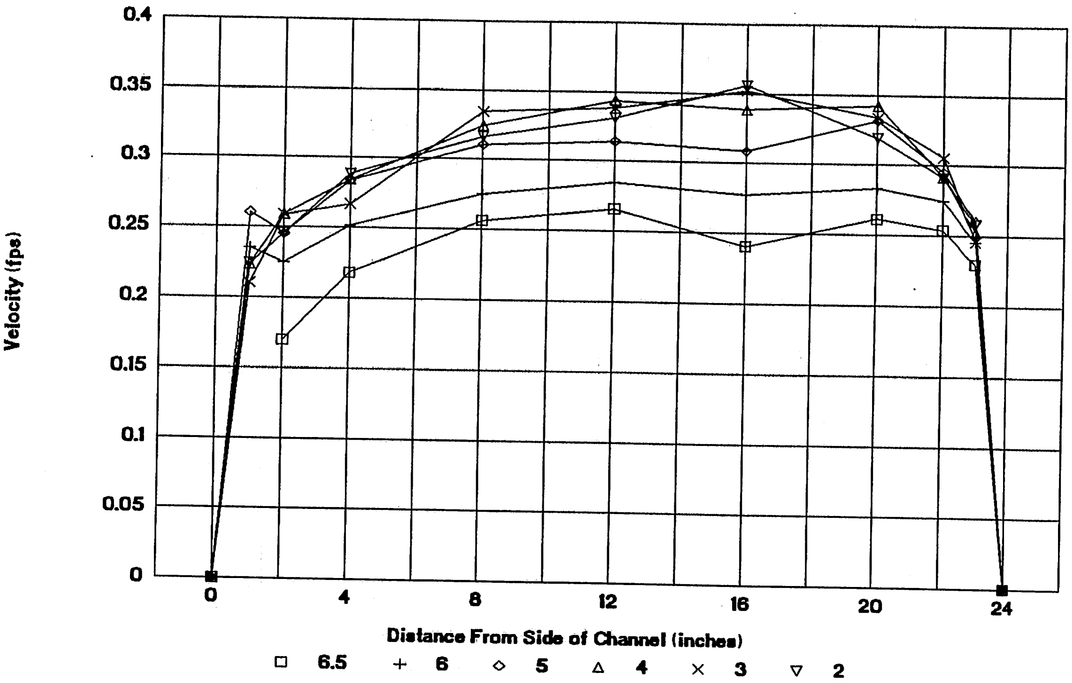

Fig. B–17 Horizontal velocity profile at 45 gpm pump flow, 6.5–2 inches above bottom of channel.

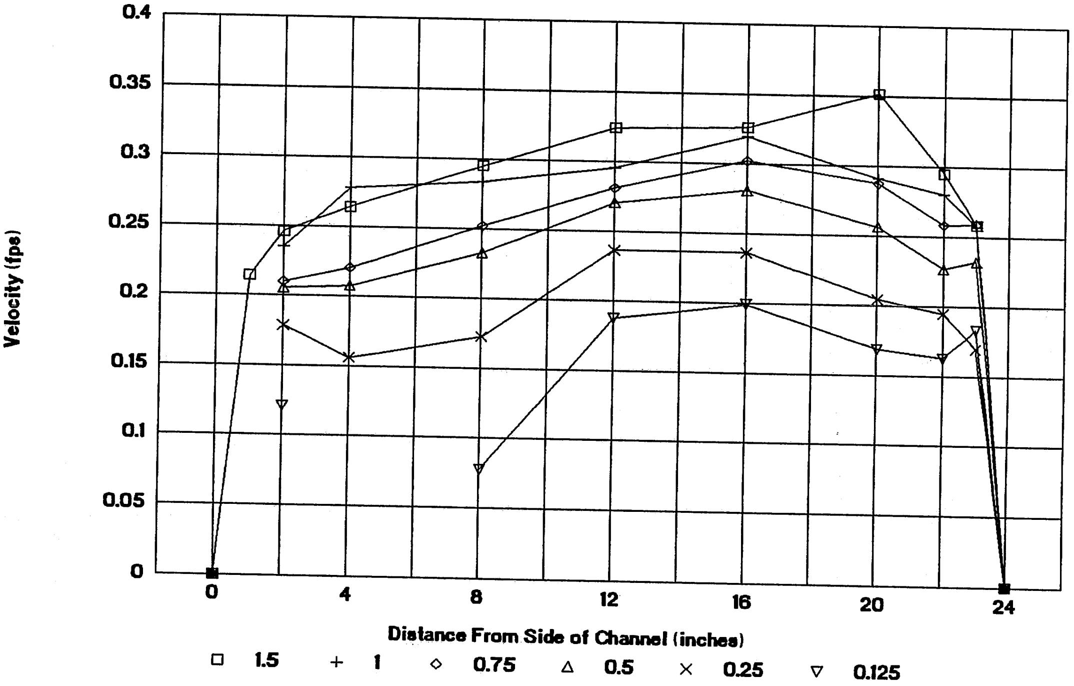

Fig. B–18 Horizontal velocity profile at 45 gpm pump flow, 1.5–0.125 above bottom of channel.

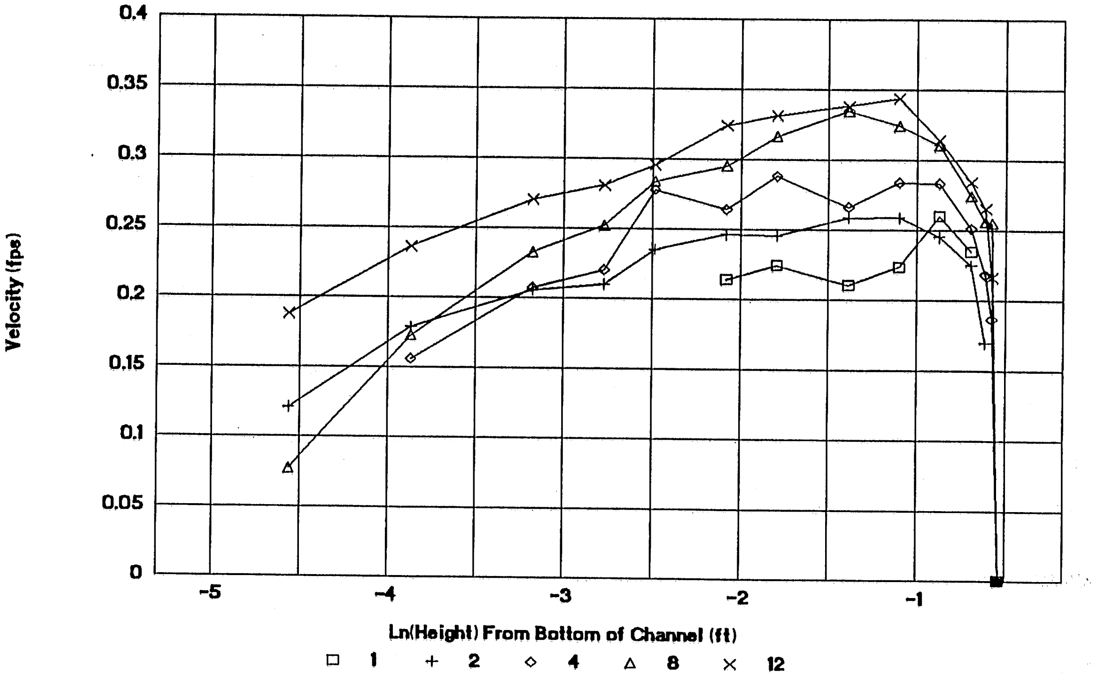

Fig. B–19 Ln (height above bottom of channel) vs. velocity at 45 gpm pump flow, 1–12 inches from sidewall.

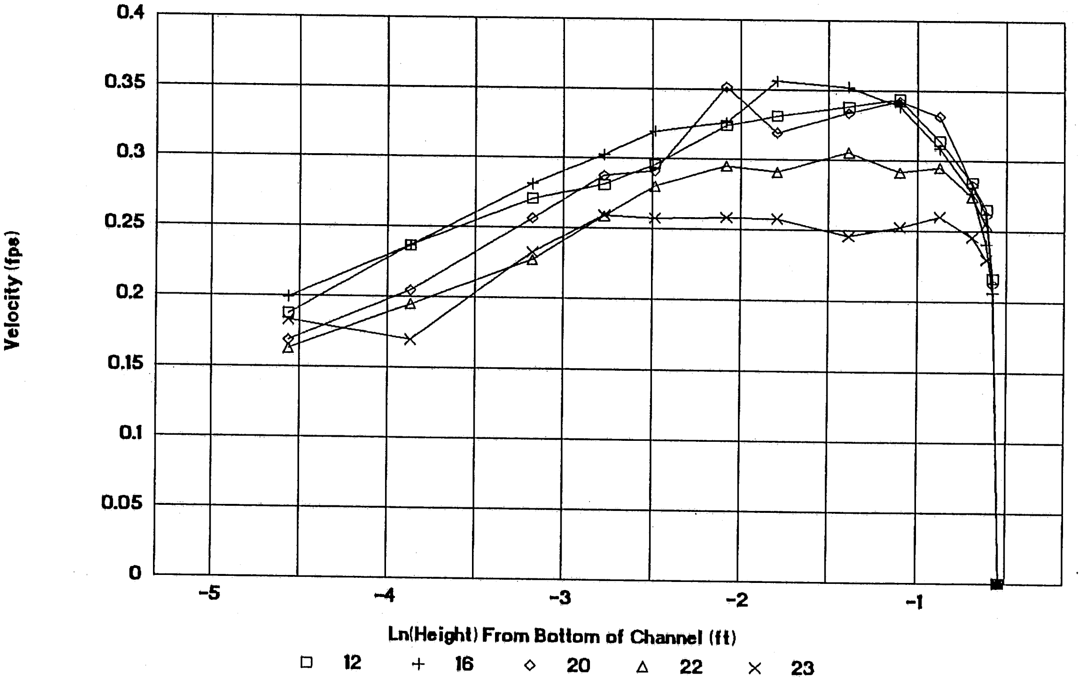

Fig. B–20 Ln (height above bottom of channel) vs. velocity at 45 gpm pump flow, 12–23 inches from sidewall.

APPENDIX C

Velocity Profile Analysis

Velocity Profile Analysis

The velocity profiles collected and presented in Appendix B were analyzed to characterize the channel with respect to centerline velocity, average velocity, shear velocity, boundary layer thickness, and bed shear stress in the test section.

The boundary layer thickness as displayed on the vertical velocity profiles of Appendix B is approximately 3.5 inches for each of the flow rates. This indicates that the flow, for the most part, is well developed. The centerline velocity is determined by taking the highest velocity from each of the vertical velocity profiles and weighing it with respect to its representative width. This average is taken as the average centerline (or maximum) velocity.

Under the laminar flow conditions of the 6 and 10 gpm pump flows, the shear velocity is calculated by determining the slope of the velocity profile nearest the wall du/dy and then using the following equation derived from Newton's shear law,

$$u_* = (\nu * \frac{du}{dy})^{0.5}$$

where ν, the kinematic velocity = $1.217*10^{-5}$ ft²/s. du/dy is computed at 4 inches and 12 inches from the sidewall and u_* is calculated for each position. A width weighted average of these u_* values is then calculated and called V_*.

See Tables C–1 and C–2 for the data used for this analysis and for the regression analysis used to determine the slope of the velocity profiles. The average velocity profiles and the line defined by the regression analyses are plotted in Figures C–1 and C–2. The regressions were forced through zero. The shear stress, τ_b, is calculated as $\tau_b = V_*^2 * \rho$ where $\rho = 1.938$ s/μg/ft³. The width weighted values of V_* and τ_b are given below:

Pump Flow (gpm)	V_* (fps)	τ_b (psf)
6	0.00270	$1.41*10^{-5}$
10	0.00443	$3.80*10^{-5}$

Table C-1, Average Velocity Profiles and Regression Analysis of Ln (Height From Bottom) vs. Average Velocity for V* Determination at 6 gpm.

Height (in)	Height (ft)	Avg. Vel. @ 4" (fps)	Avg. Vel. @ 12" (fps)	Regression Plots @ 4"	@12"
0	0	0	0	0	0
0.125	0.0104	0.0080	0.0064	0.0067	0.0053
0.25	0.0208	0.0128	0.0100	0.0134	0.0106
0.5	0.0417	0.0185	0.0152	0.0269	0.0211
0.75	0.0625	0.0226	0.0197	0.0403	0.0317
1	0.0833	0.0255	0.0235		
1.25	0.1042	0.0274	0.0268		
1.5	0.1250	0.0286	0.0289		
2	0.1667	0.0300	0.0314		
3	0.2500	0.0308	0.0336		
4	0.3333	0.0297	0.0279		
5	0.4167	0.0346	0.0239		

@ 4" Regression Output:	
Constant	0
Std Err of Y Est	0.00102
R Squared	0.975
No. of Observations	3
Degrees of Freedom	2
X Coefficient(s)	0.6451
Std Err of Coef.	0.0438

@ 12" Regression Output:	
Constant	0
Std Err of Y Est	0.000916
R Squared	0.967
No. of Observations	3
Degrees of Freedom	2
X Coefficient(s)	0.5075
Std Err of Coef.	0.0393

V* at 4" from side wall = 0.00280 fps
V* at 12" from side wall = 0.00249 fps
where nu = 1.22E-05

The width weighted average of V* at 6 gpm is 0.00270 fps.

Table C-2, Average Velocity Profiles and Regression Analysis of Ln (Height From Bottom) vs. Average Velocity for V* Determination at 10 gpm.

Height (in)	Height (ft)	Avg. Vel. @ 4" (fps)	Avg. Vel. @ 12" (fps)	Regression Plots @ 4"	@12"
0	0	0	0	0	0
0.25	0.0208	0.0344	0.0320	0.0344	0.0320
0.5	0.0417	0.0443	0.0385	0.0687	0.0640
0.75	0.0625	0.0493	0.0427	0.1031	0.0960
1	0.0833	0.0530	0.0466		
1.5	0.1250	0.0555	0.0523		
2	0.1667	0.0564	0.0555		
3	0.2500	0.0557	0.0583		
4	0.3333	0.0554	0.0548		
5	0.4167	0.0565	0.0493		

@ 4" Regression Output:	
Constant	0
Std Err of Y Est	0.0
R Squared	1
No. of Observations	2
Degrees of Freedom	1
X Coefficient(s)	1.65
Std Err of Coef.	0.0

@ 12" Regression Output:	
Constant	0
Std Err of Y Est	0.0
R Squared	1
No. of Observations	2
Degrees of Freedom	1
X Coefficient(s)	1.536
Std Err of Coef.	0.0

V* at 4" from side wall = 0.00448 fps
V* at 12" from side wall = 0.00432 fps
where nu = 1.22E-05

The width weighted average of V* at 10 gpm is 0.00443 fps.

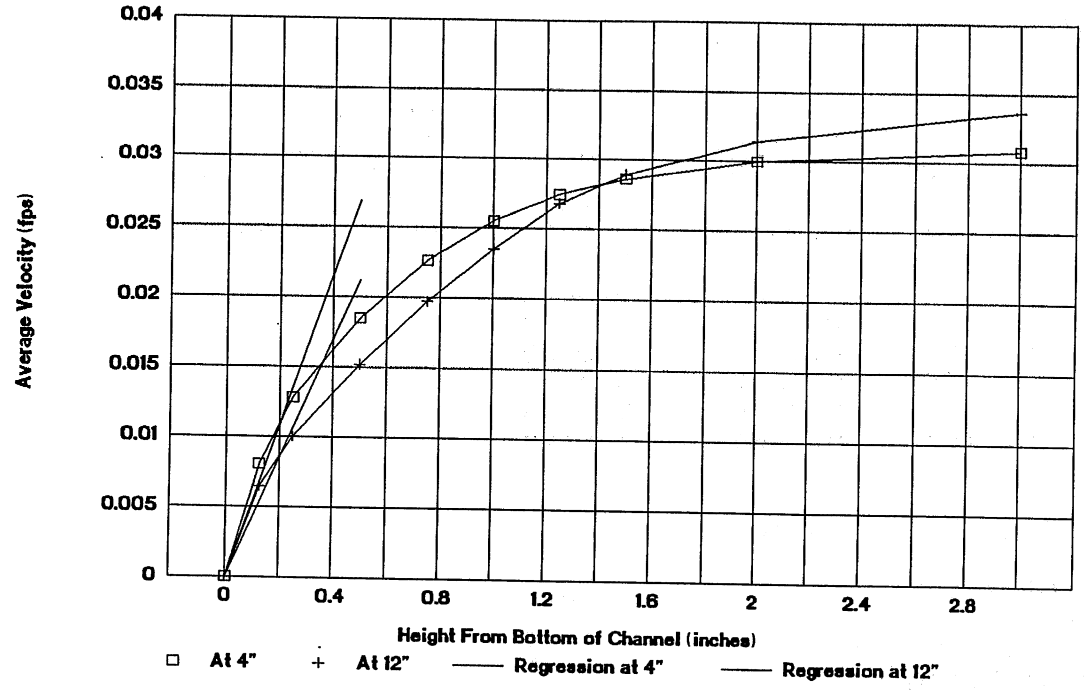

Fig. C–1 Average velocity profiles at 6 gpm pump flow rate along with estimated tangent at bottom of channel.

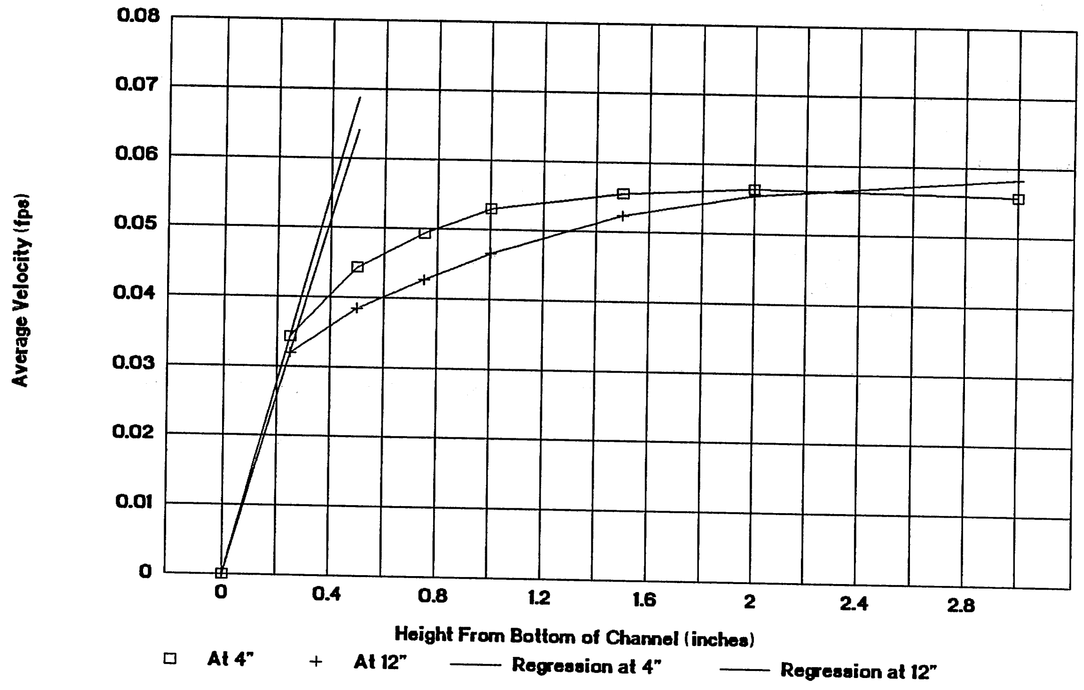

Fig. C–2 Average velocity profiles at 10 gpm pump flow rate along with estimated tangent at bottom of channel.

Under the turbulent flow conditions of the 25 and 45 gpm pump flows, the shear velocity is calculated through the use of the relationship

$$\frac{u(y)}{u_*} = \frac{1}{\kappa} \ln y + C$$

where

$u(y)$ = velocity at distance y from bottom
u_* = shear velocity = $\sqrt{\tau_b/\rho}$
τ_b = bottom shear
ρ = water density
κ = 0.41 – Van Karmen constant
C = constant of integration

The slope of the semi–log velocity profile plots, u_*/κ, was determined in Appendix B by linear regression of all of the profiles collected. A width weighted average slope was computed, $\frac{V_*}{\kappa}$, and V* was calculated by multiplication of this slope by Von Karmen's constant, κ.

The regression analyses data are contained in Tables C–3 and C–4 along with the data and results of the analyses for the 25 and 45 gpm pump flows, respectively.

The bottom shear stress, τ_b, is computed as

$$\tau_b = V_*^2 * \rho$$

where $\rho = 1.938$ slugs/ft^3

Final width weighted values for V_* and τ_b are given below.

Pump Flow (gpm)	V_* (fps)	τ_b (psf)
25	0.0104	0.000210
45	0.0242	0.00113

Shear velocity is plotted over pump flow rate in Fig. C–3

Table C-3, Regression Analyses of the Ln(Height) vs. Velocity Profiles at 25 gpm Pump Flow.

```
           Regression Output: @ 2"
Constant                        0.131
Std Err of Y Est              0.00757
R Squared                       0.924
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.02442
Std Err of Coef.              0.00313

           Regression Output: @ 4"
Constant                        0.138
Std Err of Y Est              0.00657
R Squared                       0.968
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.03323
Std Err of Coef.              0.00272

           Regression Output: @ 8"
Constant                        0.145
Std Err of Y Est              0.01373
R Squared                       0.889
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.03594
Std Err of Coef.              0.00567

           Regression Output: @ 12"
Constant                        0.155
Std Err of Y Est               0.0160
R Squared                       0.825
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.03204
Std Err of Coef.              0.00660
```

```
Weighted Avg. Constant =  0.1422
Weighted Avg. X Coeff. =  0.0260

V*/K =  0.0260
K =        0.4
V* =    0.0104 fps
To = V*^2*p =  0.000210 lb/ft^2
p =      1.938 slug/ft^3
```

```
           Regression Output: @ 16"
Constant                        0.147
Std Err of Y Est              0.00915
R Squared                       0.803
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.01708
Std Err of Coef.              0.00378

           Regression Output: @ 20"
Constant                        0.134
Std Err of Y Est              0.00715
R Squared                       0.833
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.01477
Std Err of Coef.              0.00295

           Regression Output: @ 22"
Constant                        0.137
Std Err of Y Est              0.00748
R Squared                       0.909
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.02185
Std Err of Coef.              0.00309
```

Table C-4, Regression Analysis of the Ln(Height) vs. Velocity Profiles at 45 gpm Pump Flow.

```
        Regression Output: @ 2"
Constant                        0.337
Std Err of Y Est               0.0117
R Squared                       0.943
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.04411
Std Err of Coef.              0.00485

        Regression Output: @ 4"
Constant                        0.408
Std Err of Y Est               0.0167
R Squared                       0.912
No. of Observations                 6
Degrees of Freedom                  4
X Coefficient(s)              0.06376
Std Err of Coef.              0.00987

        Regression Output: @ 8"
Constant                        0.478
Std Err of Y Est               0.0174
R Squared                       0.964
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.08279
Std Err of Coef.              0.00719

        Regression Output: @ 12"
Constant                        0.425
Std Err of Y Est              0.00615
R Squared                       0.988
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.05061
Std Err of Coef.              0.00254


Wt. Avg. C =                   0.4303
Wt. Avg. X coeff.=             0.0604

V*/K =   0.0604
K =         0.4
V* =     0.0242 fps
To = V*^2*p =    0.00113 psf
p =       1.938 slug/ft^3
```

```
        Regression Output: @ 16"
Constant                        0.451
Std Err of Y Est               0.0062
R Squared                       0.989
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.05497
Std Err of Coef.              0.00255

        Regression Output: @ 20"
Constant                        0.454
Std Err of Y Est               0.0170
R Squared                       0.941
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.06274
Std Err of Coef.              0.00704

        Regression Output: @ 22"
Constant                        0.395
Std Err of Y Est               0.0090
R Squared                       0.974
No. of Observations                 7
Degrees of Freedom                  5
X Coefficient(s)              0.05092
Std Err of Coef.              0.00372
```

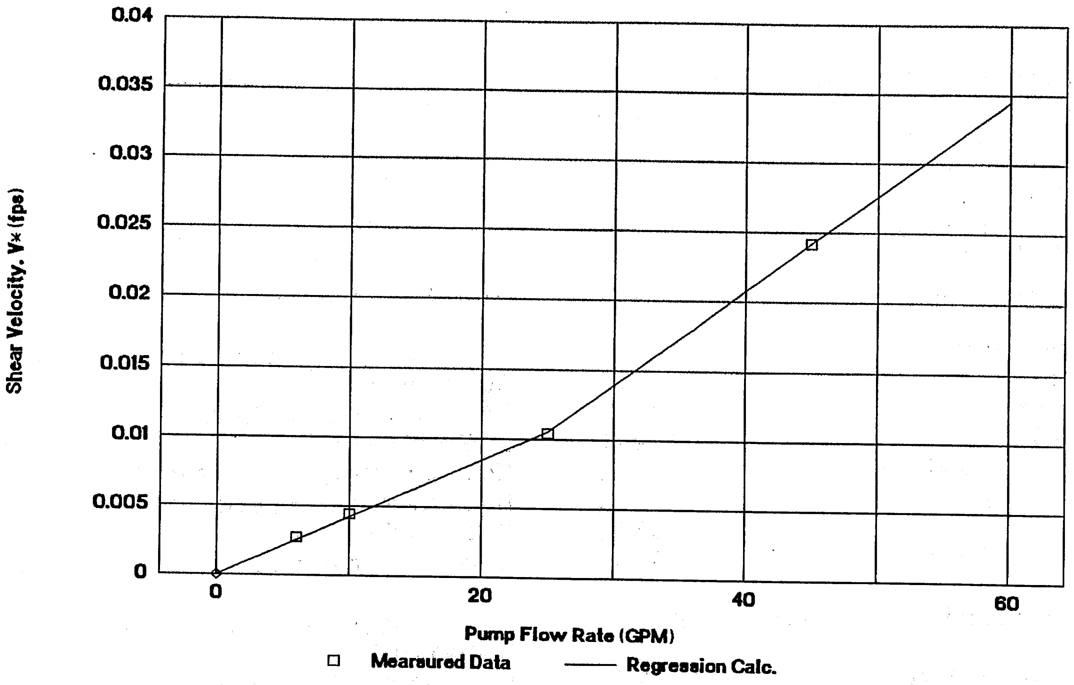

Fig. C–3 Pump flow rate vs. shear velocity.

Average velocity in the channel for each of the pump flows was computed by integrating the velocities at each point in the channel. First, velocities were integrated with respect to the height above the bottom and then with respect to width across the channel. The velocity along the boundary of the channel was assumed to be zero. This resulted in the total volumetric flow, Q, which was divided by the cross-sectional area of the channel for the average velocity, V_{avg}.

Tables C–5, C–6, C–7, and C–8 contain the calculated data and the resulting volumetric flow for the pump flow rates of 6, 10, 25, and 45 gpm, respectively. The results are shown below with the calculated average velocity. Pump flow versus average velocity is plotted in Figure C–4.

Pump flow rate (gpm)	Q (cfs)	V_{avg} (fps)
6	0.0302	0.0259
10	0.0585	0.0501
25	0.1610	0.138
45	0.3095	0.265

Table C–9 contains the regression analyses for pump flow rate vs. V_{avg} and V_c. The regression line does not intercept the origin of Figure C–4 because at low pump flow rates the relationship is nonlinear probably because of short circuiting between the manifolds.

Table C-5, Integration of Average Velocity Profiles for 6 gpm Pump Flow Rate.

	4" from sidewall		12" from side wall	
Depth From Bottom (ft)	Average Velocity (fps)	Integrated Velocity wrt Depth (ft^2/s)	Average Velocity (fps)	Integrated Velocity wrt Depth (ft^2/s)
0	0	0	0	0
0.0104	0.0080	0.000042	0.0064	0.000034
0.0208	0.0128	0.000108	0.0100	0.000086
0.0417	0.0185	0.000326	0.0152	0.000262
0.0625	0.0226	0.000428	0.0197	0.000363
0.0833	0.0255	0.000502	0.0235	0.000450
0.1042	0.0274	0.000552	0.0268	0.000524
0.1250	0.0286	0.000584	0.0289	0.000580
0.1667	0.0300	0.001220	0.0314	0.001256
0.2500	0.0308	0.002532	0.0336	0.002708
0.3333	0.0297	0.001260	0.0279	0.001282
0.4167	0.0346		0.0239	

Integrated Flow Rate = 0.0302 cfs

Table C-6, Integration of Average Velocity Profiles for 10 gpm Pump Flow Rate.

	4" from side wall		12" from side wall	
Depth From Bottom (ft)	Average Velocity (fps)	Integrated Velocity wrt Depth (ft^2/s)	Average Velocity (fps)	Integrated Velocity wrt Depth (ft^2/s)
0	0	0	0	0
0.0208	0.0320	0.00033	0.0344	0.00036
0.0417	0.0385	0.00073	0.0443	0.00082
0.0625	0.0427	0.00085	0.0493	0.00098
0.0833	0.0466	0.00093	0.0530	0.00107
0.1250	0.0523	0.00206	0.0555	0.00226
0.1667	0.0555	0.00224	0.0564	0.00233
0.2500	0.0583	0.00474	0.0557	0.00467
0.3333	0.0548	0.00236	0.0554	0.00232
0.4167	0.0493		0.0565	

Integrated Flow Rate = 0.0585 cfs

Table C-7, Integration of Velocity Profiles for 25 gpm Pump Flow Rate.

Distance From Side of Channel (inches/feet)

0	1	2	4	8	12	16	20	22	23	24
0	0.0833	0.167	0.333	0.667	1	1.33	1.67	1.83	1.92	2

Calculated Velocities (fps) (25gpm)

Ht. (in.)											
7	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0.0919	0.1182	0.1040	0.1040	0.1164	0.1053	0.1420	0.1109	0.0987	0
6.5	0	0.1116	0.1210	0.1280	0.1219	0.1339	0.1412	0.1506	0.1435	0.1198	0
6	0	0.1047	0.0990	0.1371	0.1270	0.1598	0.1498	0.1346	0.1480	0.1314	0
5	0	0.1057	0.1271	0.1399	0.1573	0.1646	0.1602	0.164	0.1302	0.1284	0
4	0	0.1173	0.1460	0.1751	0.1785	0.1870	0.1794	0.1780	0.1957	0.1039	0
3	0	0.1198	0.1520	0.1611	0.1572	0.1753	0.1651	0.1580	0.1625	0.1652	0
2	0	0.1169	0.1508	0.1530	0.1611	0.1957	0.1552	0.1450	0.1411	0.1126	0
1.5	0	0.1178	0.1461	0.1547	0.1608	0.1543	0.1540	0.1430	0.1513	0.1441	0
1	0	0.1169	0.1221	0.1381	0.1569	0.1410	0.1639	0.1254	0.1431	0.1641	0
0.75	0	0.1010	0.1247	0.1332	0.1211	0.1412	0.1320	0.1230	0.1327		0
0.5	0	0.1089	0.1141	0.1157	0.1259	0.1406	0.1312	0.1337	0.1202		0
0.25	0	0.0784	0.0869	0.0994	0.1124	0.1295	0.1240	0.1167	0.1132		0
0.125	0	0.0695	0.0884	0.0610	0.0559	0.0778	0.1128	0.0990	0.0851		0
0	0	0	0	0	0	0	0	0	0	0	0

Integrate the Velocities w.r.t. Height

Ht. (ft)											
0.583	0	0	0	0	0	0	0	0	0	0	0
0.562	0	0.0009	0.0012	0.0010	0.0010	0.0012	0.0010	0.0014	0.0011	0.0010	0
0.541	0	0.0021	0.0024	0.0024	0.0023	0.0026	0.0025	0.0030	0.0026	0.0022	0
0.5	0	0.0045	0.0045	0.0055	0.0051	0.0061	0.0060	0.0059	0.0060	0.0052	0
0.416	0	0.0087	0.0094	0.0115	0.0118	0.0135	0.0129	0.0124	0.0115	0.0108	0
0.333	0	0.0092	0.0113	0.0131	0.0139	0.0146	0.0141	0.0142	0.0135	0.0096	0
0.25	0	0.0098	0.0124	0.0140	0.0139	0.0150	0.0143	0.0140	0.0149	0.0112	0
0.166	0	0.0098	0.0126	0.0130	0.0132	0.0154	0.0133	0.0126	0.0126	0.0115	0
0.125	0	0.0048	0.0061	0.0064	0.0067	0.0072	0.0064	0.0060	0.0060	0.0053	0
0.083	0	0.0048	0.0055	0.0061	0.0066	0.0061	0.0066	0.0055	0.0061	0.0064	0
0.062	0	0.0022	0.0025	0.0028	0.0028	0.0029	0.0030	0.0025	0.0028	0.0068	0
0.041	0	0.0021	0.0024	0.0025	0.0025	0.0029	0.0027	0.0026	0.0026	0	0
0.020	0	0.0019	0.0020	0.0022	0.0024	0.0028	0.0026	0.0026	0.0024	0	0
0.010	0	0.0007	0.0009	0.0008	0.0008	0.0010	0.0012	0.0011	0.0010	0	0
0	0	0.0003	0.0004	0.0003	0.0002	0.0004	0.0005	0.0005	0.0004	0	0

x = [d(i-1)-d(i)]*[v(i)+v(i-1)]/2

(Table C-7 Continued)

Ht. (in)	Integrate the Velocities w.r.t. Width										
7	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0.0000	0.0000	0.0001	0.0003	0.0003	0.0003	0.0004	0.0002	0.0000	0.0000
6.5	0	0.0000	0.0001	0.0004	0.0007	0.0008	0.0008	0.0009	0.0004	0.0002	0.0000
6	0	0.0001	0.0003	0.0008	0.0017	0.0018	0.0020	0.0020	0.0010	0.0004	0.0002
5	0	0.0003	0.0007	0.0017	0.0038	0.0042	0.0044	0.0042	0.0020	0.0009	0.0004
4	0	0.0003	0.0008	0.0020	0.0045	0.0047	0.0048	0.0047	0.0023	0.0009	0.0004
3	0	0.0004	0.0009	0.0022	0.0046	0.0048	0.0049	0.0047	0.0024	0.0010	0.0004
2	0	0.0004	0.0009	0.0021	0.0043	0.0047	0.0048	0.0043	0.0021	0.0010	0.0004
1.5	0	0.0002	0.0004	0.0010	0.0021	0.0023	0.0022	0.0020	0.0010	0.0004	0.0002
1	0	0.0002	0.0004	0.0009	0.0021	0.0021	0.0021	0.0020	0.0009	0.0005	0.0002
0.75	0	0.0000	0.0002	0.0004	0.0009	0.0009	0.0010	0.0009	0.0004	0.0004	0.0002
0.5	0	0.0000	0.0001	0.0004	0.0008	0.0009	0.0009	0.0009	0.0004	0.0002	0
0.25	0	0.0000	0.0001	0.0003	0.0007	0.0008	0.0009	0.0008	0.0004	0.0002	0
0.12	0	0.0000	0.0000	0.0001	0.0002	0.0003	0.0003	0.0003	0.0001	0.0000	0
0	0	0.0000	0.0000	0.0000	0.0001	0.0001	0.0001	0.0001	0.0000	0.0000	0

Fi = [w(i)-w(i-1)]*[x(i)+x(i-1)]/2

Total Integrated Flow = Sum of all Fi
= 0.161 cfs

Table C-8, Integration of Velocity Profiles for 45 gpm Pump Flow Rate.

Distance From Side of channel (feet/inches)

Calculated Velocities (fps)

Ht. (in.)	0	0.0833	0.167	0.333	0.667	1	1.33	1.67	1.83	1.92	2
	0	1	2	4	8	12	16	20	22	23	24
7	0	0	0	0	0	0	0	0	0	0	0
6.75	0			0.1864	0.2548	0.2165	0.2063	0.2124			0
6.5	0		0.1698	0.2182	0.2558	0.2652	0.2406	0.2610	0.2537	0.2296	0
6	0	0.2350	0.2249	0.2511	0.2745	0.2843	0.2769	0.2825	0.2741	0.2455	0
5	0	0.2600	0.2453	0.2834	0.3104	0.3140	0.3083	0.3314	0.2948	0.2598	0
4	0	0.2236	0.2587	0.2837	0.3240	0.3436	0.3386	0.3420	0.2911	0.2522	0
3	0	0.2102	0.2585	0.2662	0.3344	0.3380	0.3522	0.3335	0.3050	0.2456	0
2	0	0.2242	0.2454	0.2879	0.3162	0.3310	0.3560	0.3188	0.2906	0.2576	0
1.5	0	0.2139	0.2461	0.2641	0.2949	0.3238	0.3258	0.3515	0.2947	0.2581	0
1	0		0.2351	0.2779	0.2836	0.2955	0.3193	0.2906	0.2799	0.2572	0
0.75	0		0.2098	0.2203	0.2520	0.2808	0.3020	0.2871	0.2582	0.2589	0
0.5	0		0.2051	0.2072	0.2326	0.2703	0.2808	0.2562	0.2268	0.2321	0
0.25	0		0.1785	0.1558	0.1726	0.2362	0.2361	0.2043	0.1945	0.1695	0
0.125	0		0.1206		0.0771	0.1873	0.1991	0.1686	0.1628	0.1830	0
0	0	0	0	0	0	0	0	0	0	0	0

Integrate the Velocities w.r.t. Height

Ht. (ft)											
0.583	0	0	0	0	0	0	0	0	0	0	0
0.562	0			0.0019	0.0026	0.0022	0.0021	0.0022			0
0.541	0		0.0035	0.0042	0.0053	0.0050	0.0046	0.0049	0.0052	0.0047	0
0.5	0	0.0097	0.0082	0.0097	0.0110	0.0114	0.0107	0.0113	0.0109	0.0099	0
0.416	0	0.0206	0.0195	0.0222	0.0243	0.0249	0.0243	0.0255	0.0237	0.0210	0
0.333	0	0.0201	0.0210	0.0236	0.0264	0.0274	0.0269	0.0280	0.0244	0.0213	0
0.25	0	0.0180	0.0215	0.0229	0.0274	0.0284	0.0287	0.0281	0.0248	0.0207	0
0.166	0	0.0181	0.0209	0.0230	0.0271	0.0278	0.0295	0.0271	0.0248	0.0209	0
0.125	0	0.0091	0.0102	0.0115	0.0127	0.0136	0.0142	0.0139	0.0121	0.0107	0
0.083	0	0.0133	0.0100	0.0112	0.0120	0.0129	0.0134	0.0133	0.0119	0.0107	0
0.062	0		0.0046	0.0051	0.0055	0.0060	0.0064	0.0060	0.0056	0.0053	0
0.041	0		0.0043	0.0044	0.0050	0.0057	0.0060	0.0056	0.0050	0.0051	0
0.020	0		0.0039	0.0037	0.0042	0.0052	0.0053	0.0047	0.0043	0.0041	0
0.010	0		0.0015	0.0016	0.0013	0.0022	0.0022	0.0019	0.0018	0.0018	0
0	0		0.0006		0.0004	0.0009	0.0010	0.0008	0.0008	0.0009	0

$x = [d(i-1)-d(i)]*[v(i)+v(i-1)]/2$

(Table C-8 Continued)

Distance From Side of channel (feet/inches)

Integrate the Velocities w.r.t. Width

Ht. (in)	0	0.083	0.167	0.333	0.667	1	1.33	1.67	1.83	1.92	2
	0	1	2	4	8	12	16	20	22	23	24
7	0	0	0	0	0	0	0	0	0	0	0
6.75	0	0	0	0.0003	0.0007	0.0008	0.0007	0.0007	0.0003		
6.5	0	0	0.0002	0.0006	0.0015	0.0017	0.0016	0.0015	0.0008	0.0004	0.0001
6	0	0.0004	0.0007	0.0015	0.0034	0.0037	0.0037	0.0036	0.0018	0.0008	0.0004
5	0	0.0008	0.0016	0.0034	0.0077	0.0082	0.0082	0.0083	0.0041	0.0018	0.0008
4	0	0.0008	0.0017	0.0037	0.0083	0.0089	0.0090	0.0091	0.0043	0.0019	0.0008
3	0	0.0007	0.0016	0.0037	0.0083	0.0093	0.0095	0.0094	0.0044	0.0018	0.0008
2	0	0.0007	0.0016	0.0036	0.0083	0.0091	0.0095	0.0094	0.0043	0.0019	0.0008
1.5	0	0.0003	0.0008	0.0018	0.0040	0.0043	0.0046	0.0046	0.0021	0.0009	0.0004
1	0	0.0005	0.0009	0.0017	0.0038	0.0041	0.0043	0.0044	0.0021	0.0009	0.0004
0.75	0	0	0.0003	0.0008	0.0017	0.0019	0.0020	0.0020	0.0009	0.0004	0.0002
0.5	0	0	0.0003	0.0007	0.0015	0.0017	0.0019	0.0019	0.0008	0.0004	0.0002
0.25	0	0	0.0003	0.0006	0.0013	0.0015	0.0017	0.0016	0.0007	0.0004	0.0002
0.12	0	0	0.0001	0.0002	0.0004	0.0005	0.0007	0.0007	0.0003	0.0003	0.0001
0	0	0	0.0000	0.0001	0.0001	0.0002	0.0003	0.0003	0.0001	0.0000	0.0000

Fi = [w(i)-w(i-1)]*[x(i)+x(i-1)]/2

Total Integrated Flow = Sum of all Fi
= 0.310 cfs

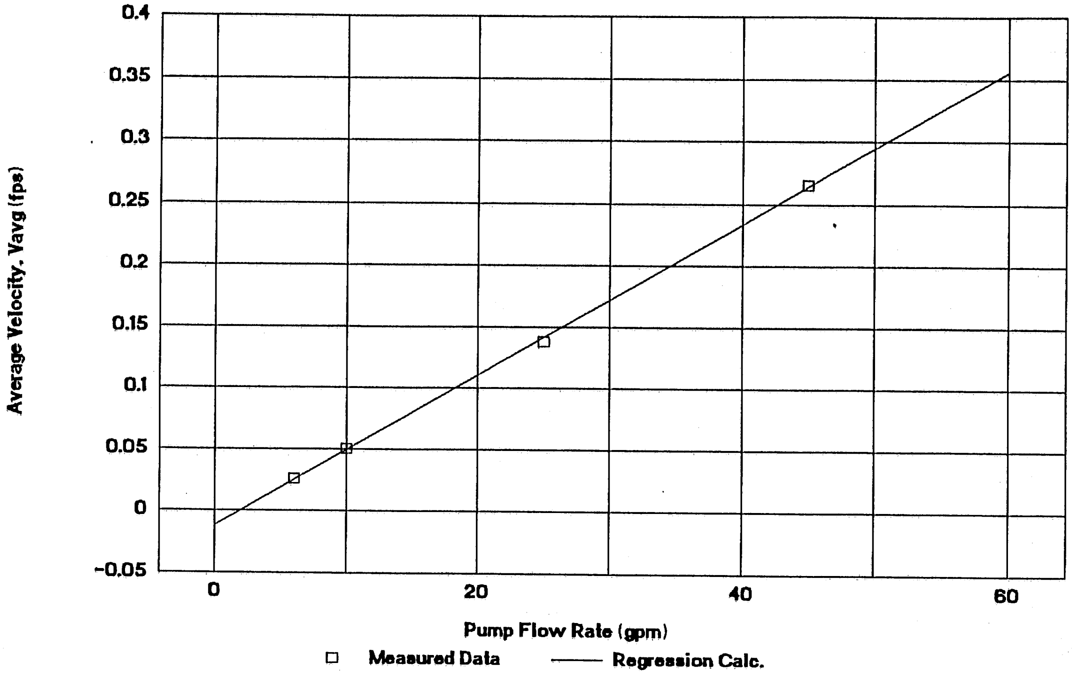

Fig. C–4 Pump flow rate vs. average velocity.

Table C-9, Regression Analyses of Pump Flow Rate vs. Average Velocity, Vavg, and Centerline Velocity, Vc.

Pump Flow vs. Vavg.

```
         Regression Output:
Constant                      -0.01188
Std Err of Y Est               0.00265
R Squared                        1.000
No. of Observations                  4
Degrees of Freedom                   2
X Coefficient(s)              0.006127
Std Err of Coef.              0.000086
```

Pump Flow vs. Vc

```
         Regression Output:
Constant                      -0.01587
Std Err of Y Est              0.004861
R Squared                        0.999
No. of Observations                  4
Degrees of Freedom                   2
X Coefficient(s)              0.007372
Std Err of Coef.              0.000158
```

APPENDIX D

Results of Sediment Tests

Results of Sediment Tests

Preliminary evaluation of alternative sediments was performed to detect which sediment handled the best, was the most stable over time, and had the highest rate of SOD. Early in the test, it was noticed that soon after cracked corn was placed under water, it became an odor problem. Therefore, it was eliminated from further consideration. The procedure for the preliminary sediment evaluation involved placing a layer of the sediment under water for a few days until saturated. The water above the saturated sediment was then drained off and was replaced with tap water. The container was covered and then the D.O. level in the container (5 gal. bucket) was monitored over time.

Sawdust, scratch grain (a mixture of feed grains), and organic lake bottom sediment were tested. The results are contained in Table D–1 and plotted in Figures D–1, D–2, and D–3. It was observed that the SOD of the lake bottom sediment was relatively low, and it was difficult to handle. The scratch grain performed well, but it also became an odor problem after about 2 weeks. The sawdust performed well early, but the rate of SOD decreased between tests. This might be due to a washout of the fine material when the water is drained off and replaced.

Further evaluation of the sawdust and the scratch grain was desired. The procedure was changed so that the water was reaerated between tests rather than replaced. This was designed to eliminate the removal of the fines from the sawdust. The results are contained in Table D–2 and plotted in Figures D–4 and D–5. It was observed that the sawdust was more consistent over time than the scratch grain.

Because of the ease of handling, the cleanliness, and the stability of the sawdust, it was chosen for the channel experiments.

Table D-1, Preliminary Sediment Evaluation Data

Elapsed Time (hours)	Sawdust Test #				Lake Bottom Sediment Test #				Scratch Grain Test #	
	1	2	3	4	1	2	3	4	1	2
	DO Level Above Test Sediment (mg/L)									
0.5	6.65				4.4					
25	0.2				3.25					
0.5		6.5				4.55				
16.5		2.7				2.5				
20.5		0.1				1.1				
0			7.9				7.5		7.5	
3			7.65				7.15		6.55	
6							7		6.25	
22.5			6.4				6.15		0	
0				8.55				6.85		8.35
6.5				8				6.1		7
24				7				5.25		0

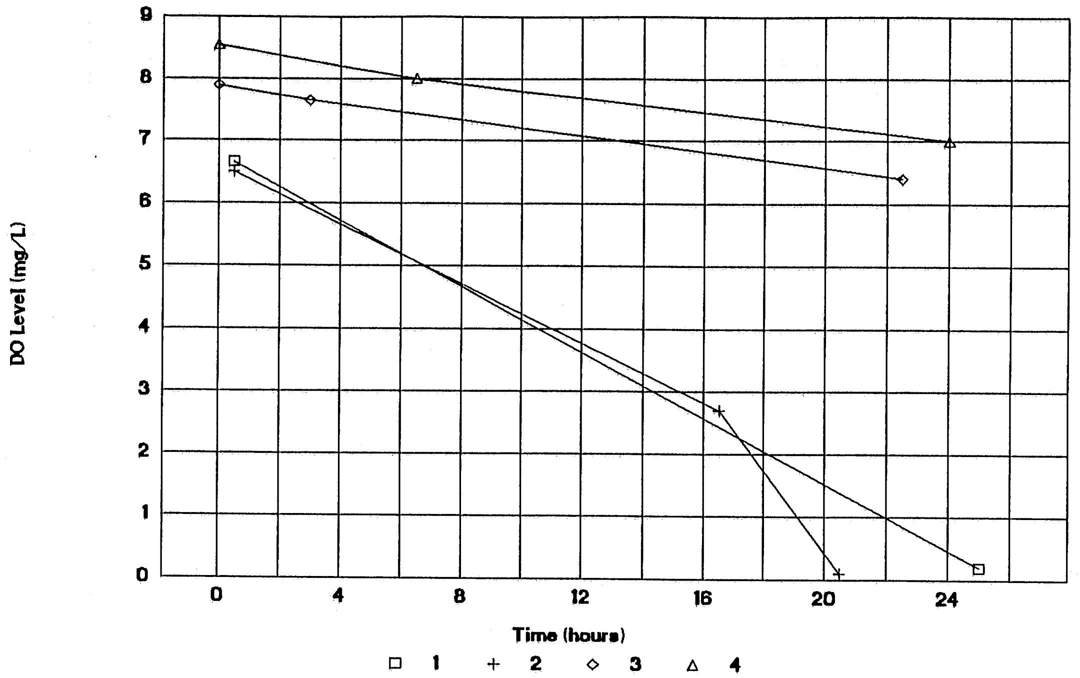

Fig. D–1 Preliminary sawdust evaluation test data (DO level over time).

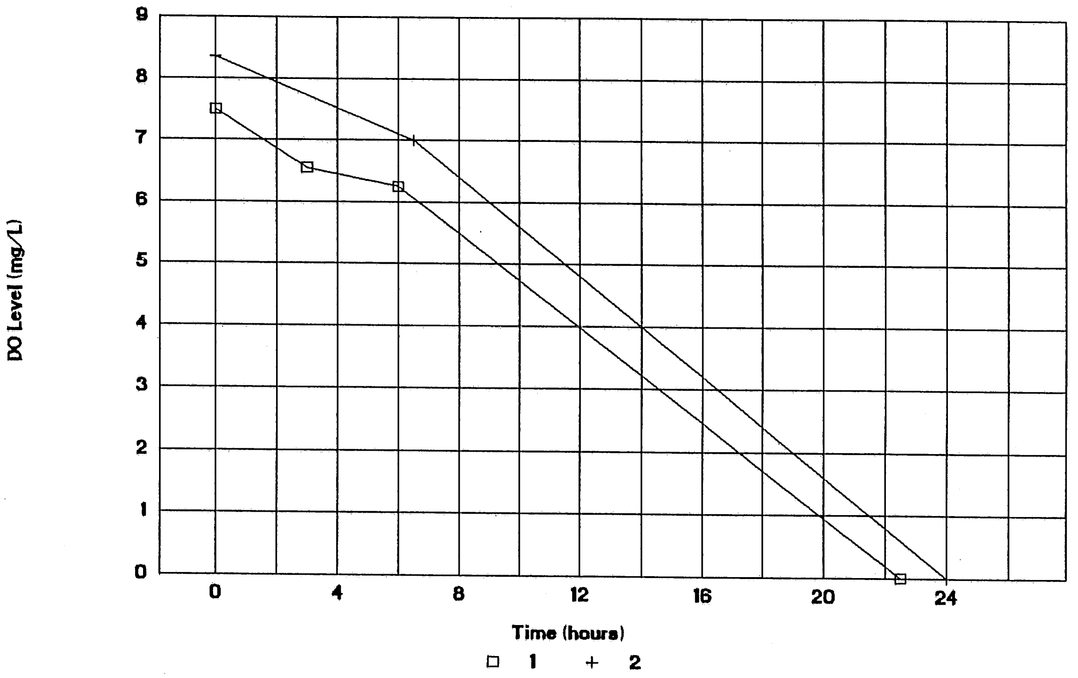

Fig. D–2 Preliminary scratch grains sediment evaluation test data (DO level over time).

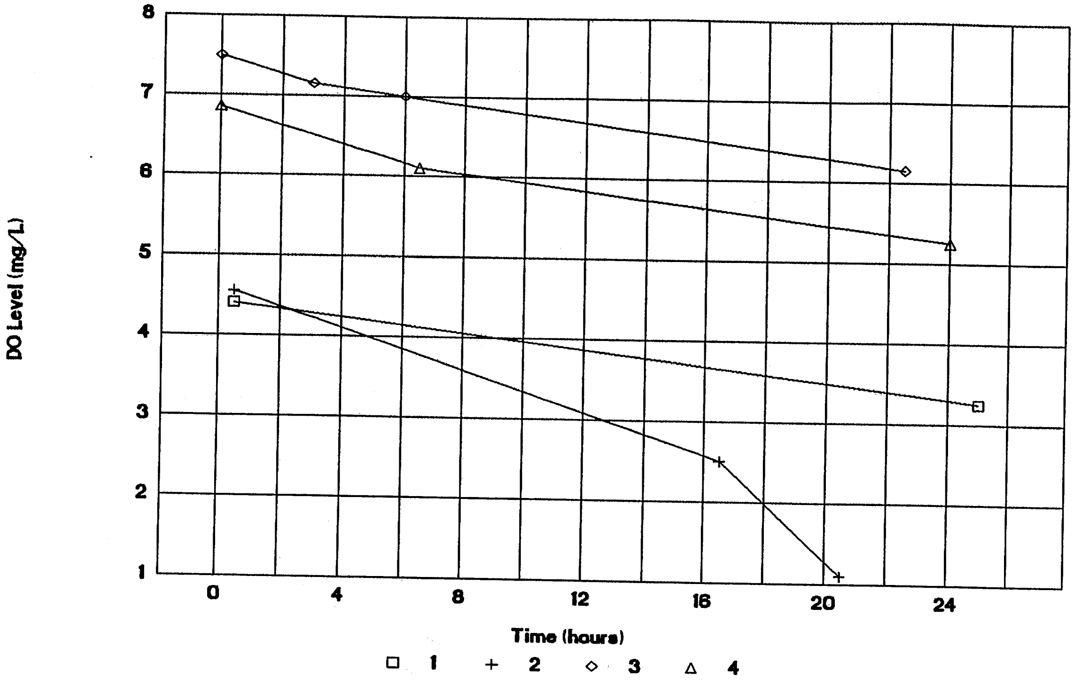

Fig. D–3 Preliminary lake bottom sediment evaluation test data (DO level over time).

Table D-2, Continuing Sediment Evaluation Tests with Areation
(DO Level of Water Above Samples vs. Time)

Test 1
Fresh sediment samples covered with tap water.

Elapsed Time (hr)	Muck	Sawdust	Scratch Grain	Tap Water	Temp (F)
0.08	11.2	8	10.8	10.6	58
1.33	11.2	8.25	10.6		
4.83	10.55	8.4	9.8		59
144.00	7.6	0	0		64

Test 2
After 7 days under water and 1/2 hour areation.

Elapsed Time (hr)	Sawdust	Scratch Grain	Temp (F)
0.25	6.4	7	64
3.33	4.5	2.8	
5.45	1.8	0	
24.00	0	0	

Test 3
After 8 days under water, 1/2 hour of areation, and five minutes wait.

Elapsed Time (hr)	Sawdust	Scratch Grain	Temp (F)
0.08	5.6	6	63
1.83	4.75		
1.33		4.05	
3.17	2.85		
2.67		1.25	
4.50	0.6		
4.00		0	
5.83	0		

Test 4
Sawdust has been under water for 3 weeks. Water is cloudy and a thin film has formed on the surface. The scratch grain had been under water for one night. Both were areated for 35 minutes.

Elapsed Time (hr)	Sawdust	Scratch Grain	Temp (F)
0.00	5.8	7.8	63
0.25	5.8	7.8	
1.67	4.25	8.5	
2.25	3.5	8.2	
3.33	1.5	7.5	
4.17	0.55	7.35	
5.17	0	7.15	

Test 5

Sawdust has been under water for 4 weeks. Water is discolored and a thin film has formed on the surface. The scratch grain had been under water for one week. Both were areated for 30 minutes.

Elapsed Time (hr)	Sawdust	Scratch Grain	Temp (F)
0.00	5.75	6.75	63
0.83	5.15	5.75	
1.83	3.55	5.55	
2.42	3.5	5	
3.08	2.55	4.65	
4.00	1.5	4	
4.58	0.9	3.55	

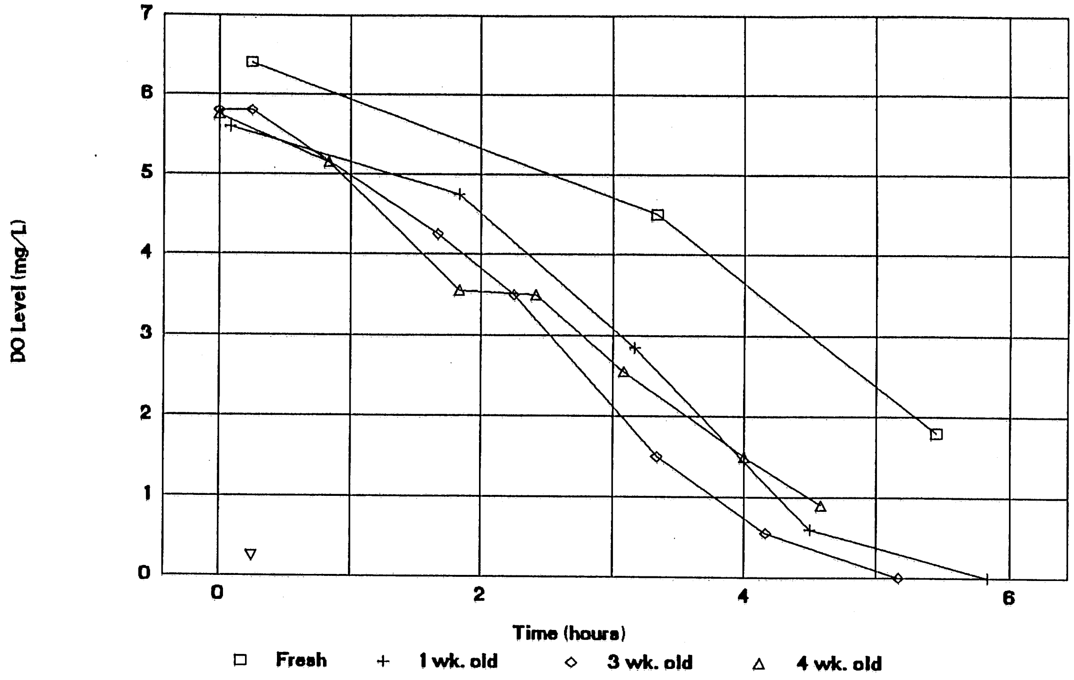

Fig. D–4 Extended evaluation of sawdust with aeration between tests.

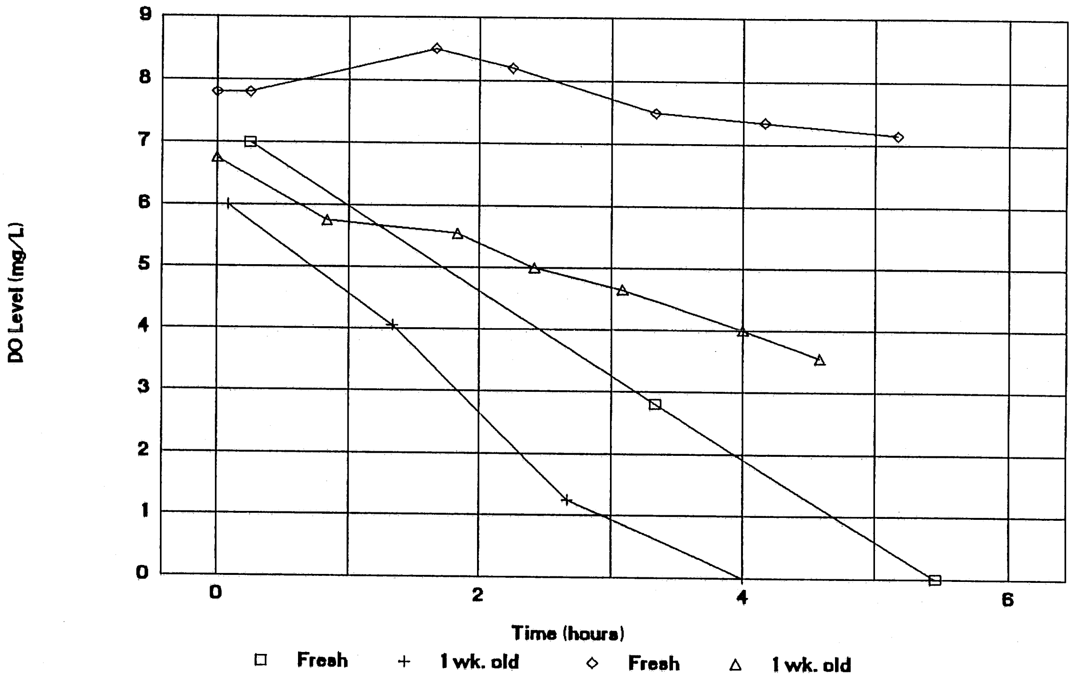

Fig. D–5 Extended evaluation of scratch grains as sediment with aeration between tests.

APPENDIX E

Experimental DO and BOD Data

This appendix contains the data collected and comments concerning each test run performed for the experiment. The data are analyzed in Appendix F.

1st Channel Run
Pump Flow = 15 gpm
Average Velocity = 0.072 fps
Water Temp. = 63 F
Channel had been areated over the weekend with the pump running at 14 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1040	0	9.23	9.23	0
1145	65	9.1	9.2	0.1
1300	140	9.1	9.2	0.1
1405	205	9.04	NA	NA
1510	270	8.9	9.1	0.2
1610	330	8.92	9.1	0.18

Data is the result of a Winkler analysis of 1 bottle for the BOD and one bottle for the channel DO level determination. The time length of the run was not great enough for the DO analysis to yeild reliable results.

** Cheese cloth was overlaid on the sediment to prevent resuspention during the first 4 runs. The last 3.5 feet of the bed was not covered to allow for monitoring of resuspension.

2nd Channel Run
Pump Flow = 30 gpm
Average Velocity = 0.162 fps
Water Temp. = 63 F
Channel had been areated over night with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
845	0	8.525	8.525	0.000
945	60	8.62	NA	NA
1037	112	8.425	NA	NA
1140	175	8.125	8.5	0.375
1240	235	8.125	8.525	0.400
1340	295	8.05	NA	NA
1445	360	8.05	8.5	0.450
1545	420	7.8	8.5	0.700

Data is the result of a Winkler analysis of 2 bottles for the channel DO level determination and one bottle for the BOD measurement.

3rd Channel Run
Pump Flow = 45 gpm
Average Velocity = 0.256 fps
Water Temp. = 63 F
Channel had been areated over night with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
945	0	8.35	8.35	0.000
1010	25	8.2		
1045	60	8	8.18	0.180
1145	120	7.81	8.12	0.310
1300	195	7.5	8.05	0.550
1350	245	7.31	7.95	0.640
1445	300	7.1	7.86	0.760
1600	375	6.75	7.725	0.975
830	1365	2.45		

DO measurements made as in the 2nd run.

4th Channel Run
Pump Flow = 60 gpm
Average Velocity = 0.344 fps
Water Temp. = 63 F
Channel had been areated 1.75 hours with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1040	0	7.45	7.45	0.000
1130	50	7	7.20	0.200
1330	170	6.075	6.715	0.640
1535	295	5.325	6.35	1.025

DO data is the average of two samples for both the BOD and the channel DO level measurements.

* Some movement of the sediment is noticed at the beginning of the run, but it appeared to have stopped later.

** After this run the channel was disassembled and the cheese cloth was removed because resuspension was not a problem the cheese cloth had trapped a few small bubbles which caused the cloth to rise above the sediment.

5th Channel Run
Pump Flow = 15 gpm
Average Velocity = 0.073 fps
Water Temp. = 63 F
Channel had been areated for 5 days with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1300	0	8.1	8.1	0.000
1545	165	7.65	NA	NA
730	1110	6.05	7.20	1.150
1340	1480	5.38	6.95	1.575

It was noticed that there were numerous small gas bubbles in the BOD bottles during the 2nd day.

6th Channel Run
Pump Flow= 20 gpm
Average Velocity = 0.103 fps
Water Temp. = 63 F
Channel had been areated for 3 hours with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1605	0	7.68	7.68	0.000
1900	175	7.23	7.62	0.390
1135	1170	4.69	7.15	2.465
1350	1305	4.35	6.98	2.625

7th Channel Run
Pump Flow= 30 gpm
Average Velocity = 0.163 fps
Water Temp. = 64 F
Channel had been areated for 5 days with the pump running at 25 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1400	0	7.35	7.35	0.000
1615	135	7.05		
1100	1260	4.50	6.95	2.450
1300	1380	4.24	6.9	2.660

8th Channel Run
Pump Flow= 10 gpm
Average Velocity = 0.043 fps
Water Temp. = 63 F
Channel had been areated for 3 hours with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1615	0	8.875	8.875	0.000
900	1005	6.26	7.19	0.930
2015	1680	5.40	6.925	1.525

9th Channel Run
Pump Flow= 5 gpm
Average Velocity = 0.012 fps
Water Temp. = 64 F
Channel had been areated for 38 hrs. with the pump running at 15 gpm.

Channel measurements

Time	Time Chng. Min.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment
1245	0	8.38	8.38	0.000
1605	200	8.00	8.19	0.185
2215	570	7.70	8.10	0.400
1410	1525	6.94	7.92	0.980

10th Channel Run
Pump Flow= 20 gpm
Average Velocity = 0.103 fps
Water Temp. = 65 F
Channel had been areated for 40 hours with the pump running at 20 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
12:45	0	8.15	8.15	0.000	0
16:05	03:20	7.85	8.01	0.160	200
23:10	10:25	7.20	7.90	0.700	625
12:10	23:25	6.14	7.70	1.560	1405

* Notice that the water is beginning to get a bit cloudier than it had been in the beginning.

11th Channel Run
Pump Flow= 15 gpm
Average Velocity = 0.073 fps
Water Temp. = 65 F
Channel had been areated for 12 hours with the pump running at 15 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
10:00	0	7.87	7.87	0.000	0
16:00	06:00	7.39	7.75	0.360	360
14:15	04:15	5.87	7.51	1.645	1695
16:10	06:10	5.74	7.51	1.765	1810

12th Channel Run
Pump Flow= 45 gpm
Average Velocity = 0.254 fps
Water Temp. = 65 F
Channel had been areated for 12 hours with the pump running at 15 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
13:50	0	7.80	7.80	0.000	0
16:05	02:15	7.59	7.83	0.235	135
22:50	09:00	6.85	7.69	0.840	540
11:15	21:25	5.69	7.54	1.850	1285

* The channel is now quite cloudy. There is microbial growth in patches up to 2 inches in diameter on the sediment bed. A film has formed in the flow meter also clouding the glass. The growth is filamentous and might be fungal.

13th Channel Run
Pump Flow= 60 gpm
Average Velocity = 0.344 fps
Water Temp. = 65 F
Channel had been areated for 3 hours with the pump running at 45 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
15:05	0	7.63	7.63	0.000	0
22:30	07:25	6.85	7.57	0.720	445
11:00	19:55	5.32	7.31	1.985	1195

* No resuspension is noticed.

14th Channel Run

Pump Flow= 30 gpm
Average Velocity = 0.163 fps
Water Temp. = 64.5 F
Channel had been areated for 1 week with the pump running at 15 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
11:45	0	8.65	8.65	0.000	0
15:55	04:10	8.36			250
19:00	07:15	6.66	8.31	1.650	1875

* The final data was taken on 5/6/93 at 1900 hours (the following day)

15th Channel Run

Pump Flow= 5 gpm
Average Velocity = 0.012 fps
Water Temp. = 64.5 F
Channel had been areated for 1.5 hours with the pump running at 20 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
20:45	0	8.22	8.22	0.000	0
11:30	14:45	7.56	8.00	0.435	885
16:15	19:30	7.43	7.97	0.545	1170

* The water is noticeably clearer than it was last week. Microbial growth on the sediment seems to have stabilized.

16th Channel Run

Pump Flow= 10 gpm
Average Velocity = 0.043 fps
Water Temp. = 64 F
Channel had been areated for 1.5 hours with the pump running at 10 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
22:10	0	7.93	7.93	0.000	0
10:20	12:10	7.35	7.74	0.390	730
15:45	17:35	7.11	7.69	0.585	1055

* No areation for up to 2 days over the weekend because it was accidentally disconnected. The channel may have become anaerobic briefly.

17th Channel Run
Pump Flow= 15 gpm
Average Velocity = 0.073 fps
Water Temp. = 64 F
Channel had been areated for 1.5 hours with the pump running at 10 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
18:10	0	7.65	7.65	0.000	0
12:45	18:35	6.86	7.46	0.598	1115
15:20	21:10	6.69	7.44	0.750	1270

18th Channel Run
Pump Flow= 20 gpm
Average Velocity = 0.103 fps
Water Temp. = 64 F
Channel had been areated for 36 hours with the pump running at 20 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
14:30	0	8.50	8.50	0.000	0
11:10	ERR	7.41	8.27	0.857	1240
15:10	ERR	7.18	8.26	1.075	1480

19th Channel Run
Pump Flow= 30 gpm
Average Velocity = 0.163 fps
Water Temp. = 65 F
Channel had been areated for 1 hour with the pump running at 30 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
16:25	0	7.86	7.86	0.000	0
14:00	21:35	6.64	7.70	1.057	1295
18:05	01:40	6.47	7.69	1.220	1540

* The water is now clear (Yellow). Microbial growth is stabilized??

20th Channel Run
Pump Flow= 45 gpm
Average Velocity = 0.254 fps
Water Temp. = 65 F
Channel had been areated for 1 hour with the pump running at 45 gpm.

Channel measurements

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	DO lost to Sediment	Delta t (min)
18:50	0	7.74	7.74	0.000	0
09:50	15:00	6.41	7.61	1.200	900
18:55	00:05	5.80	7.61	1.808	1445

APPENDIX F

Analysis of DO and BOD Data

Analysis of DO and BOD Data

The first step in the analysis of the experimental data presented in Appendix E was to determine the rate at which the sediment removed DO from the water. The measured DO concentration in the channel was subtracted from the DO concentration in the BOD bottles at each time increment. This is the value taken as the DO consumed by the sediment. These values are plotted over time for each run in Figures F–1 through F–20. A regression analysis of each set of these data was performed, and the line defined by this regression was also plotted on Figures F–1 through F–20.

A regression of the BOD data was also performed for each data set. The slope of the line defined by the regression of the BOD data is the BOD rate. The BOD rate is plotted over time in Figure IV–2 of the report. Both of the regressions and the related data are contained on the pages following this summary.

The SOD taken as the slope of the regression analysis was corrected to a standard temperature of 20° Celsius, and these data are contained in the main report in Table IV–1. The data were divided into 3 sets according to when the tests were performed. Tables F–1, F–2, and F–3 contain the regression analyses for the average velocity, maximum velocity, and shear velocity versus temperature corrected SOD, respectively.

Figure IV–5 through Figure IV–7 contain the average velocity, maximum velocity, and shear velocity along with the lines defined by the regressions plotted versus temperature corrected SOD.

1st Channel Run
Pump Flow = 15 gpm
Average Velocity = 0.072 fps
Water Temp.= 63 F.

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1040	0	9.23	9.23	0	0
1145	65	9.1	9.2	0.1	0.042
1300	140	9.1	9.2	0.1	0.091
1405	205	9.04			0.133
1510	270	8.9	9.1	0.2	0.176
1610	330	8.92	9.1	0.18	0.215

SOD Regression Output:	
Constant	0
Std Err of Y Est	0.0361
R Squared	0.7927
No. of Observations	5
Degrees of Freedom	4
X Coefficient(s)	0.000651
Std Err of Coef.	0.000079

BOD Regression Output:	
Constant	9.235
Std Err of Y Est	0.019
R Squared	0.926
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	-0.000429
Std Err of Coef.	0.0000698

2nd Channel Run
Pump Flow = 30 gpm
Average Velocity = 0.162 fps
Water Temp. = 63 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
845	0	8.525	8.525	0	0
1037	112	8.425			0.176
1140	175	8.125	8.5	0.375	0.275
1240	235	8.125	8.525	0.4	0.369
1340	295	8.05			0.463
1445	360	8.05	8.5	0.45	0.566
1545	420	7.8	8.5	0.7	0.660

SOD Regression Output:	
Constant	0
Std Err of Y Est	0.0805
R Squared	0.8971
No. of Observations	5
Degrees of Freedom	4
X Coefficient(s)	0.001571
Std Err of Coef.	0.000128

BOD Regression Output:	
Constant	8.523
Std Err of Y Est	0.012
R Squared	0.446
No. of Observations	5
Degrees of Freedom	3
X Coefficient(s)	-0.000055
Std Err of Coef.	0.0000357

3rd Channel Run

Pump Flow = 45 gpm
Average Velocity = 0.256 fps
Water Temp. = 63 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
945	0	8.35	8.35	0	0
1010	25	8.2			0.065
1045	60	8	8.18	0.18	0.157
1145	120	7.81	8.12	0.31	0.313
1300	195	7.5	8.05	0.55	0.509
1350	245	7.31	7.95	0.64	0.640
1445	300	7.1	7.86	0.76	0.784
1600	375	6.75	7.725	0.975	0.980

SOD Regression Output:	
Constant	0
Std Err of Y Est	0.0215
R Squared	0.9960
No. of Observations	7
Degrees of Freedom	6
X Coefficient(s)	0.002612
Std Err of Coef.	0.000036

BOD Regression Output:	
Constant	8.320
Std Err of Y Est	0.031
R Squared	0.982
No. of Observations	7
Degrees of Freedom	5
X Coefficient(s)	-0.001549
Std Err of Coef.	0.0000932

4th Channel Run

Pump Flow= 60 gpm
Average Velocity = 0.344 fps
Water Temp. = 63 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1040	0	7.45	7.45	0	0
1130	50	7	7.20	0.20	0.178
1330	170	6.075	6.715	0.64	0.605
1535	295	5.325	6.35	1.025	1.049

SOD Regression Output:	
Constant	0.00
Std Err of Y Est	0.0279
R Squared	0.9963
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.003556
Std Err of Coef.	0.000080

BOD Regression Output:	
Constant	7.407
Std Err of Y Est	0.061
R Squared	0.990
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-0.003712
Std Err of Coef.	0.0002676

5th Channel Run
Pump Flow= 15 gpm
Average Velocity = 0.073 fps
Water Temp. = 63 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1300	0	8.1	8.1	0	0
1545	165	7.65	7.80	0.15	0.174
730	1110	6.05	7.20	1.15	1.168
1340	1480	5.375	6.95	1.575	1.558

SOD Regression Output:

Constant	0
Std ErRegression Output	0.0219
R Squared	0.9992
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.001052
Std Err of Coef.	0.000011

BOD Regression Output:

Constant	8.012
Std Err of Y Est	0.093
R Squared	0.979
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-0.000727
Std Err of Coef.	0.0000747

6th Channel Run
Pump Flow= 20 gpm
Average Velocity = 0.103 fps
Water Temp. = 63 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1605	0	7.675	7.675	0	0
1900	175	7.23	7.60	0.37	0.360
1135	1170	4.69	7.15	2.47	2.404
1350	1305	4.35	6.975	2.625	2.681

SOD Regression Output:

Constant	0
Std ErRegression Output	0.0484
R Squared	0.9988
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.002054
Std Err of Coef.	0.000027

BOD Regression Output:

Constant	7.683
Std Err of Y Est	0.054
R Squared	0.983
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-0.000503
Std Err of Coef.	0.0000464

7th Channel Run
Pump Flow= 30 gpm
Average Velocity = 0.163 fps
Water Temp. = 64 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1400	0	7.35	7.35	0	0
1615	135	7.05	7.31	0.26	0.260
1100	1260	4.50	6.95	2.45	2.427
1300	1380	4.24	6.9	2.66	2.658

SOD Regression Output:	
Constant	0
Std ErRegression Output	0.1364
R Squared	0.9914
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.001926
Std Err of Coef.	0.000072

BOD Regression Output:	
Constant	7.351
Std Err of Y Est	0.006
R Squared	1.000
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-0.000322
Std Err of Coef.	0.0000044

8th Channel Run
Pump Flow= 10 gpm
Average Velocity = 0.043 fps
Water Temp. = 63 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1615	0	8.875	8.875	0	0
900	1005	6.26	7.19	0.93	0.917
2015	1680	5.40	6.925	1.52	1.533

SOD Regression Output:	
Constant	0
Std ErRegression Output	0.0108
R Squared	0.9998
No. of Observations	3
Degrees of Freedom	2
X Coefficient(s)	0.000912
Std Err of Coef.	0.000005

BOD Regression Output:	
Constant	8.738
Std Err of Y Est	0.421
R Squared	0.921
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	-0.001200
Std Err of Coef.	0.0003518

9th Channel Run
Pump Flow= 5 gpm
Average Velocity = 0.012 fps
Water Temp. = 64 F

Time	Elapsed Time (min.)	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression
1245	0	8.38	8.38	0	0
1605	200	8.00	8.19	0.19	0.131
2215	570	7.70	8.10	0.40	0.373
1410	1525	6.94	7.92	0.98	0.997

SOD Regression Output:	
Constant	0
Std ErRegression Output	0.0364
R Squared	0.9927
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.000653
Std Err of Coef.	0.000022

BOD Regression Output:	
Constant	8.296
Std Err of Y Est	0.079
R Squared	0.884
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-0.000262
Std Err of Coef.	0.0000671

10th Channel Run
Pump Flow= 20 gpm
Average Velocity = 0.103 fps
Water Temp. = 65 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
12:45	0	8.15	8.15	0	0	0
16:05	03:20	7.85	8.01	0.16	0.221	200
23:10	10:25	7.20	7.90	0.70	0.692	625
12:10	23:25	6.14	7.70	1.56	1.555	1405

SOD Regression Output:	
Constant	0
Std ErRegression Output	0.0359
R Squared	0.9974
No. of Observations	4
Degrees of Freedom	3
X Coefficient(s)	0.001106
Std Err of Coef.	0.000023

BOD Regression Output:	
Constant	8.107
Std Err of Y Est	0.044
R Squared	0.965
No. of Observations	4
Degrees of Freedom	2
X Coefficient(s)	-0.000299
Std Err of Coef.	0.0000404

11th Channel Run
Pump Flow= 15 gpm
Average Velocity = 0.073 fps
Water Temp. = 65 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
10:00	0	7.87	7.87	0	0	0
16:00	06:00	7.39	7.75	0.36	0.350	360
14:15	04:15	5.87	7.51	1.64	1.650	1695
16:10	06:10	5.74	7.51	1.765	1.762	1810

SOD Regression Output:		BOD Regression Output:	
Constant	0	Constant	7.848
Std ErRegression Output	0.0065	Std Err of Y Est	0.027
R Squared	0.9999	R Squared	0.986
No. of Observations	4	No. of Observations	4
Degrees of Freedom	3	Degrees of Freedom	2
X Coefficient(s)	0.000973	X Coefficient(s)	-0.000195
Std Err of Coef.	0.000002	Std Err of Coef.	0.0000166

12th Channel Run
Pump Flow= 45 gpm
Average Velocity = 0.254 fps
Water Temp. = 65 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
13:50	0	7.80	7.80	0	0	0
16:05	02:15	7.59	7.83	0.24	0.197	135
22:50	09:00	6.85	7.69	0.84	0.788	540
11:15	21:25	5.69	7.54	1.85	1.876	1285

SOD Regression Output:		BOD Regression Output:	
Constant	0	Constant	7.822
Std ErRegression Output	0.0399	Std Err of Y Est	0.029
R Squared	0.9977	R Squared	0.966
No. of Observations	4	No. of Observations	4
Degrees of Freedom	3	Degrees of Freedom	2
X Coefficient(s)	0.001459	X Coefficient(s)	-0.000220
Std Err of Coef.	0.000028	Std Err of Coef.	0.0000293

13th Channel Run

Pump Flow= 60 gpm
Average Velocity = 0.344 fps
Water Temp. = 65 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
15:05	0	7.63	7.63	0	0	0
22:30	07:25	6.85	7.57	0.72	0.737	445
11:00	19:55	5.32	7.31	1.98	1.979	1195

SOD Regression Output:	
Constant	0
Std ErRegression Output	0.0127
R Squared	0.9998
No. of Observations	3
Degrees of Freedom	2
X Coefficient(s)	0.001655
Std Err of Coef.	0.000009

BOD Regression Output:	
Constant	7.655
Std Err of Y Est	0.049
R Squared	0.959
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	-0.000280
Std Err of Coef.	0.0000577

14th Channel Run

Pump Flow= 30 gpm
Average Velocity = 0.163 fps
Water Temp. = 64.5 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
11:45	0	8.65	8.65	0.000	0	0
15:55	04:10	8.36			0.22	250
19:00	07:15	6.66	8.31	1.650	1.65	1875

SOD = 1.650/1875
= 0.00088

BOD = (8.31-8.65)/1875
= -0.0001

15th Channel Run
Pump Flow= 5 gpm
Average Velocity = 0.012 fps
Water Temp. = 64.5 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
20:45	0	8.22	8.22	0.000	0	0
11:30	14:45	7.56	8.00	0.435	0.421	885
16:15	19:30	7.43	7.97	0.545	0.556	1170

SOD Regression Output:		BOD Regression Output:	
Constant	0	Constant	8.215
Std Err of Y Est	0.0128	Std Err of Y Est	0.028
R Squared	0.9980	R Squared	0.979
No. of Observations	3	No. of Observations	3
Degrees of Freedom	2	Degrees of Freedom	1
X Coefficient(s)	0.000475	X Coefficient(s)	-0.000223
Std Err of Coef.	0.000008	Std Err of Coef.	0.0000325

16th Channel Run
Pump Flow= 10 gpm
Average Velocity = 0.043 fps
Water Temp. = 64 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
22:10	0	7.93	7.93	0	0	0
10:20	12:10	7.35	7.74	0.390	0.400	730
15:45	17:35	7.11	7.69	0.585	0.578	1055

SOD Regression Output:		BOD Regression Output:	
Constant	0	Constant	7.921
Std Err of Y Est	0.0086	Std Err of Y Est	0.018
R Squared	0.9992	R Squared	0.990
No. of Observations	3	No. of Observations	3
Degrees of Freedom	2	Degrees of Freedom	1
X Coefficient(s)	0.000547	X Coefficient(s)	-0.000227
Std Err of Coef.	0.000006	Std Err of Coef.	0.0000233

17th Channel Run

Pump Flow= 15 gpm
Average Velocity = 0.073 fps
Water Temp. = 64 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
18:10	0	7.65	7.65	0	0	0
12:45	18:35	6.86	7.46	0.598	0.632	1115
15:20	21:10	6.69	7.44	0.750	0.720	1270

SOD Regression Output:	
Constant	0
Std Err of Y Est	0.0320
R Squared	0.9935
No. of Observations	3
Degrees of Freedom	2
X Coefficient(s)	0.000567
Std Err of Coef.	0.000018

BOD Regression Output:	
Constant	7.653
Std Err of Y Est	0.008
R Squared	0.998
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	-0.000171
Std Err of Coef.	0.0000084

18th Channel Run

Pump Flow= 20 gpm
Average Velocity = 0.103 fps
Water Temp. = 64 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
14:30	0	8.50	8.50	0.000	0	0
11:10	20:40	7.41	8.27	0.857	0.883	1240
15:10	00:40	7.18	8.26	1.075	1.053	1480

SOD Regression Output:	
Constant	0
Std Err of Y Est	0.0239
R Squared	0.9982
No. of Observations	3
Degrees of Freedom	2
X Coefficient(s)	0.000711
Std Err of Coef.	0.000012

BOD Regression Output:	
Constant	8.494
Std Err of Y Est	0.018
R Squared	0.991
No. of Observations	3
Degrees of Freedom	1
X Coefficient(s)	-0.000169
Std Err of Coef.	0.0000163

19th Channel Run
Pump Flow= 30 gpm
Average Velocity = 0.163 fps
Water Temp. = 65 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
16:25	0	7.86	7.86	0.000	0	0
14:00	21:35	6.64	7.70	1.057	1.039	1295
18:05	01:40	6.47	7.69	1.220	1.235	1540

SOD Regression Output:		BOD Regression Output:	
Constant	0	Constant	7.858
Std Err of Y Est	0.0166	Std Err of Y Est	0.013
R Squared	0.9994	R Squared	0.991
No. of Observations	3	No. of Observations	3
Degrees of Freedom	2	Degrees of Freedom	1
X Coefficient(s)	0.000802	X Coefficient(s)	-0.000114
Std Err of Coef.	0.000008	Std Err of Coef.	0.0000110

20th Channel Run
Pump Flow= 45 gpm
Average Velocity = 0.254 fps
Water Temp. = 65 F

Time	Time Chng.	Channel DO Level	BOD Bottle DO Level	SOD as BOD - DO chng	SOD Calc'd From Regression	Delta t (min)
18:50	0	7.74	7.74	0.000	0	0
09:50	15:00	6.41	7.61	1.200	1.147	900
18:55	00:05	5.80	7.61	1.808	1.841	1445

SOD Regression Output:		BOD Regression Output:	
Constant	0	Constant	7.723
Std Err of Y Est	0.0442	Std Err of Y Est	0.038
R Squared	0.9977	R Squared	0.868
No. of Observations	3	No. of Observations	3
Degrees of Freedom	2	Degrees of Freedom	1
X Coefficient(s)	0.001274	X Coefficient(s)	-0.000095
Std Err of Coef.	0.000025	Std Err of Coef.	0.0000371

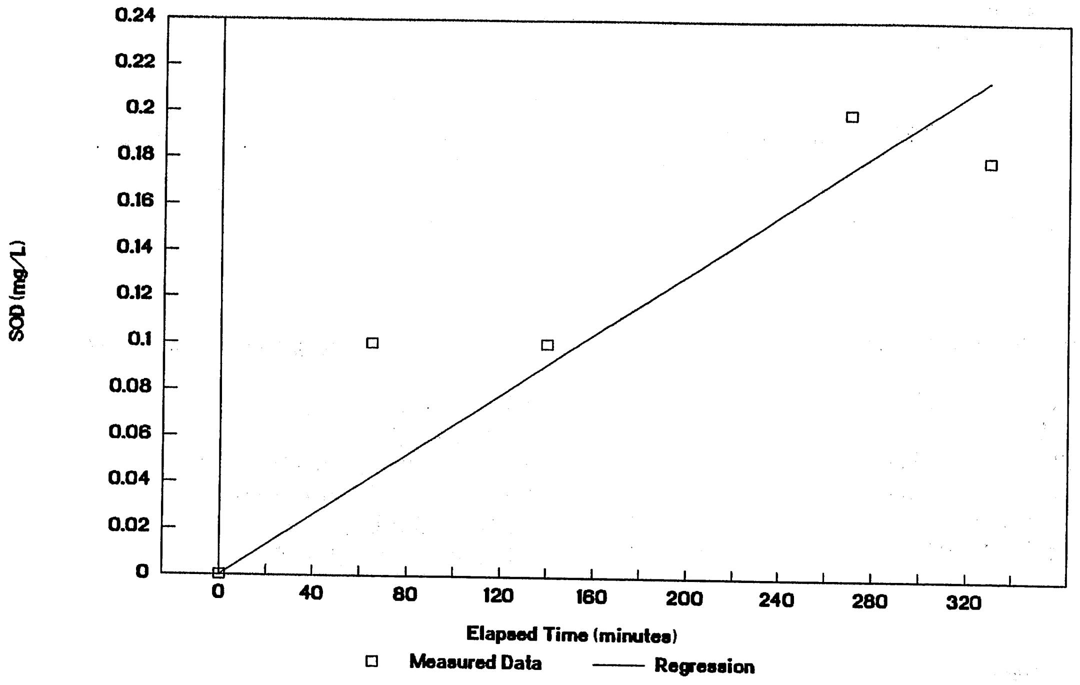

Fig. F–1 Sediment oxygen utilization, 1st Experimental Run, 15 gpm pump flow.

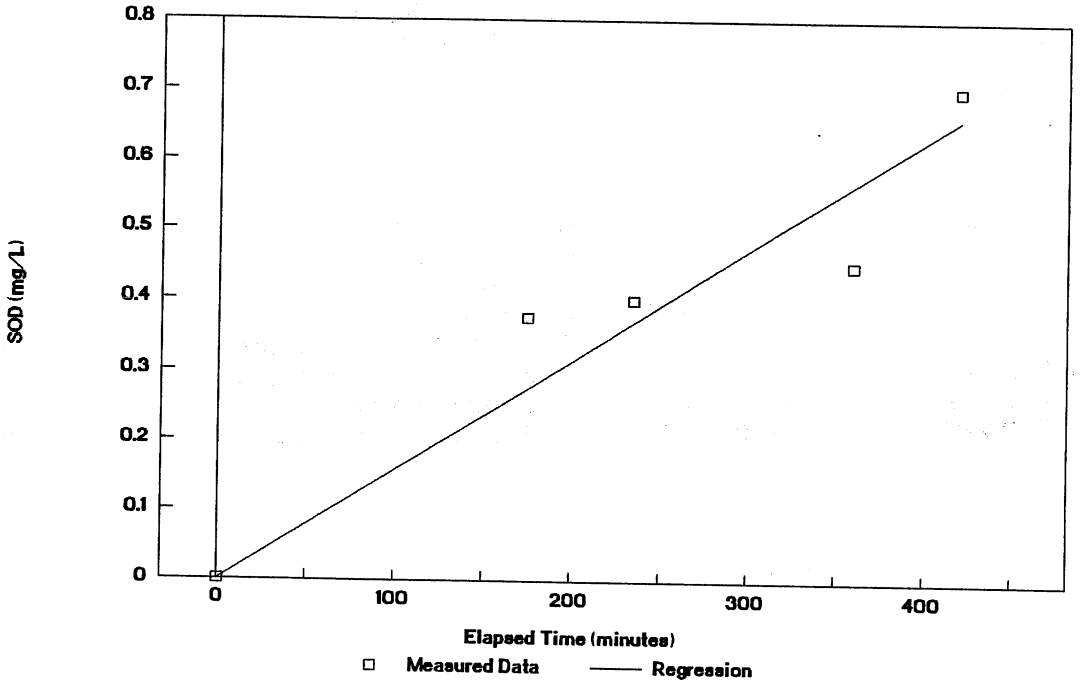

Fig. F–2 Sediment oxygen utilization, 2nd Experimental Run, 30 gpm pump flow.

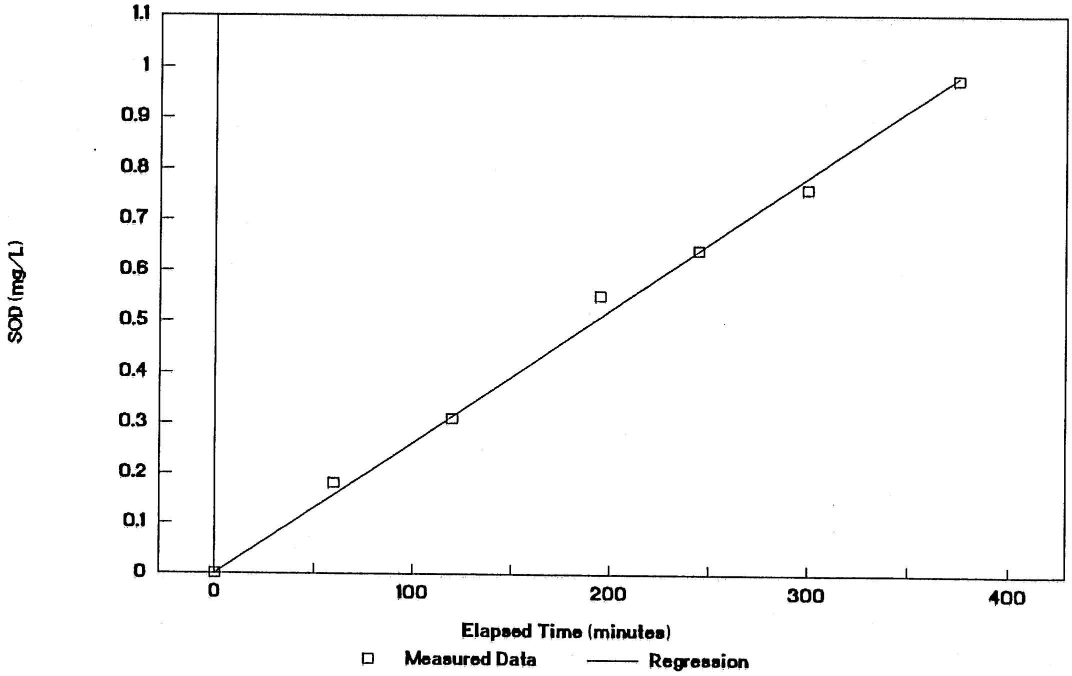

Fig. F–3 Sediment oxygen utilization, 3rd Experimental Run, 45 gpm pump flow.

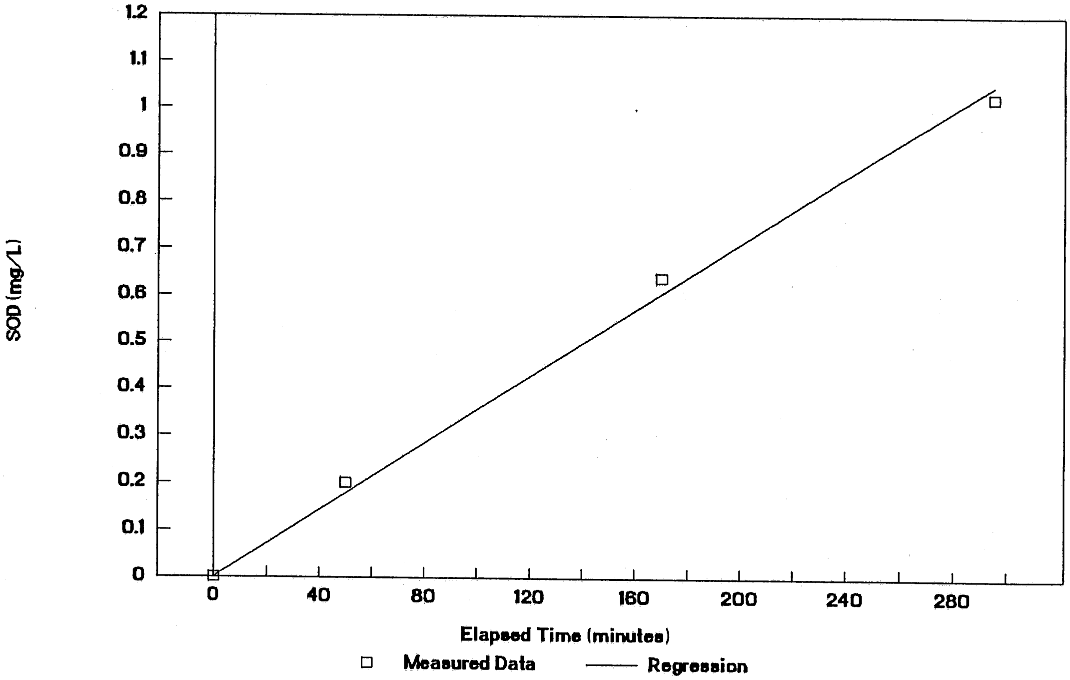

Fig. F–4 Sediment oxygen utilization, 4th Experimental Run, 60 gpm pump flow.

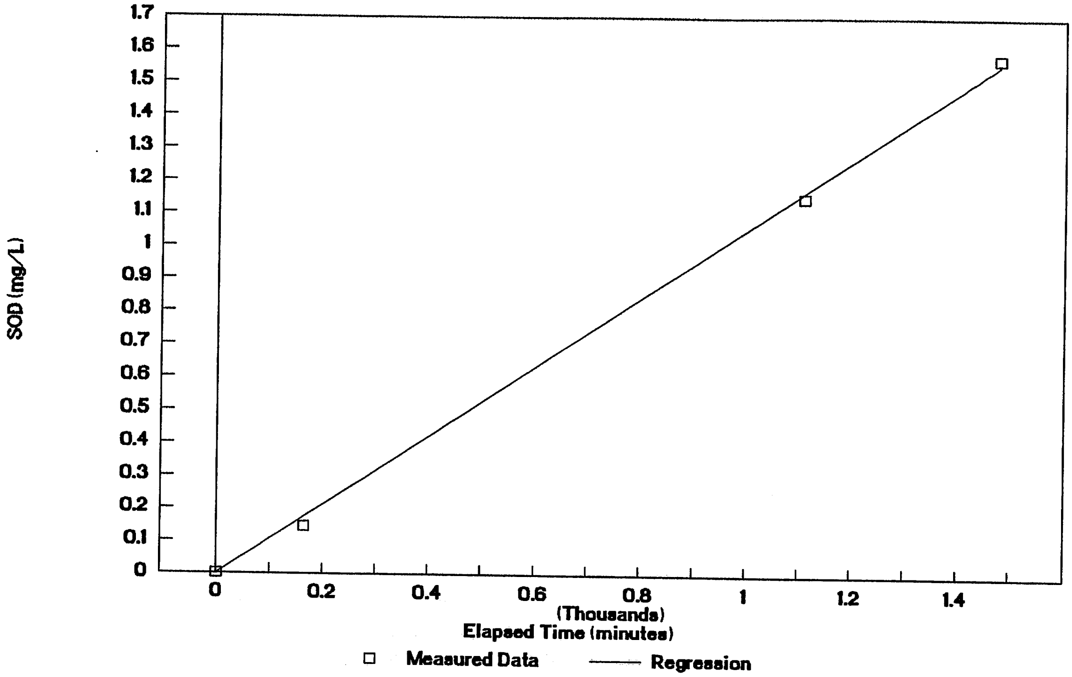

Fig. F–5 Sediment oxygen utilization, 5th Experimental Run, 15 gpm pump flow.

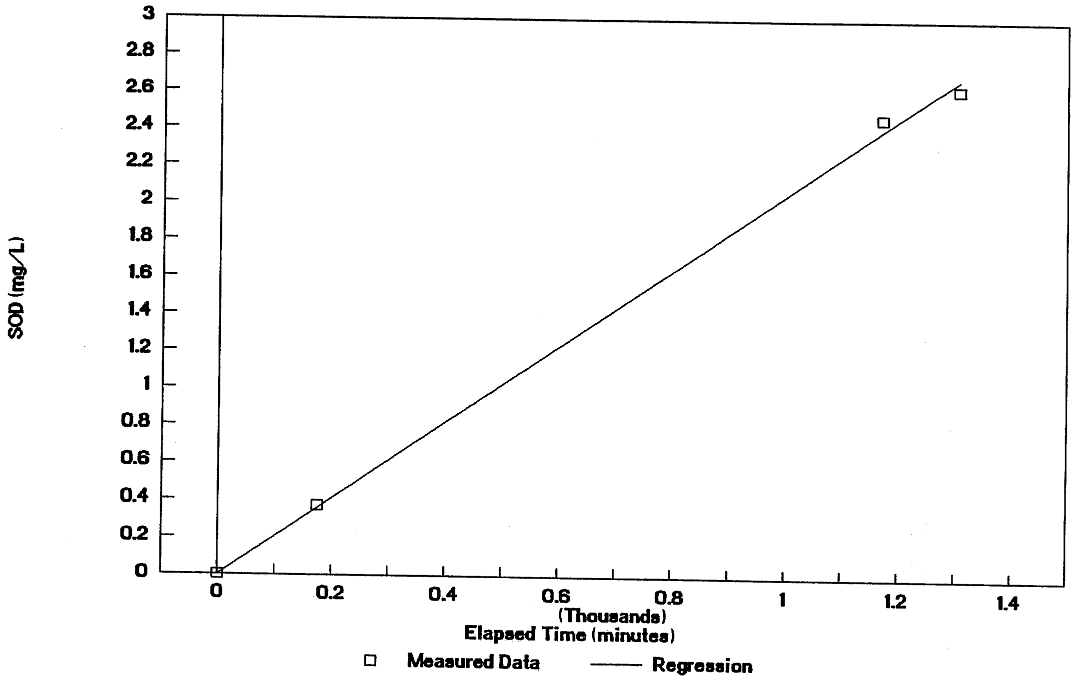

Fig. F–6 Sediment oxygen utilization, 6th Experimental Run, 20 gpm pump flow.

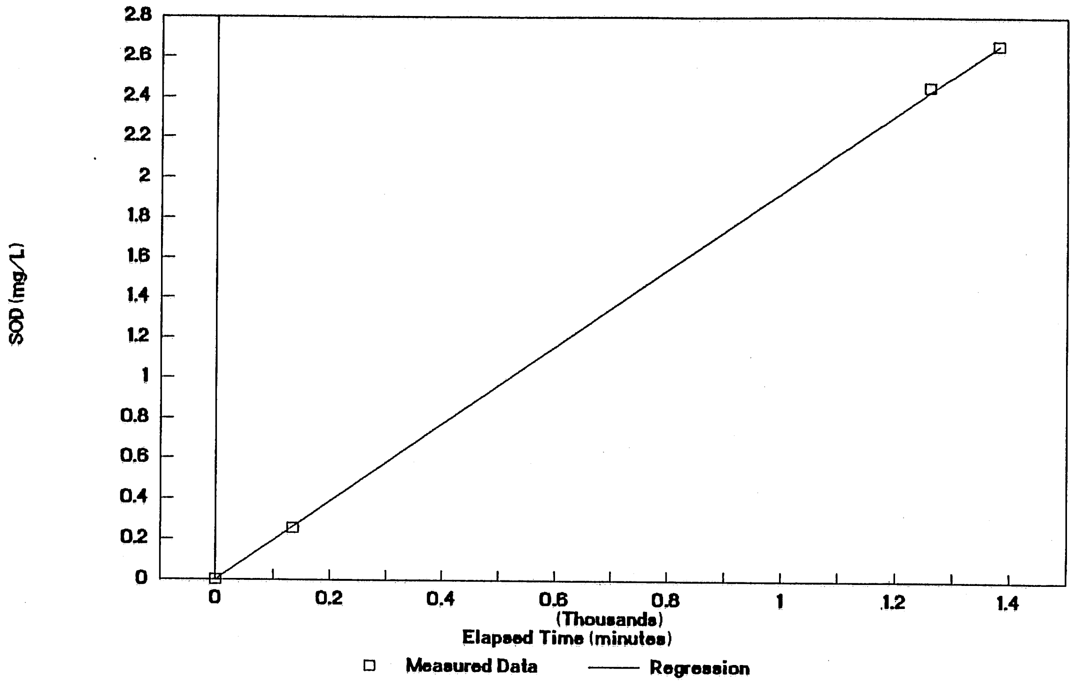

Fig. F–7 Sediment oxygen utilization, 7th Experimental Run, 30 gpm pump flow.

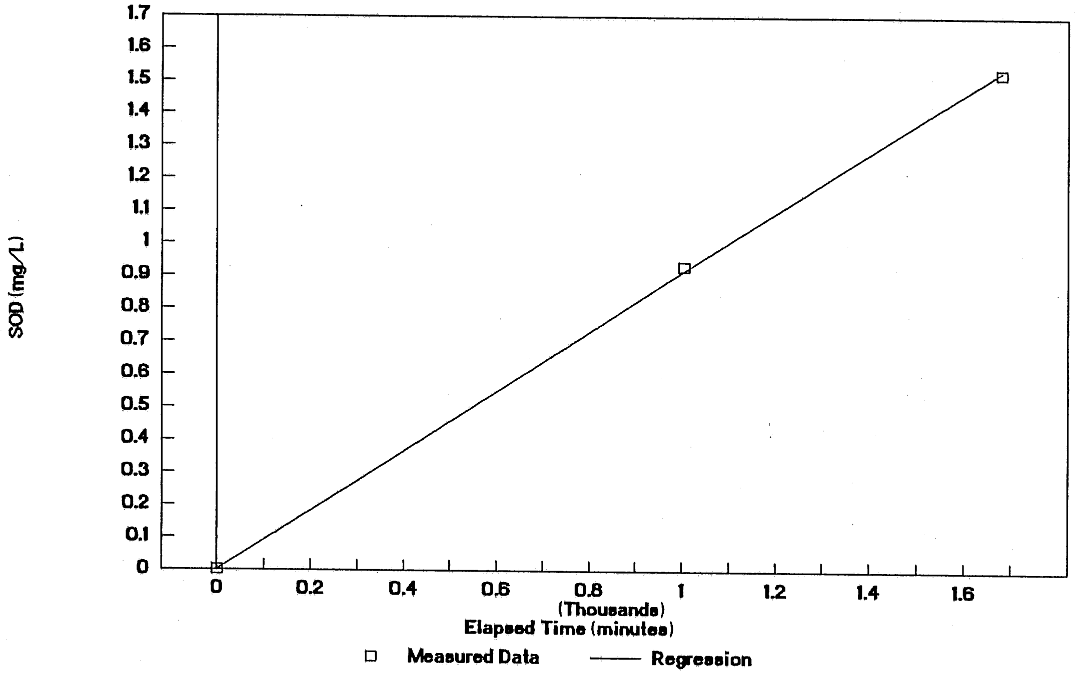

Fig. F–8 Sediment oxygen utilization, 8th Experimental Run, 10 gpm pump flow.

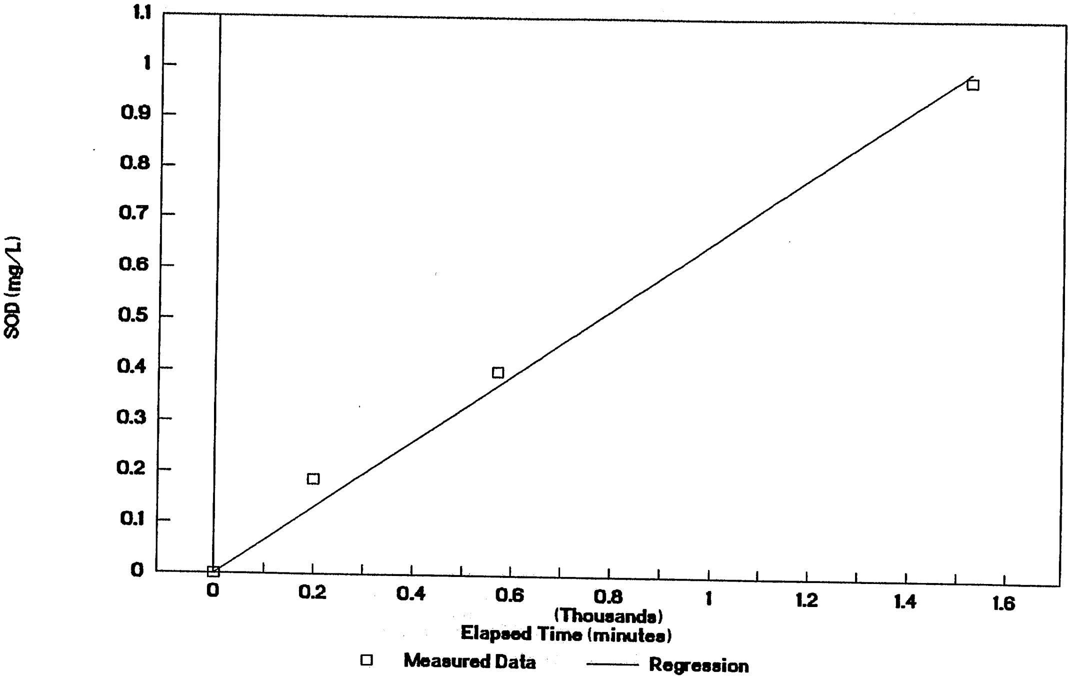

Fig. F–9 Sediment oxygen utilization, 9th Experimental Run, 5 gpm pump flow.

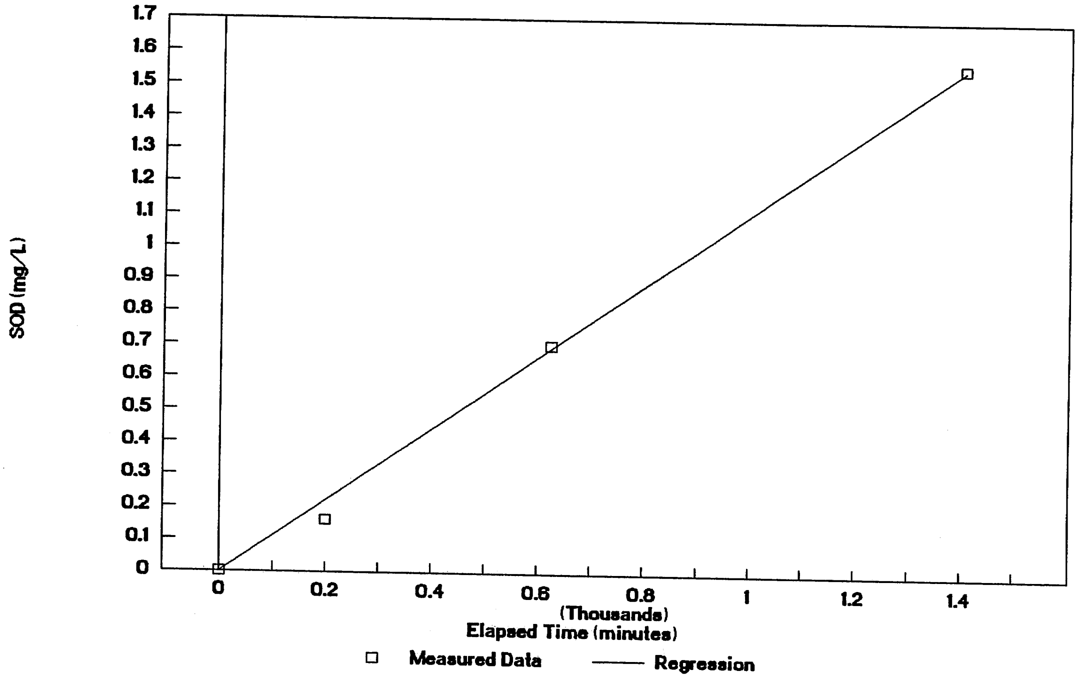

Fig. F–10 Sediment oxygen utilization, 10th Experimental Run, 20 gpm pump flow.

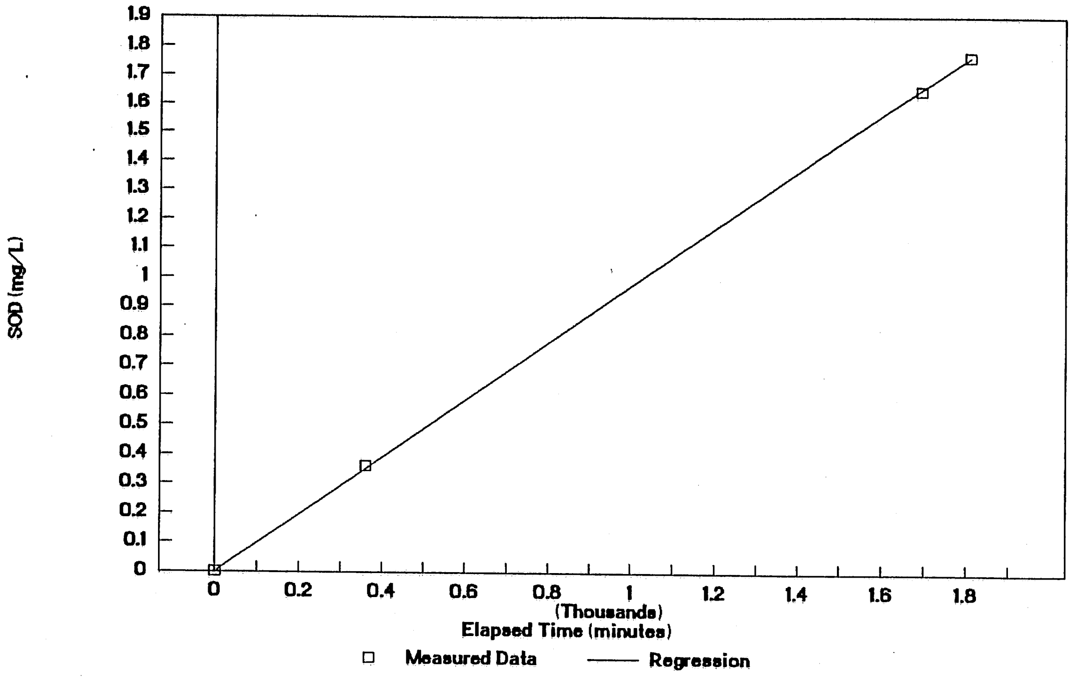

Fig. F–11 Sediment oxygen utilization, 11th Experimental Run, 15 gpm pump flow.

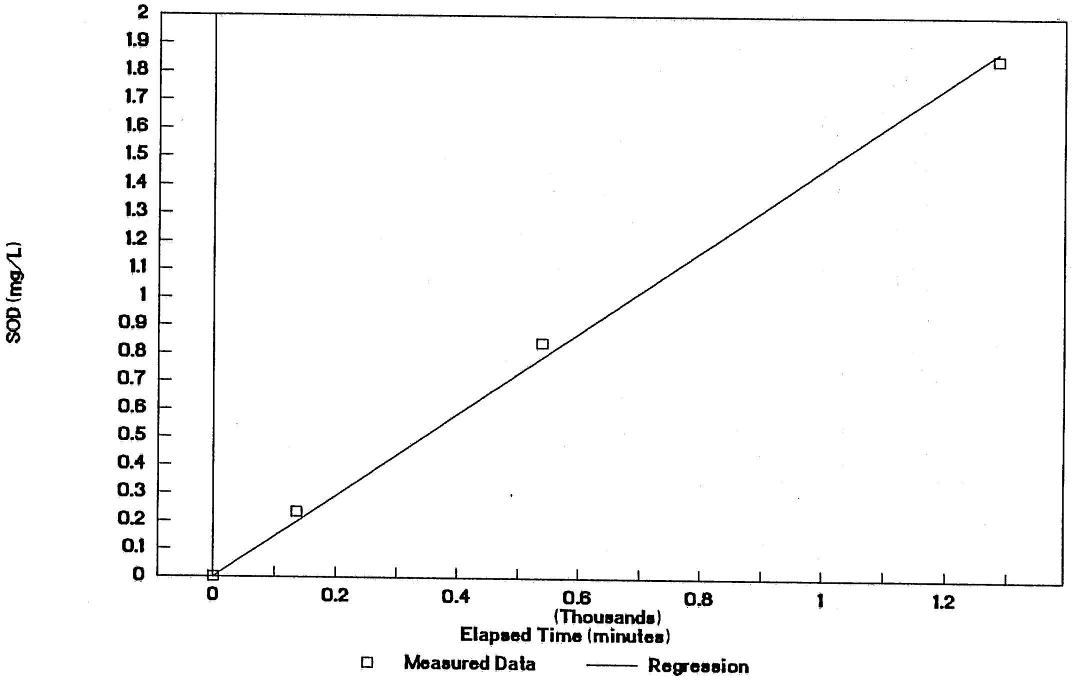

Fig. F–12 Sediment oxygen utilization, 12th Experimental Run, 45 gpm pump flow.

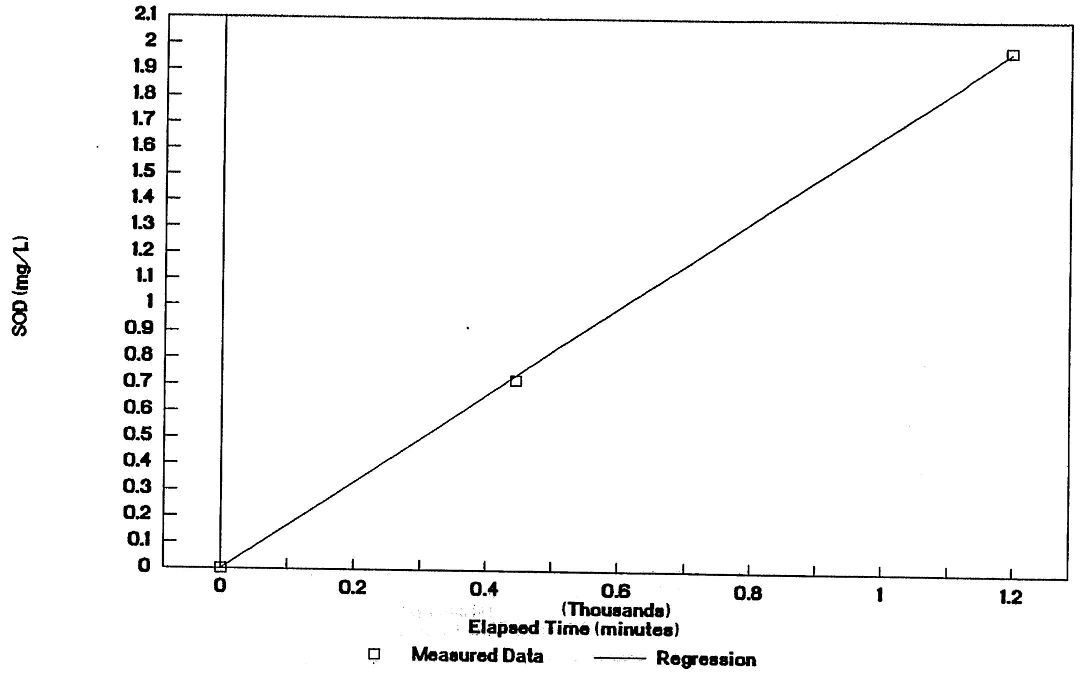

Fig. F–13 Sediment oxygen utilization, 13th Experimental Run, 60 gpm pump flow.

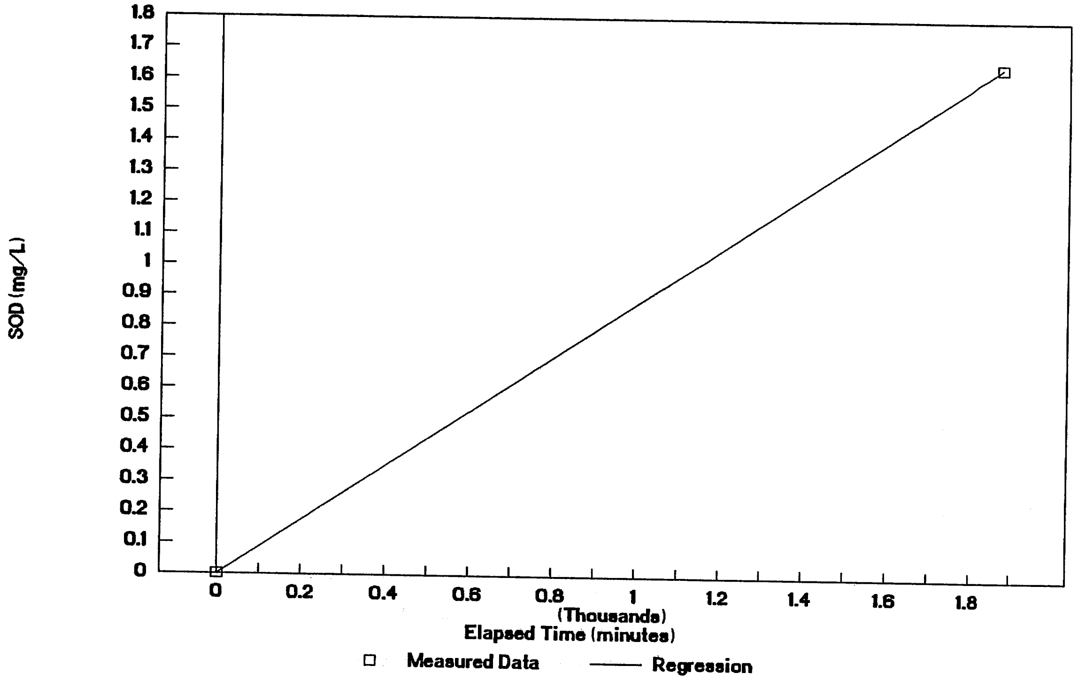

Fig. F–14 Sediment oxygen utilization, 14th Experimental Run, 30 gpm pump flow.

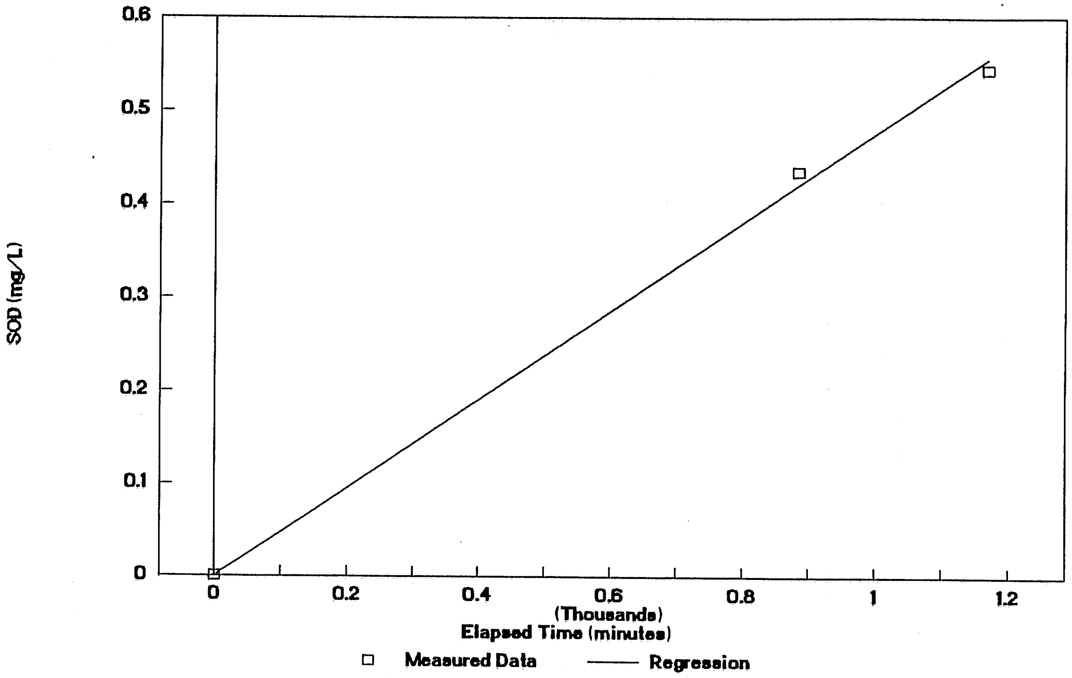

Fig. F–15 Sediment oxygen utilization, 15th Experimental Run, 5 gpm pump flow.

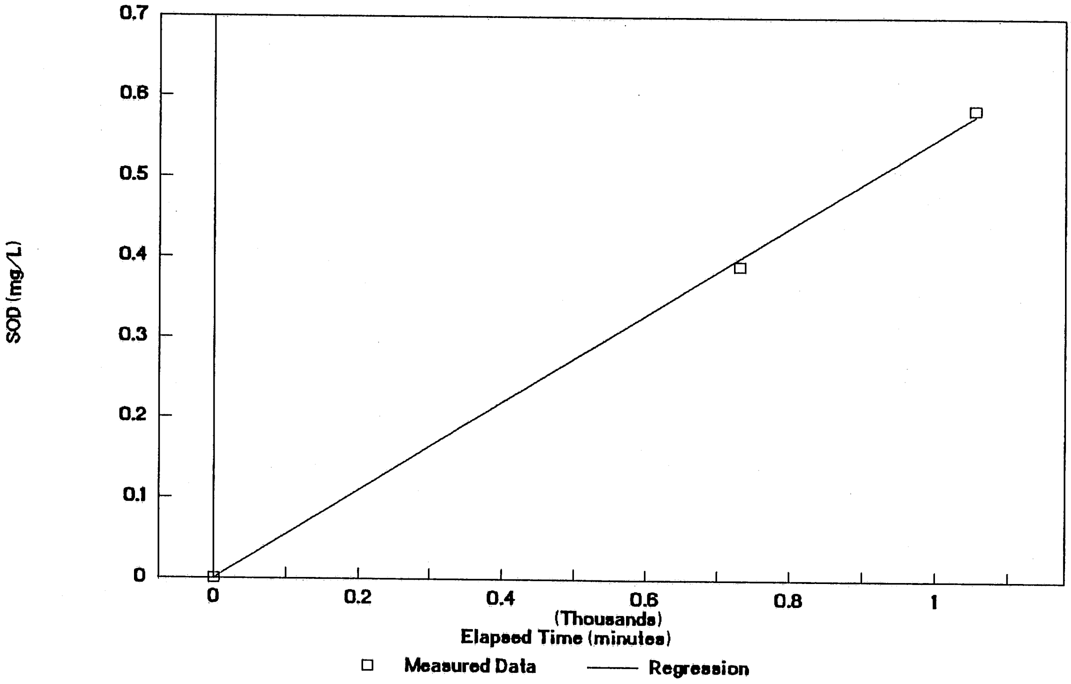

Fig. F–16 Sediment oxygen utilization, 16th Experimental Run, 10 gpm pump flow.

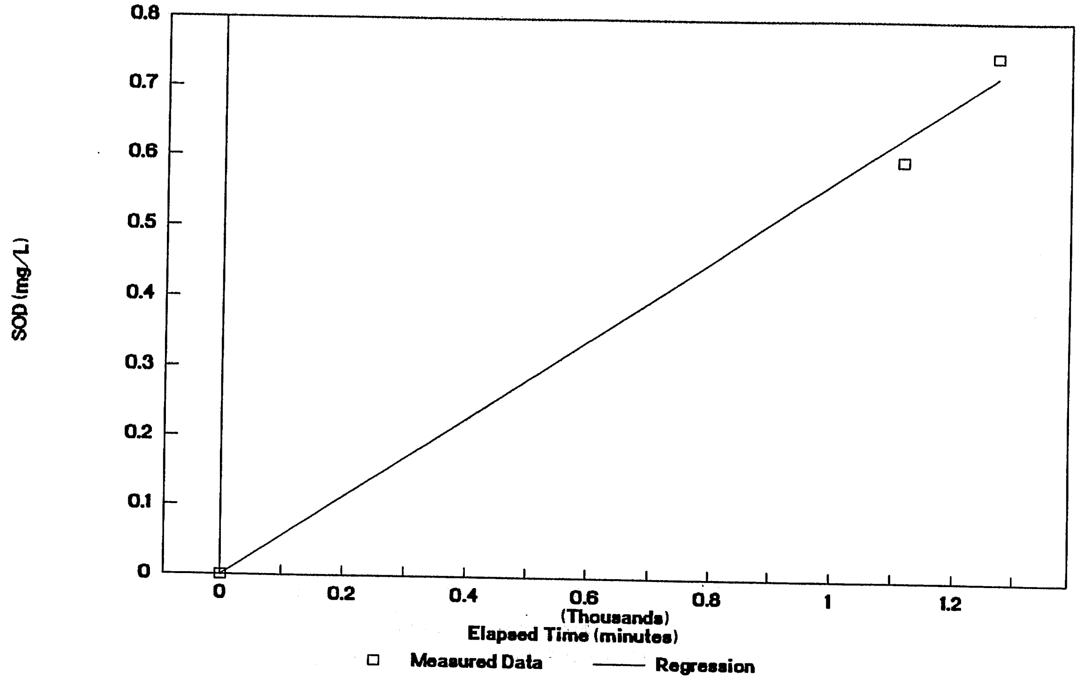

Fig. F–17 Sediment oxygen utilization, 17th Experimental Run, 15 gpm pump flow.

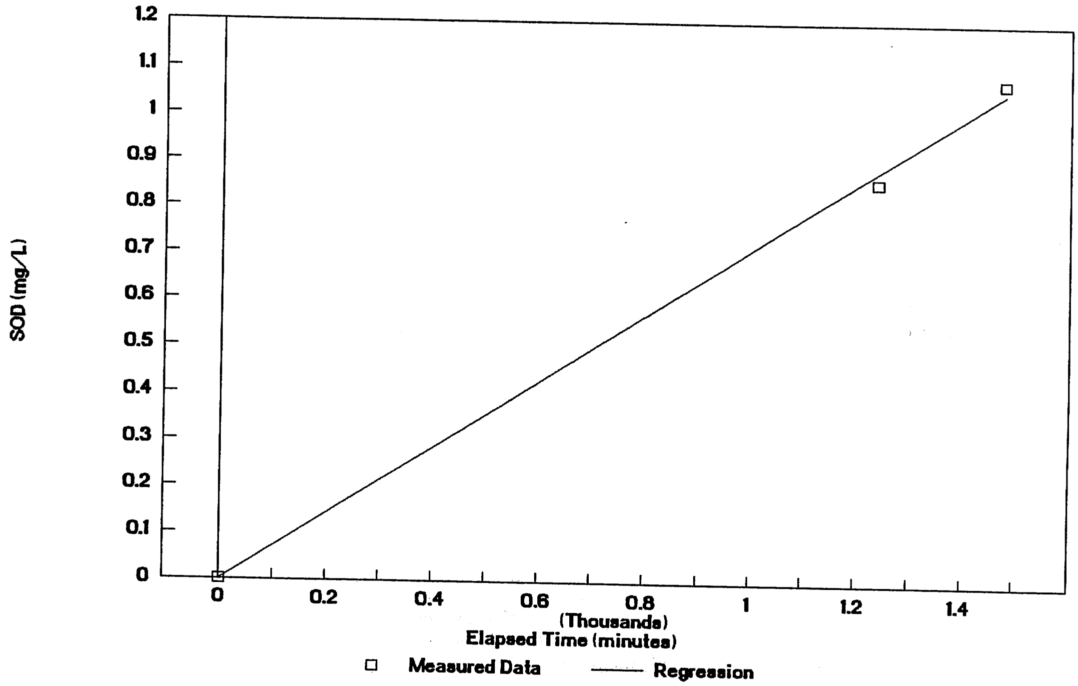

Fig. F–18 Sediment oxygen utilization, 18th Experimental Run, 20 gpm pump flow.

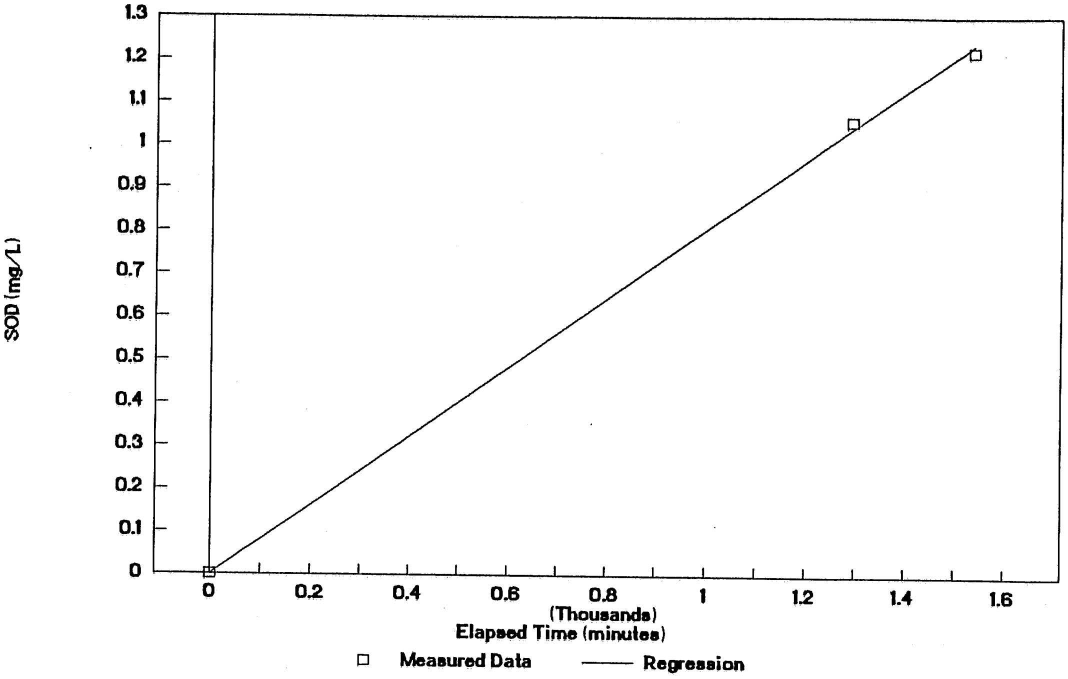

Fig. F–19 Sediment oxygen utilization, 19th Experimental Run, 30 gpm pump flow.

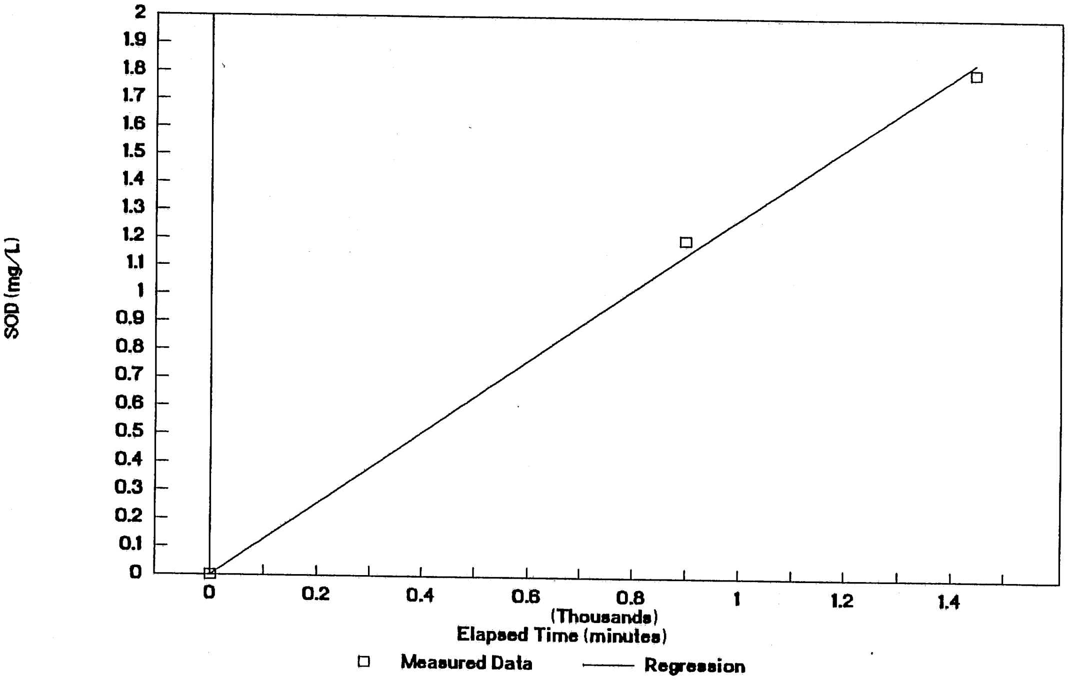

Fig. F–20 Sediment oxygen utilization, 20th Experimental Run, 45 gpm pump flow.

Table F-1,
Average Velocity, Vavg (cm/s) vs.
Temp. Corr. SOD (g 02/m^2*day)

```
Runs 1-4
        Regression Output:
Constant                         -0.352
Std Err of Y Est                  0.058
R Squared                         0.999
No. of Observations                   4
Degrees of Freedom                    2

X Coefficient(s)       0.569
Std Err of Coef.       0.009

Runs 5 - 11
        Regression Output:
Constant                          0.721
Std Err of Y Est                  0.580
R Squared                         0.631
No. of Observations                   7
Degrees of Freedom                    5

X Coefficient(s)       0.462
Std Err of Coef.       0.158

Runs 13 - 20
        Regression Output:
Constant                          0.557
Std Err of Y Est                  0.120
R Squared                         0.967
No. of Observations                   8
Degrees of Freedom                    6

X Coefficient(s)       0.176
Std Err of Coef.       0.013
```

Table F-2,
Average Max. Velocity, Vc (cm/s)
vs. Temp. Corr. SOD (g 02/m^2*day)

```
Runs 1-4
        Regression Output:
Constant                         -0.329
Std Err of Y Est                  0.058
R Squared                         0.999
No. of Observations                   4
Degrees of Freedom                    2

X Coefficient(s)       0.473
Std Err of Coef.      0.0077

Runs 5 - 11
        Regression Output:
Constant                          0.740
Std Err of Y Est                  0.580
R Squared                         0.631
No. of Observations                   7
Degrees of Freedom                    5

X Coefficient(s)       0.384
Std Err of Coef.       0.131

Runs 13 - 20
        Regression Output:
Constant                          0.531
Std Err of Y Est                  0.120
R Squared                         0.967
No. of Observations                   8
Degrees of Freedom                    6

X Coefficient(s)       0.144
Std Err of Coef.       0.011
```

Table F-3,
Shear Velocity, V* (cm/s) vs.
Temp. Corr. SOD (g 02/m^2*day)

```
Runs 1-4
        Regression Output:
Constant                        0.152
Std Err of Y Est                0.202
R Squared                       0.994
No. of Observations                 4
Degrees of Freedom                  2

X Coefficient(s)     5.45
Std Err of Coef.     0.31
```

```
Runs 5 - 11
        Regression Output:
Constant                        0.589
Std Err of Y Est                0.593
R Squared                       0.613
No. of Observations                 7
Degrees of Freedom                  5

X Coefficient(s)     6.34
Std Err of Coef.     2.25
```

```
Runs 13 - 20
        Regression Output:
Constant                        0.589
Std Err of Y Est                0.062
R Squared                       0.991
No. of Observations                 8
Degrees of Freedom                  6

X Coefficient(s)    1.817
Std Err of Coef.    0.070
```