University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 231

# NEARFIELD WATER QUALITY OF THE METRO WWTP EFFLUENT MIXING ZONE IN THE MISSISSIPPI RIVER UNDER SUMMER CONDITIONS

by

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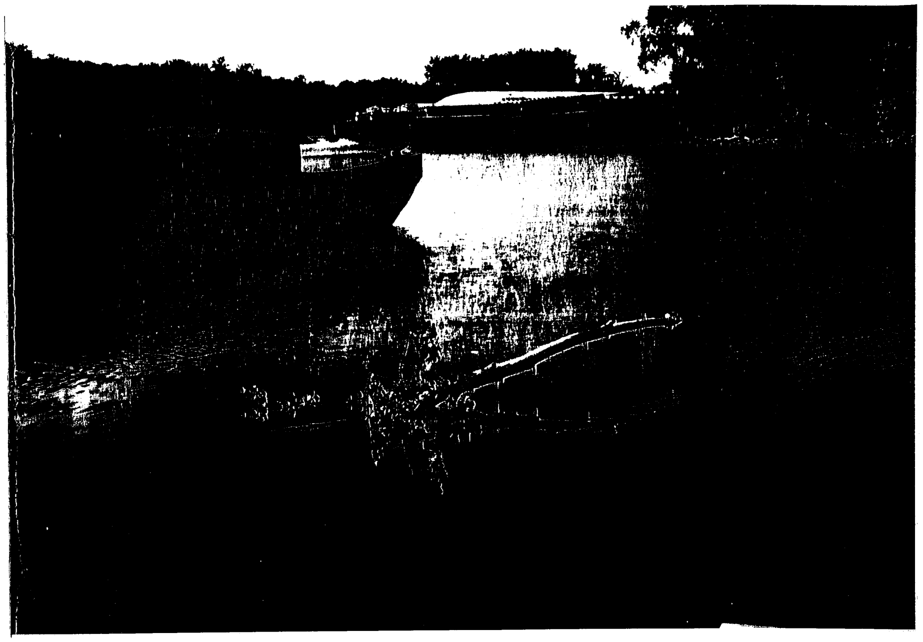
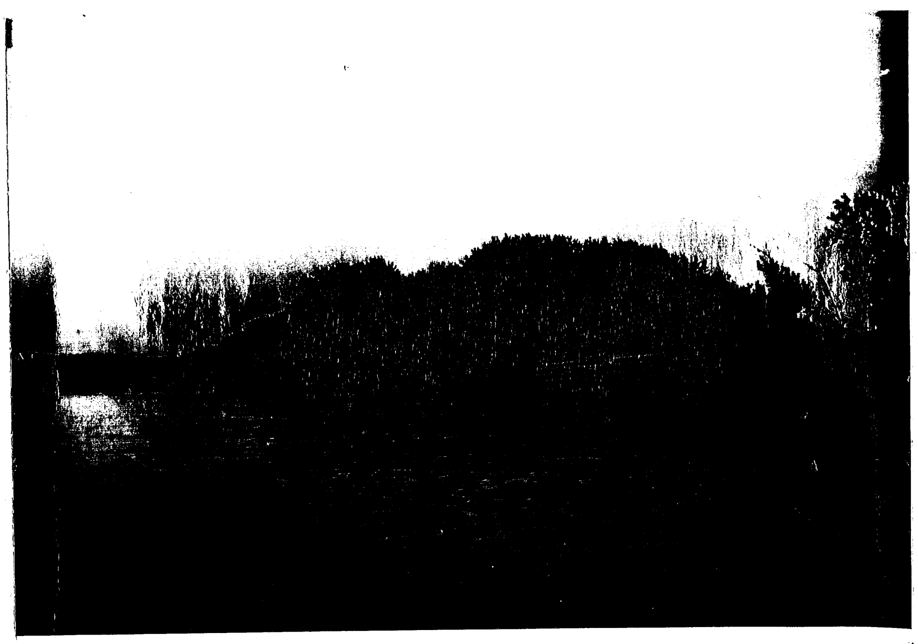


View from south to north across the mouth of the Metro WWTP effluent channel. Moored barges in foreground, towboat moving upstream in background.



View from south to north along bank of the Mississippi River. Metro WWTP effluent channel enters from right behind moored barges in foreground.

View from the Metro WWTP outlet channel towards the Mississippi River. Barges are moored along the left bank of the river.

View of the Metro WWTP discharge channel from the Mississippi River. Debris accumulation near plunging region of the effluent.

## ABSTRACT

Since 1982 the flow and dilution processes in the vicinity of the Metro Waste Water Treatment Plant outlet into the Mississippi River have been under investigation. An earlier report (St. Anthony Falls Hydraulic Laboratory Project Report No. 214) focused on the main features of the flow processes which cause the mixing of the effluent with the river water; it also provided some theoretical background for their analysis. This report describes in more detail the features of flow and mixing in the nearfield which have been observed under summer conditions: the plunging of the effluent at the end of the discharge canal and the transverse spreading of the effluent across the river as an underflow. Field data are analyzed to quantify the length of the nearfield and the dilution of the effluent. It is then shown how with this information an estimate of the entire mixing zone length can be made.

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ACKNOWLEDGEMENTS

The field data used in this report were collected and analyzed with the help of staff from the Metropolitan Waste Control Commission, particularly Mr. Garry Durland. Assistance for data collection and drafting was provided by Michael Roach and Alan Rindells.

# I. MIXING PROCESSES

A side channel discharge such as that from the Metro Wastewater Treatment Plant (WWTP) into the Mississippi River interacts with the river flow in several ways before the two become fully mixed. Among the flow and mixing processes generally to be considered are:

(a) Jet effects due to the momentum of the discharge.

(b) Lateral displacement of river flow by the effluent input. Conservation of mass requires that the streamlines in the river are displaced towards the center to make room for the effluent flow rate in the river.

(c) Downstream advection by the river flow.

(d) Transverse turbulent mixing due to bed shear and secondary flow in the river.

(e) Buoyant spreading caused by the density difference between effluent water and river water. The density depends on water temperature and total solids content.

(f) Vertical turbulent mixing by the river due to bed shear.

(g) Mixing by tug boats and barge traffic.

Effluent models are usually subdivided into a NEARFIELD and a FARFIELD. In the nearfield the mixing and dilution are influenced by effluent conditions including jet effects, buoyant or plunging plumes, and lateral displacement of the river. In the farfield, the mixing is passive and imposed by the river geometry, roughness and advection. Mixing by towboat and barge passages affects both the nearfield and farfield mixing.

In the summer of 1982 it was established that the effluent mixing zone with the Mississippi River shows a seasonally strong variable behavior. The effluent is warmer than the river for most of the year, resulting in a lower density buoyant plume. During the summer, the situation reverses as the river warms and the effluent becomes a plunging plume and enters the Mississippi River as an underflow. In both cases, the river develops a vertically stratified flow which becomes fully mixed by turbulence induced by bed shear, secondary currents, and towboat traffic. Complete vertical mixing due to turbulent shear is dependent on the flow rate. For flow rates less than 5000 cfs, the stratified flow condition may extend several miles downstream from the discharge site. Barges were found to have a considerable effect on the vertical mixing of the stratified river reach and are the most significant source of vertical mixing for flow rate less than 5000 cfs (Riley and Stefan, 1984).

Since the last report (Stefan, 1982) additional information for the illustration and prediction of the effluent flow and mixing has become available and has been analyzed.

(1) The river geometry in the vicinity of the outfall has been measured (St. Anthony Falls Hydraulic Laboratory, External Memorandum No. 184) using a recording echosounder. Contour lines at 2 ft intervals are shown in Fig. I-1.

(2) Aerial photographs of the Metro WWTP outfall taken on four different dates have been located and examined. The Metro WWTP effluent is visible on the water surface over a short distance on all four pictures. The four observed spring or fall conditions are shown in Fig. I-2. The differences are noticeable and attributed mostly to differences in effluent buoyancy and river flow. The strength of the buoyancy has been expressed by an outlet densimetric Froude number. All four cases are for weak buoyancy and not representative for midsummer conditions.

(3) The buoyancy of the effluent is dependent on temperature and total solids (mostly dissolved solids) in the effluent and the river. The seasonal temperature variation for the year 1975 is shown in Fig. I-3.

(4) Water quality measurements in the Mississippi River below the Metro WWTP outfall are affected by the effluent flow rate and river flow rates, both of which can be highly variable in time. This is illustrated in Fig. I-4.

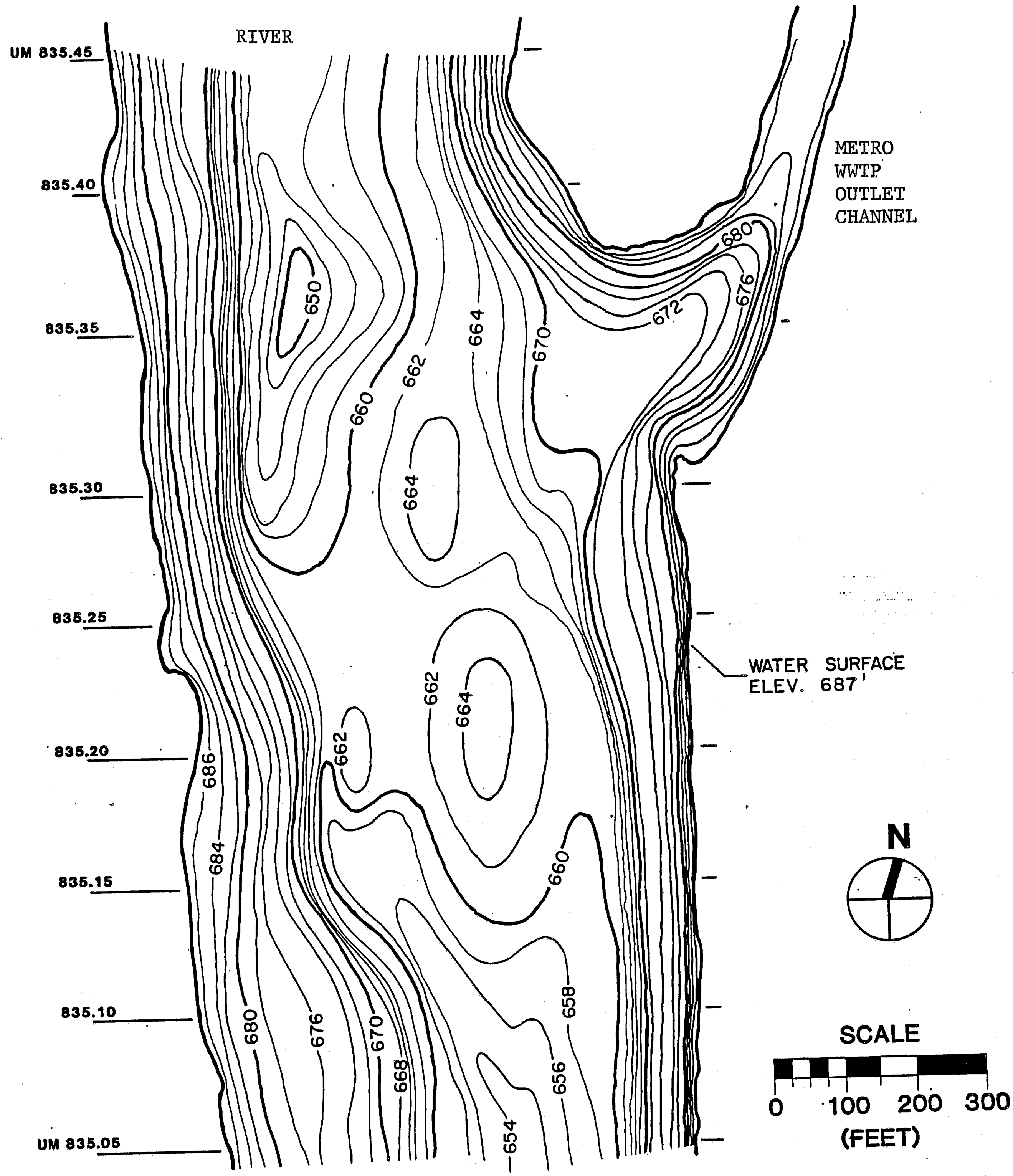
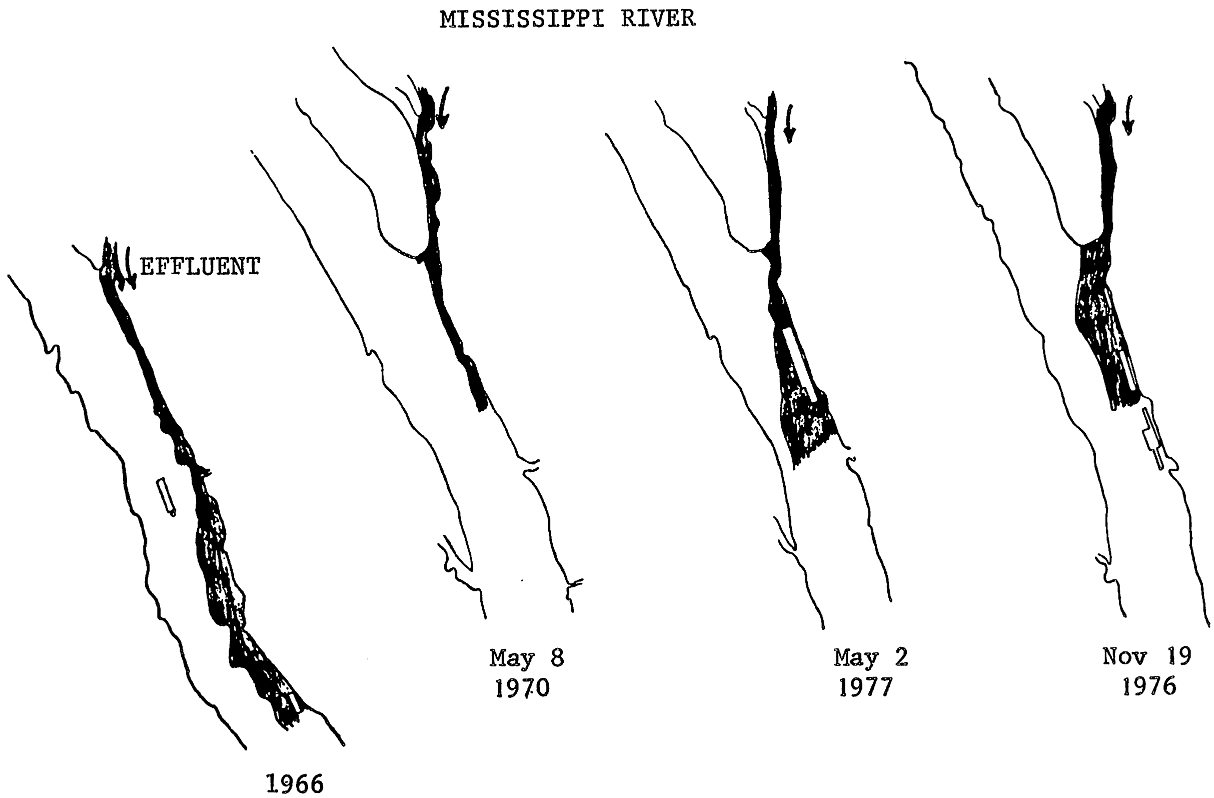



Fig. I-1. Estimated contours of the river channel in the vicinity of the Metro WWTP outlet.




| | May 8, 1970 | May 2, 1977 | Nov. 19, 1976 |
|---|---|---|---|
| Effluent densimetric Froude number | .042 Sinking | (0.109) Floating | 0.32 Sinking |
| Plant discharge divided by river flow rate | 0.014 | 0.24 | 0.063 |

Fig. I-2. Metro WWTP effluent plume configuration at the water surface on four observation dates.

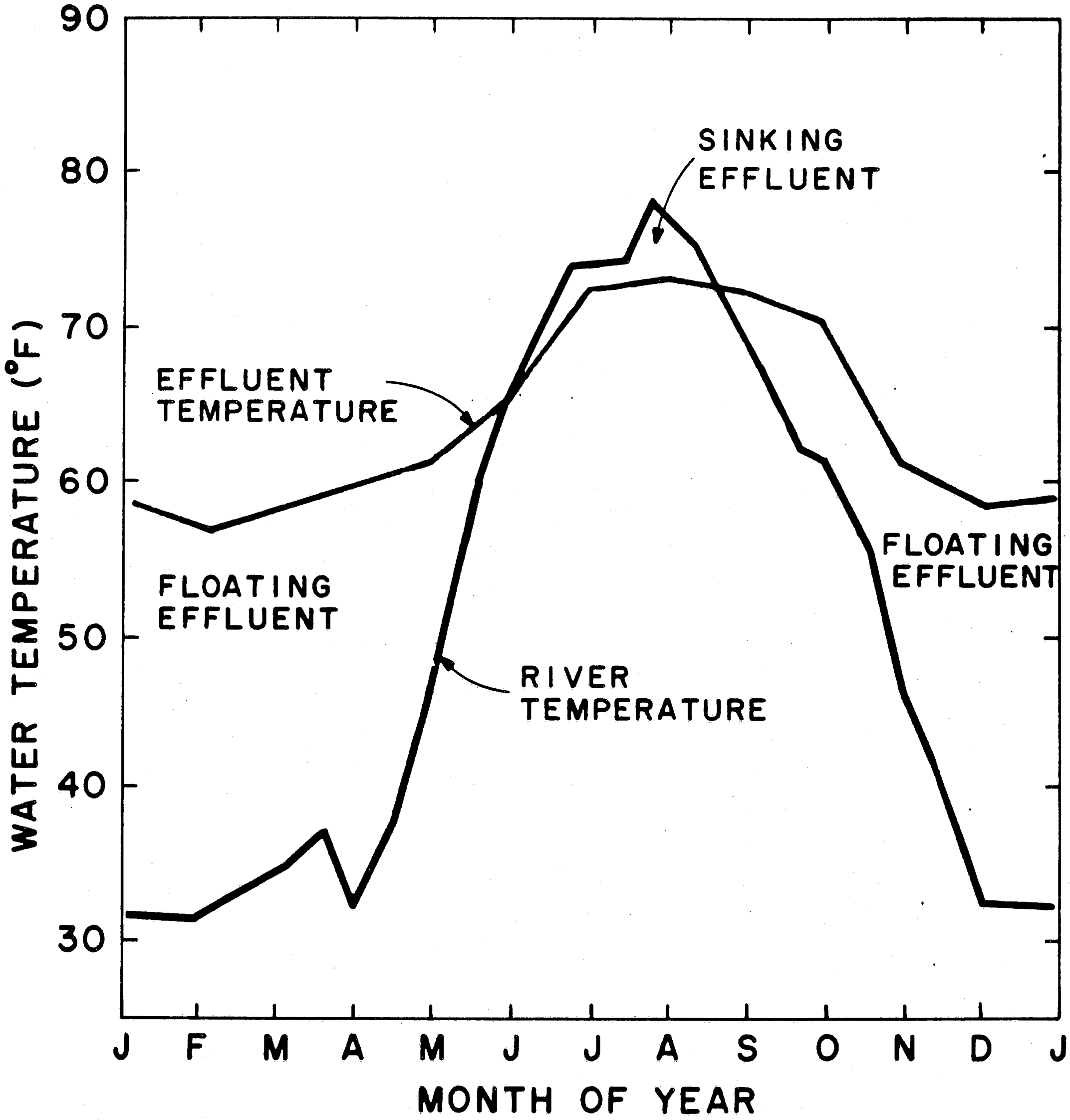



Fig. I-3. Approximate seasonal variation of the Mississippi River and the Metro WWTP effluent water temperatures in 1975.

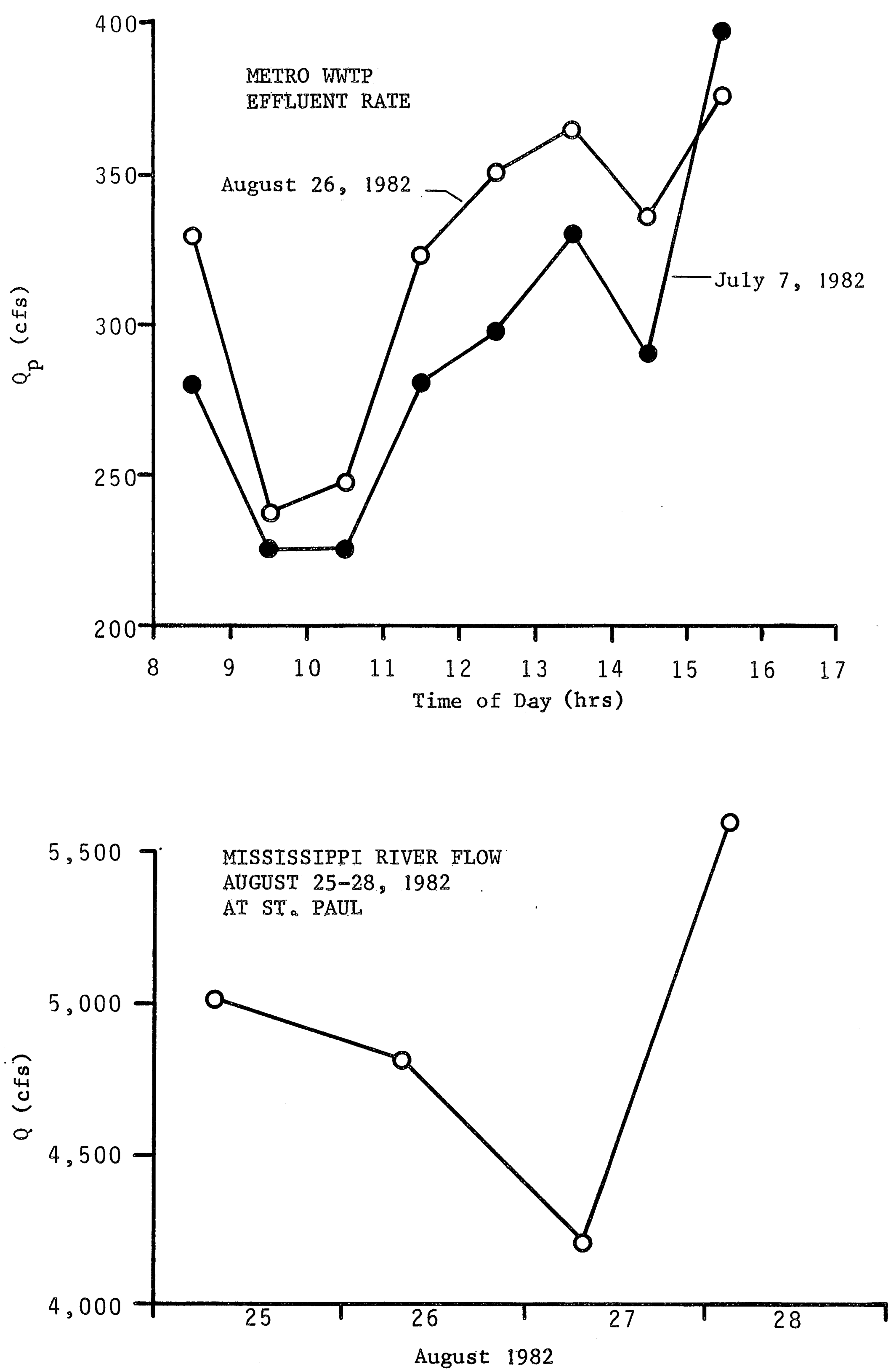



Fig. I-4. Time variability of plant and river flow rates.

## II. NEARFIELD MIXING ZONE MODEL CONCEPT

Under typical midsummer conditions the Metro WWTP effluent behaves as schematically shown in Fig. II-1. Within the confines of the discharge channel and before reaching the river, the effluent plunges (dives) beneath the river water because it is slightly heavier due to colder temperature and higher dissolved solid content. It spreads as a subsurface (underflow) current across the river until a hydrostatic equilibrium is reached. The flow continues downstream as a weakly stratified flow. Vertical mixing is then produced by turbulence generated by bed shear, wind, or tow boat (barge) traffic.

The mixing (dilution) of the effluent is progressive. From the outlet channel to the end of the nearfield the effluent flow rate increases from $Q_p$ to $Q_n$ by entrainment of ambient (river) water.

$$Q_n = Q_p(1 + \gamma_p)(1 + \gamma_u)$$

where $\gamma_p$ = entrainment rate coefficient of the plunging flow

$\gamma_u$ = entrainment rate coefficient of the transverse underflow

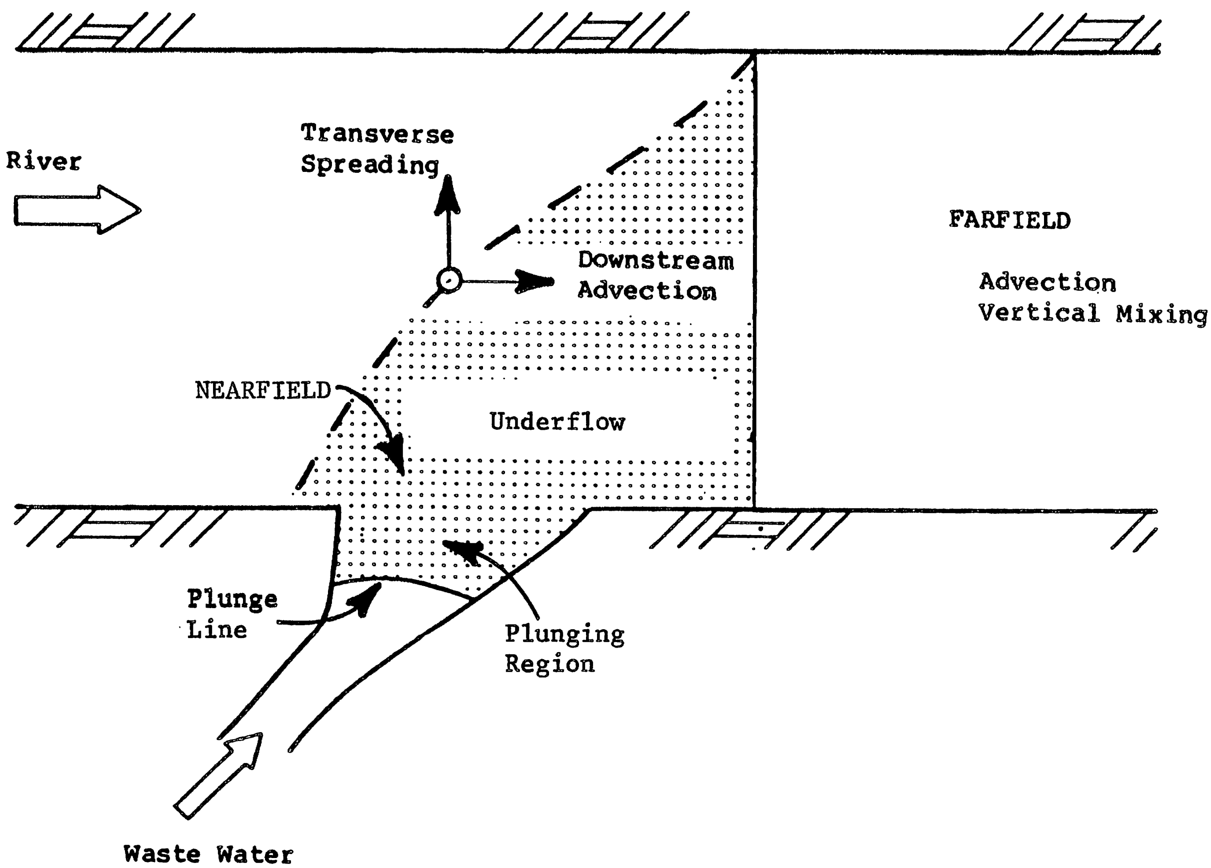



Fig. II-1. Schematic diagram of the nearfield mixing zone of a plunging effluent and transverse spreading underflow.

## III. PLUNGING FLOW

Very little information exists about the dilution rate at plunging. Field measurements and laboratory experiments are used to determine $\gamma_p$. In general, dilution of a flow can be determined from measurements of concentration of an effluent tracer C(x,y,z) and flow velocities u(x,y,z) in a cross section. The total tracer flux is

$$\dot{m} = \int_A u(x,y,z)\ C(x,y,z)dA \tag{1}$$

For a conservative tracer and steady-state flow $\dot{m}$ = const. The dilution coefficient is determined by comparing the mean concentration in a cross section $C_m$ to the concentration in the outlet channel, $C_o$.

$$1 + \gamma_p = \frac{C_o}{C_m} \tag{2}$$

Since $C_m = \dfrac{\int_{(A)} C\ u\ dA}{\int_{(A)} u\ dA} = \dfrac{\dot{m}}{Q}$

and $\dot{m} = Q_o\ C_o$

$$1 + \gamma_p = \frac{C_o}{\dot{m}/Q} = \frac{C_o}{Q_o\ C_o/Q} = \frac{Q}{Q_o}$$

where $C_o$ = concentration at outlet (discharge upstream from plunge line)

$Q_o$ = volumetric discharge rate

A = cross-sectional area containing tracer material downstream from plunge line

Q = volumetric flow rate downstream from plunge line

It is not unreasonable to consider that the vertical concentration profile downstream from the plunge line has approximately the shape of a

Gaussian distribution, defined by an excess concentration value $C_{max}$ at the bottom and a standard deviation $\sigma_z$. Both these values will depend on the "underflow" mechanics, i.e. bottom slope, density differential etc. An idealized sinking plume is presented in Fig. III-1.

In a field study enough data can be collected to determine $\sigma_z$ and $C_{max}$. To compute $C_{max}$ and $\sigma_z$ it is necessary to analyze the plunging flow and the underflow, taking into consideration the density differential, bed slope, discharge velocity, and other parameters. Such an analysis has so far been made only for two dimensional (laterally confined) flow, and without entrainment at the plunge line. No theory presently exists for the plunging flow with mixing (dilution) for the two-dimensional flow.

Dilution of the plunging flow and the transverse spreading underflow in the nearfield of Fig. II-1 can at present be determined only from experimental or field data. A plunging flow in a diverging laboratory channel with horizontal bottom has been studied at St. Anthony Falls Hydraulic Laboratory. The geometry resembled that of the Metro outlet, except that the laboratory channel bottom was horizontal, while the Metro outlet channel has a sloping bottom (see Fig. I-1). In the laboratory the plunging was induced by temperature differentials much as in the case of the Metro outlet. The dilution coefficient $\gamma$ derived from temperature profiles measured upstream and downstream of the plunge line was found to depend very much on the divergence angle $\alpha$ of the diffuser (see Fig. III-2).

The divergence angle $\alpha$ at the Metro outlet is on the order of 43°, and the diffuser is very short. An extrapolation of the laboratory data in Fig. III-2 to 43° is problematic.

Measurements of temperature, dissolved oxygen (D.O.), chloride ($C\ell^-$), and total dissolved solids (TDS) profiles at the end of the outlet channel were made on August 26, 1982, and the results were reported by Stefan et al. (1982). Referring to the points MPO, A and AA in Fig. III-3, and the resulting excess concentrations, dilution rates $Q_d/Q_p$ have been calculated in Tables III-1 and III-2. More data across the mouth of the outlet channel were collected on 20 July and 10 August 1983. $Q_d/Q_p$ for the 1983 data at section II are listed in Table III-3. Examples of concentration distributions across the outlet mouth are shown in Fig. III-4 to III-6. The outlet diffuser at the Metro site has a bottom slope which is estimated to be on the order of 10/750 = 0.013. This can be considered as a hydraulically steep channel for internal flow purposes, meaning that the plunging phenomenon is not much affected by the density underflow in the river. The plunge line configuration is similar to that seen in the laboratory experiments for a divergence angle of 15°.

Dilution rates in the plunging region may be a function of effluent densimetric Froude numbers. The effluent densimetric Froude number in the concrete portion of the effluent channel has been calculated for effluent conditions in 1983 (Table III-4). The 1982 and 1983 data suggest a decreasing $Q_d/Q_p$ ratio with a decreasing densimetric Froude number.

The data at Section II for 20 July, 10 August, and 7 September, 1983 were translated into normalized excess concentrations and averaged for all

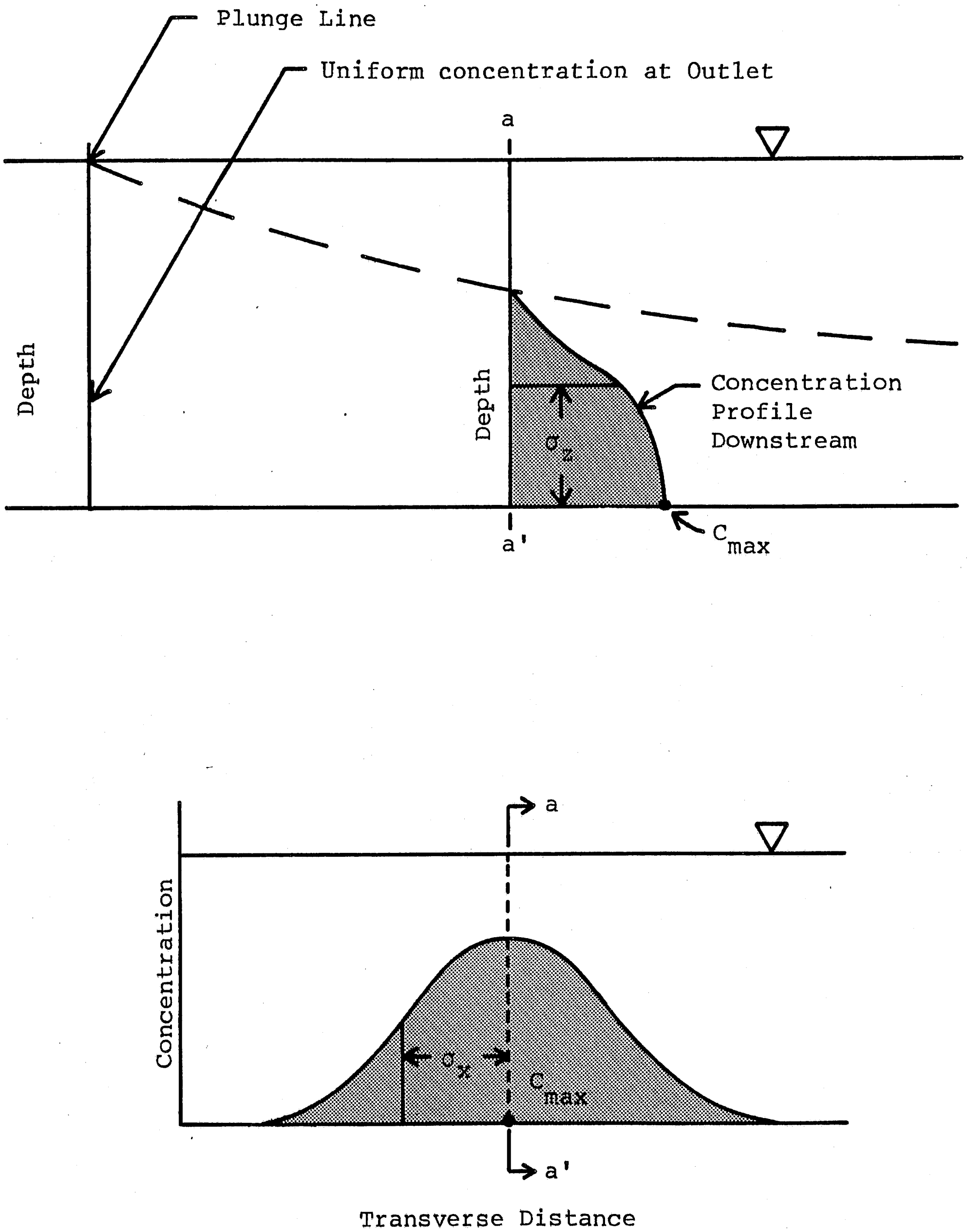
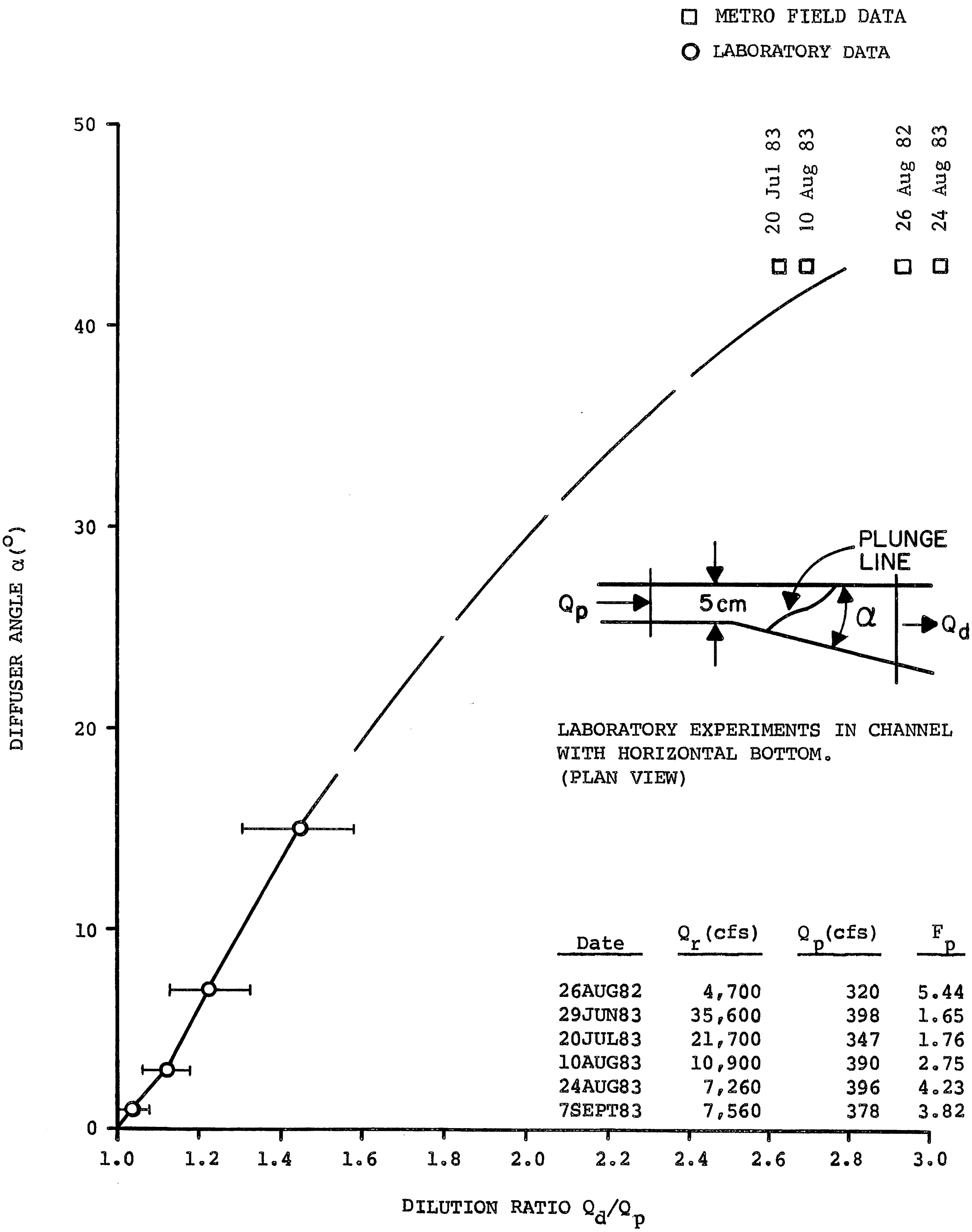



Fig. III-1. Idealized plunging plume with Gaussian distribution in both horizontal and vertical directions.




| Date | $Q_r$ (cfs) | $Q_p$(cfs) | $F_p$ |
|---|---|---|---|
| 26AUG82 | 4,700 | 320 | 5.44 |
| 29JUN83 | 35,600 | 398 | 1.65 |
| 20JUL83 | 21,700 | 347 | 1.76 |
| 10AUG83 | 10,900 | 390 | 2.75 |
| 24AUG83 | 7,260 | 396 | 4.23 |
| 7SEPT83 | 7,560 | 378 | 3.82 |

Fig. III-2. Dilution of the plunging flow in relation to the diffuser angle. -o- Laboratory data. -□- observed dilution at Metro WWTP.

TABLE III-1. ESTIMATE OF AVERAGE DILUTION OF PLUNGING FLOW FROM METRO WWTP BASED ON AUGUST 26, 1982 FIELD MEASUREMENTS

| | Profile A | | Profile AA | |
|---|---|---|---|---|
| | Mean | $Q_d/Q_p$ | Mean | $Q_d/Q_p$ |
| Temp. (°F) | 73.05 | 3.1 | 72.9 | 2.3 |
| D.O. (mg/ℓ) | 6.55 | 4.0 | 6.55 | 4.0 |
| Spec. Conductivity (μmhos/cm) | 880 | 2.1 | 820 | 2.8 |
| Chloride ($C\ell^-$) | -- | -- | -- | -- |
| TDS (mg/ℓ) | -- | -- | 420 | 2.6 |
| Average | | 3.1 | | 2.9 |
| Combined Average | | 3.0 | | |

TABLE III-2. MINIMUM BOTTOM DILUTION OF PLUNGING FLOW FROM METRO WWTP BASED ON AUGUST 26, 1982, FIELD MEASUREMENTS

| | Outlet | Ambient | Maximum Difference | Accuracy | Profile A | | Profile AA | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Bottom | Min. Dil. | Bottom | Min. Dil. |
| | $C_p$ | $C_r$ | $C_p - C_r$ | | $C_{bottom}$ | | $C_{bottom}$ | |
| Temp. (°F) | 72.1 | 73.5 | 1.4 | .1 | 72.9 | 2.3 | 72.7 | 1.7 |
| D.O. (mg/ℓ) | 8.2 | 6.0 | 2.2 | .1 | 7.4 | 1.6 | 7.1 | 2.0 |
| Spec. cond. (μmhos/cm) | 1180 | 615 | 565 | 20 | 950 | 1.7 | 930 | 1.8 |
| Cℓ⁻ (mg/ℓ) | 121 | 17.0 | 104 | 2 | Sample lost | | Sample lost | |
| TDS (mg/ℓ) | 623 | 196 | 327 | 5 | 480 | 1.8 | 502 | 1.6 |
| | | | | Average | | 1.85 | | 1.8 |
| | | | | Total Average | | 1.8 (56%) | | |

$$\text{Minimum point (bottom) dilution} = \frac{C_p - C_r}{C_{bottom} - C_r}$$

TABLE III-3. ESTIMATION OF AVERAGE AND MINIMUM BOTTOM DILUTION OF PLUNGING FLOW FROM METRO WWTP BASED ON 1983 FIELD MEASUREMENTS IN SECTION II

| Date | $Q_p$ (cfs) | $Q_d/Q_p$* | Min Dil. |
|---|---|---|---|
| 29 June | 398 | | 1.25 |
| 20 July | 347 | 2.63 | 1.21 |
| 10 August | 390 | 2.70 | 1.43 |
| 24 August | 396 | 3.00 | 1.60 |
| 7 Sept (AM) | 378 | | 1.33 |
| 7 Sept (PM) | 378 | | 1.29 |

$$\frac{Q_d}{Q_p} = \left( \frac{C_p - C_r}{\overline{C}_d - C_r} \right)$$

$\overline{C}_d$ = Average concentration downstream from plunging line in Section II.

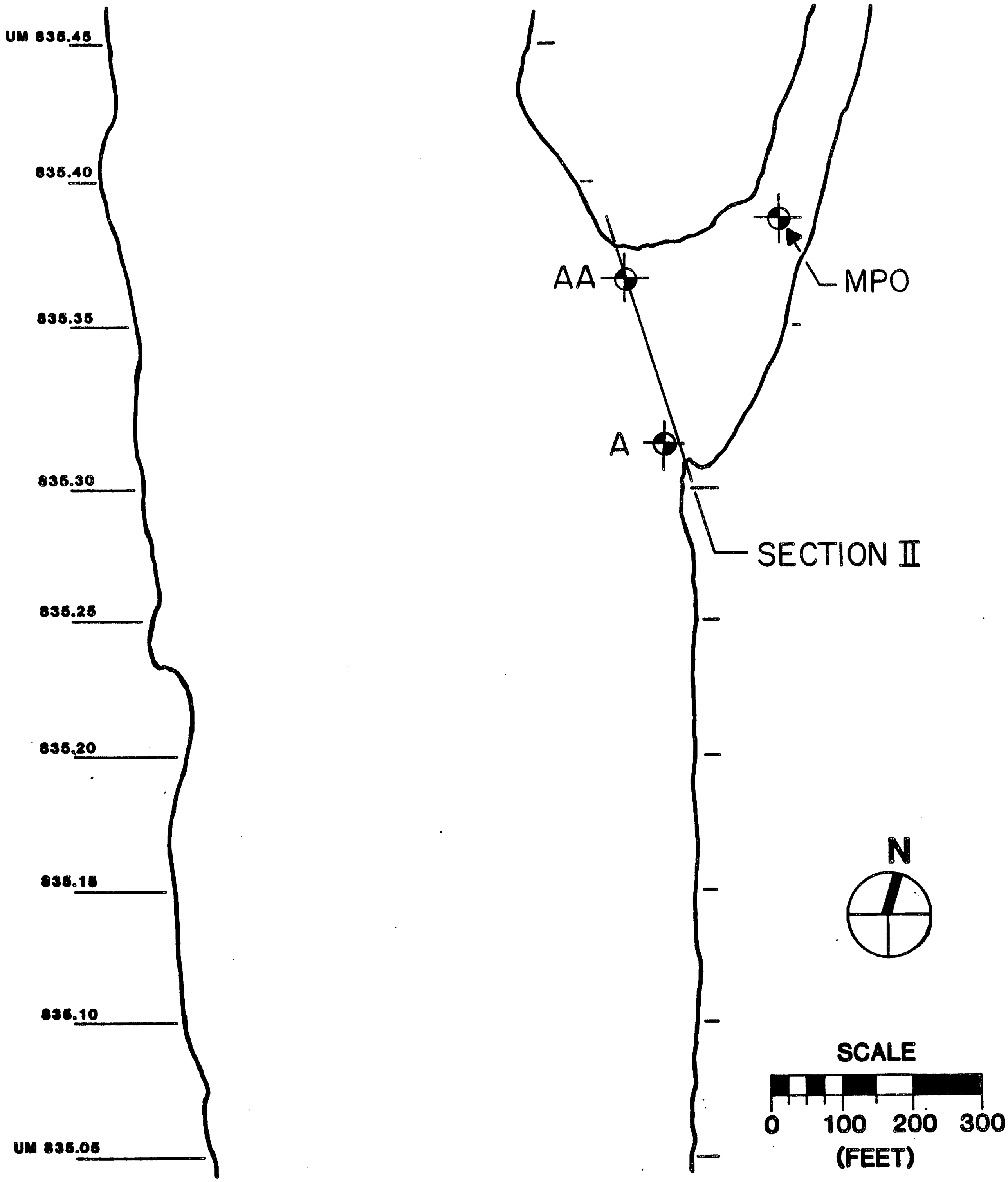



Fig. III-3. Sampling sites at the Metro WWTP outlet during the 1982 field study.

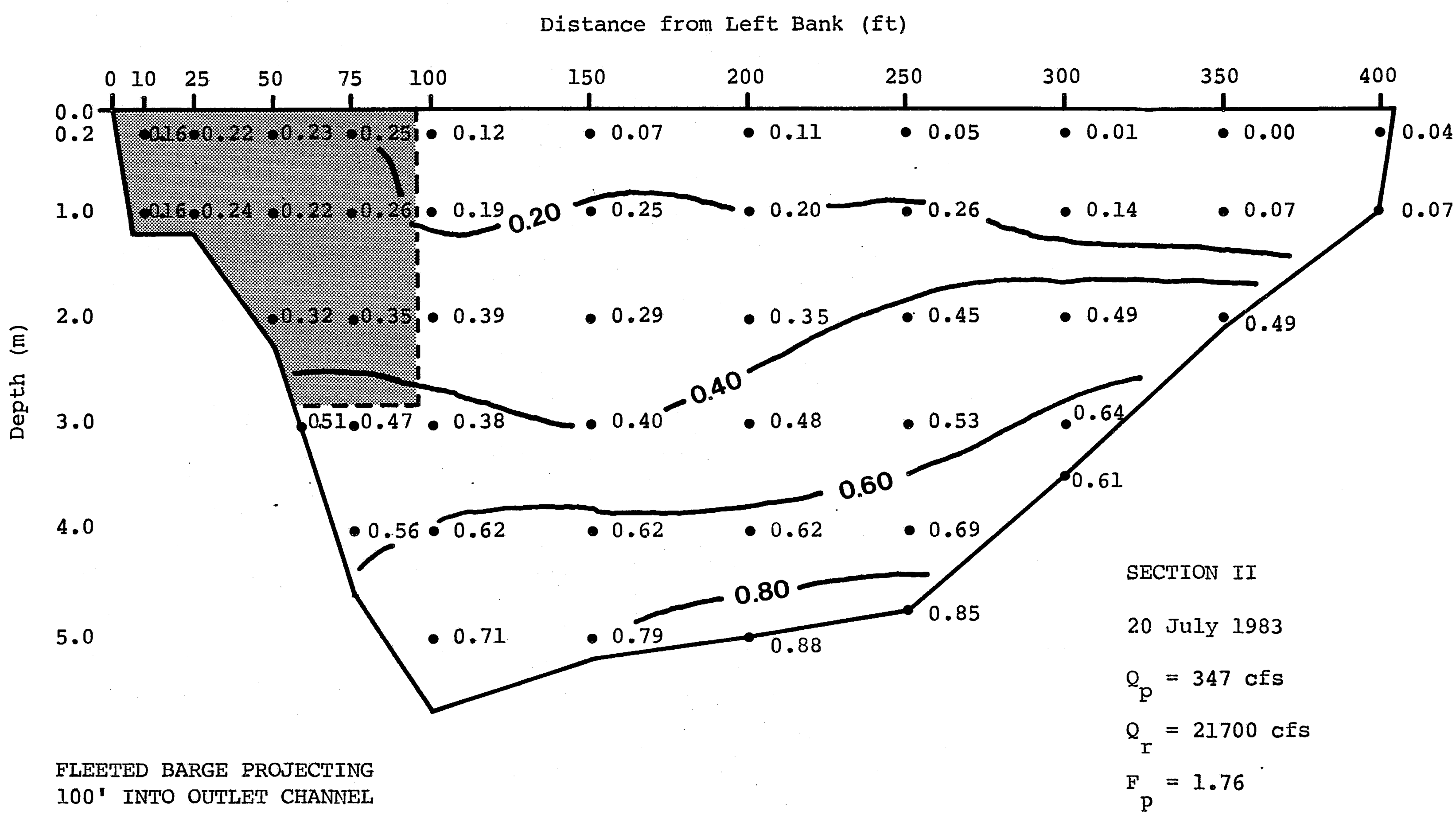



Fig. III-4. Dimensionless excess concentration distribution in Section II on 20 July 1983.

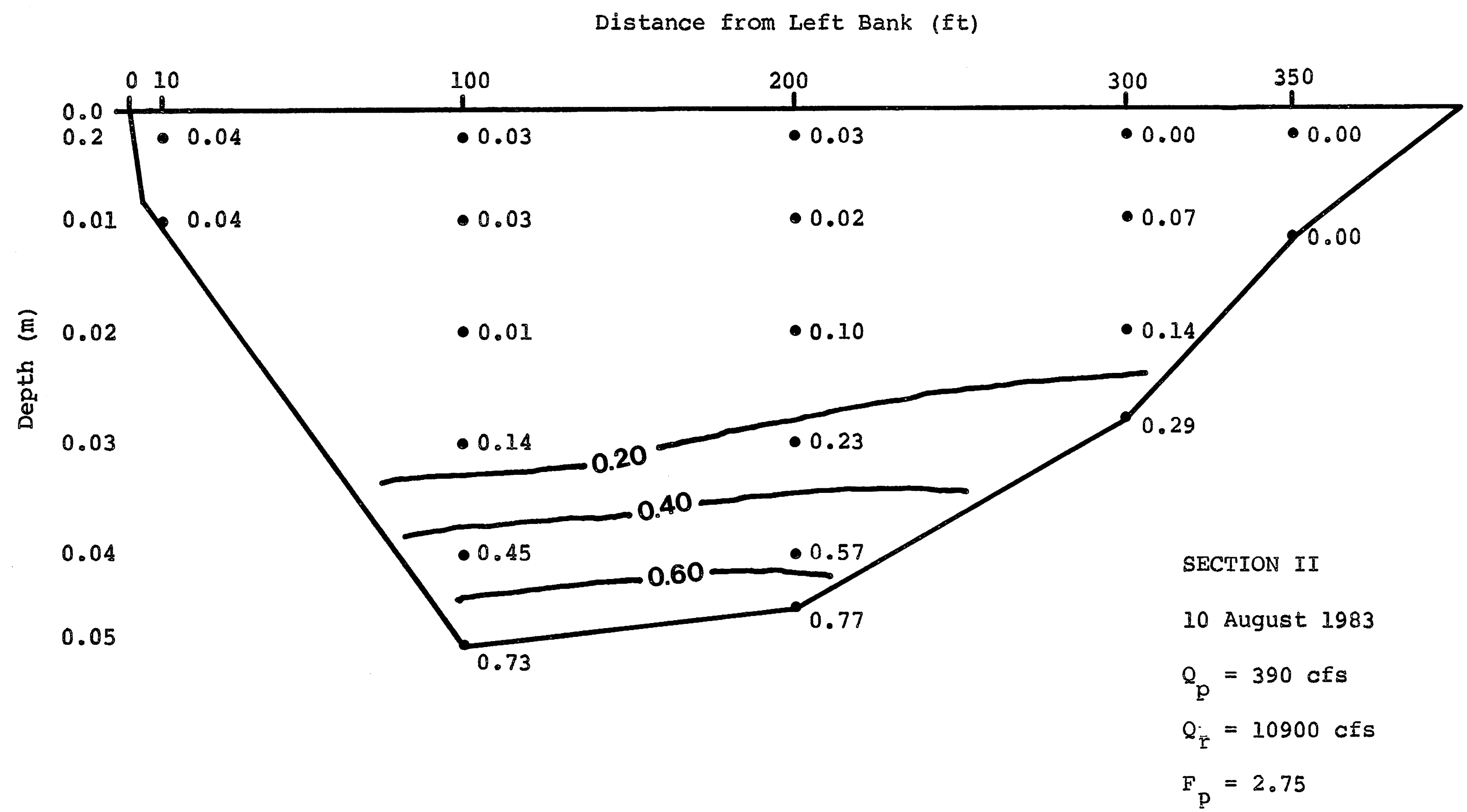



Fig. III-5. Dimensionless excess concentration distribution in Section II on 10 August 1983.

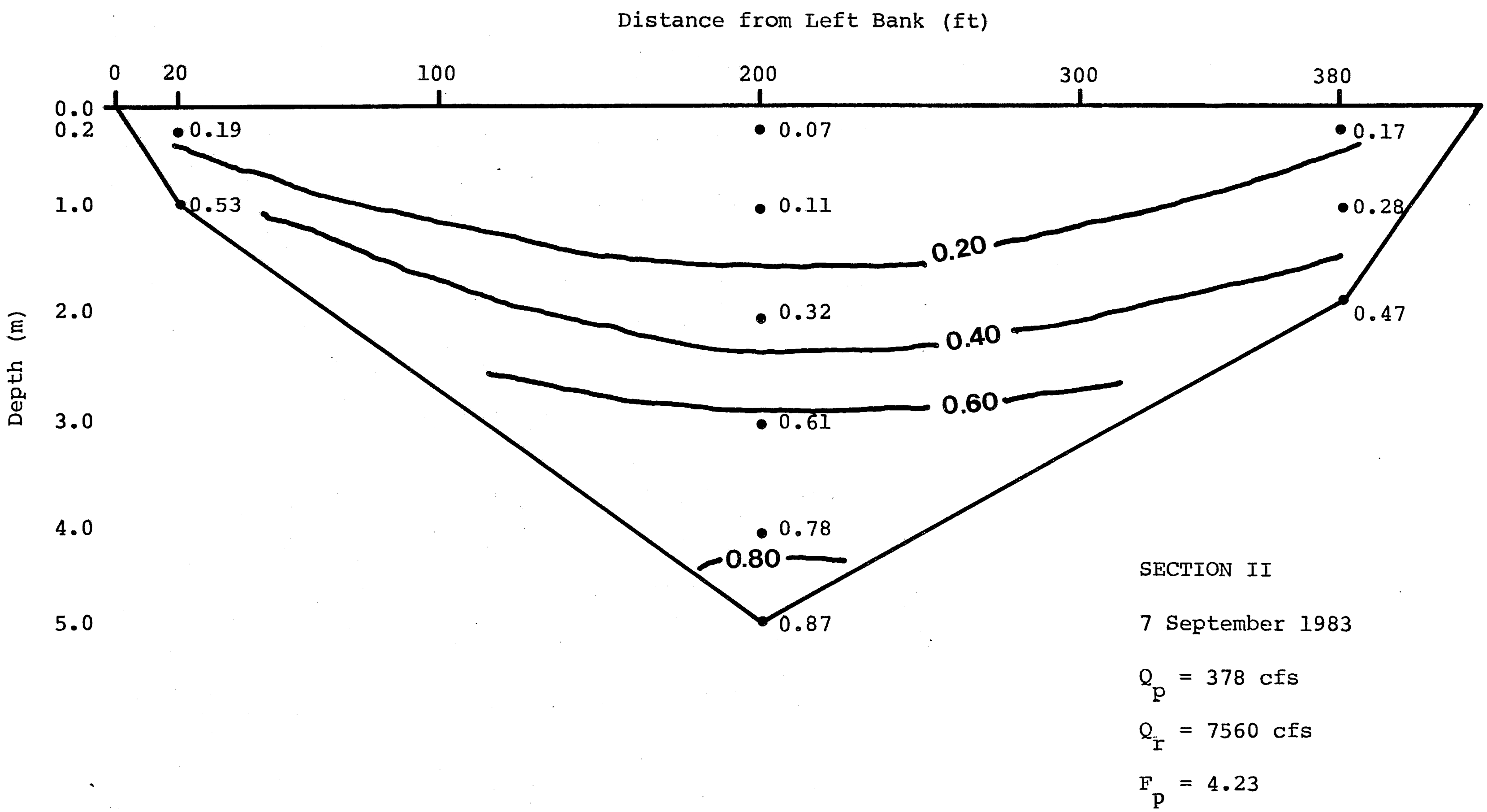



Fig. III-6. Dimensionless excess concentration distribution in Section II on 7 September 1983.

TABLE III-4 DENSIMETRIC FROUDE NUMBERS OF EFFLUENT ON SURVEY DATES

| Date | $\rho_p$ | $\rho_r$ | Approx. W.S. (ft) | H (ft) | Area ($ft^2$) | U (ft/s) | $F_p$ | |
|---|---|---|---|---|---|---|---|---|
| 29 June 83 | .998796 | .998216 | 690.8 | 6.8 | 670 | 0.59 | 1.65 | |
| 20 July 83 | .998165 | .997136 | 688.6 | 5.6 | 455 | 0.76 | 1.76 | |
| 10 Aug 83 | .998222 | .996865 | 687.2 | 4.2 | 330 | 1.18 | 2.75 | |
| 24 Aug 83 | .998078 | .997341 | 687.2 | 4.2 | 330 | 1.20 | 3.80 | |
| 7 Sept (AM) | .998326 | .997682 | 687.0 | 4.0 | 310 | 1.22 | 4.23 | |
| 7 Sept (PM) | .998508 | .997868 | 687.0 | 4.0 | 310 | 1.22 | 4.23 | |
| 22 Sept 83 | .998846 | .999633 | 686.9 | 3.9 | 300 | 1.20 | 3.82 | (Floating) |
| 26 Aug 82 | .998237 | .997794 | ~ 687.0 | 4.0 | 310 | 1.30 | 5.44 | |

$$F_p = \frac{U}{\left(\frac{\Delta\rho}{\rho} gH\right)^{1/2}}$$

U = mean flow velocity in concrete section

H = depth of flow in concrete section

measured water quality parameters. The result is shown in Figs. III-4 to III-6.

The normalized excess concentration $C'$ was calculated for each of the measured parameters (T, D.O., $C\ell^-$, Cond., TDS), according to the formula:

$$C' = \frac{C - C_r}{C_p - C_r} \tag{3}$$

where $C$ = dimensional value of the measured concentration

$C_r$ = river (ambient) reference value (usually taken to be the measured value at a location upstream of the effluent discharge site)

$C_p$ = value representative of the undiluted effluent (usually measured in the discharge canal upstream from the diffuser)

Assuming that each of the measured parameters (substances) is uniformly distributed in the undiluted effluent, accepting Reynolds analogy, and in view of the linearity of the diffusion equation, $C'$ should be the same for all substances. It is therefore expected that the arithmetic mean ($C'_m$) of all five parameters measured provides a better index of the dimensionless value than a single parameter. Further comments on the calculation of $C'_m$ are as follows:

a) In some cases the value of $C'$ for one parameter was so different from the others that it was probably incorrect. The following criterion was used to discard such values.

If one of the five values of $C'$ was outside the range $[r - 30\sigma, r + 30\sigma]$, where $r$ and $\sigma$ are the mean and the standard deviation, respectively, of the remaining four points, it was discarded and $C'_m$ was taken to be equal to the mean of the other four values of $C'$. If, however, it was within the above range, then $C'_m$ was set equal to the arithmetic mean of all five values.

b) The value of $C'$ should lie in the range [0, 1]. In some cases, however, the value of $C'$ was outside the range. This could be due to an erroneous individual field measurement or to changes in the river or plant reference values over time. If the original river reference was questionable, a new river reference value was calculated based on values of the parameter measured at a part of the cross section under consideration outside the mixing zone.

Negative values of $C'$ were made equal to zero and then included in the average.

The results are presented in Figs. III-4, III-5, and III-6. The figures verify the presence of a stratified effluent from the mouth of the diffuser. The isopleths are approximately horizontal in all cases with some disturbances on 20 July 1983 due to moored barges projecting across the mouth of the diffuser.

# IV. TRANSVERSE SPREADING FLOW

In the transverse spreading region, the plunging flow from the plant diffuser channel continues as an underflow along the diffuser bottom into the river channel. The effluent already diluted by plunging in the diffuser, becomes further diluted from the effect of the cross current in the river and the sinking into the river channel. The river flow rate determines the extent of mixing from the cross current and the density of the effluent determines the extent of mixing from plunging. The underflow current spreads across the river bottom while mixing with the river water and thereby reduces the density difference between the plume and the river. The bottom plume continues to spread transversely while turning into the direction of the river flow. The transverse spreading rate is strongly dependent on the degree of mixing in the diffuser channel and the flow rate in the river. At the end of the diffuser channel, which also marks the beginning of the transverse spreading in the river, the flow is quite uniformly stratified as shown in Fig. III-4 to Fig. III-6. The Metro WWTP effluent meets the river as a stratified flow.

Presently, there is no theoretical formulation for the extent of transverse spreading under different density and flow conditions. The degree of mixing can be analyzed in a manner similar to the plunging flow by characterizing the plume by a maximum excess concentration and a standard deviation in both the horizontal and vertical directions. The slope of the underflow plume determines if the appropriate farfield model is a vertical or horizontal mixing model. For high river flow rates with high shear and mixing from the cross currents, the plume does not spread significantly and a horizontal two-dimensional mixing model is more appropriate. At low river flow, the underflow is well developed and a vertical two-dimensional mixing model is applicable in the farfield (Stefan, 1982). The point at which the vertical mixing model is applied cannot be determined from theoretical considerations, but must be evaluated from field data which account for the river bed topography at the site.

## Field Study

In addition to the two sets of data from 1982, field measurements on the Mississippi River were taken during the summer of 1983. Six separate surveys were performed from June 29 to September 22. The dates and flow conditions for each survey are presented in Table IV-1. In each survey, measurements of temperature, dissolved oxygen, conductivity, total dissolved solids, and chloride were taken. Sampling stations varied from day to day, but generally included stations across the outlet and three or four stations across the river at river mile 835.3 and 835.05. Reference measurements for the river were taken upstream of the outlet and references for the plant were taken at the point where the effluent entered the diffuser and well before plunging occurred. A detailed presentation of the data and sampling locations can be found in SAFHL External Memorandum No. 185, "Water Quality Data for the Metro Wastewater Treatment Plant Effluent

TABLE IV-1. FLOW CONDITIONS AT THE METRO WWTP ON SURVEY DATES

| Date | River Discharge (cfs) | Plant Discharge (cfs) |
|---|---|---|
| 7 July 82 | 11,100 | 340 |
| 26 August 82 | 4,700 | 403 |
| 29 June 83 | 35,600 | 398 |
| 20 July 83 | 21,700 | 347 |
| 10 August 83 | 10,900 | 390 |
| 24 August 83 | 7,260 | 396 |
| 7 September 83 | 7,560 | 378 |
| 22 September 83 | 9,670 | 359 |

Mixing Zone in the Mississippi River Below St. Paul, Minnesota, from June 29 to September 22, 1983." A diagram of the site and the survey stations are presented in Fig. IV-1.

The ultimate well mixed river concentration can be computed from the data collected using

$$C_o = \frac{Q_p C_p + Q_r C_r}{Q_p + Q_r} \quad (4)$$

where $Q_p$ and $Q_r$ are the plant and river discharge, respectively, and $C_p$ and $C_p$ are the concentration in the plant discharge and in the river, respectively.

The edge of the plume was defined as 95 percent of the difference between the fully mixed condition, and the plant reference concentration:

$$C_{95} = .95(C_o - C_p) + C_p = 0.95\ C_o + 0.05\ C_p \quad (5)$$

Plots of the approximate plume configuration are presented in Figs. IV-2 through IV-7. The plume shape is presented for the parameter which most closely represents the average plume shape for all parameters measured.

Figure IV-5 indicates a well formed plume at river mile 835.3. Fig. IV-5 also illustrates the effect of loaded barges moored in such a way that the end of the barges extend upstream along the mouth of the diffuser. At mile 835.3, the concentrations between the moored barges and the bank indicate that the plume extends downstream along the inside edge of the barges. At river mile 835.05, just downstream of the barges, the plume has an atypical shape extending up the left bank. This is considered to be due to the portion of the plume discharging along the side of the barges and entering the river just upstream of river mile 835.05, resulting in a distorted plume shape.

The diagrams of the estimated plume cross section also illustrate the effect of the moving barge traffic. A more detailed discussion of the effect of barge traffic on the stratified flow was presented in SAFHL External Memorandum No. 186, "Mixing of WWTP Effluents by the Barge Tows in the Upper Mississippi and Minnesota Rivers." The barge traffic completely mixes the water column throughout much of the cross section depending on the size and speed of the barge tow. The time for the stratified flow condition to become reestablished is affected by the size of the barge tow and the river flow rate. In several instances during the 1982 and 1983 surveys, profiles were taken shortly after the passage of a barge. The barge passage results in a distorted profile and may explain anomalies in some of the plume shapes.

The presence of considerable barge traffic also explains the limited transverse spreading and stratified flow found in the river on 26 August 1982 (Fig. IV-3). At the low flow rate of 4700 cfs, extensive spreading

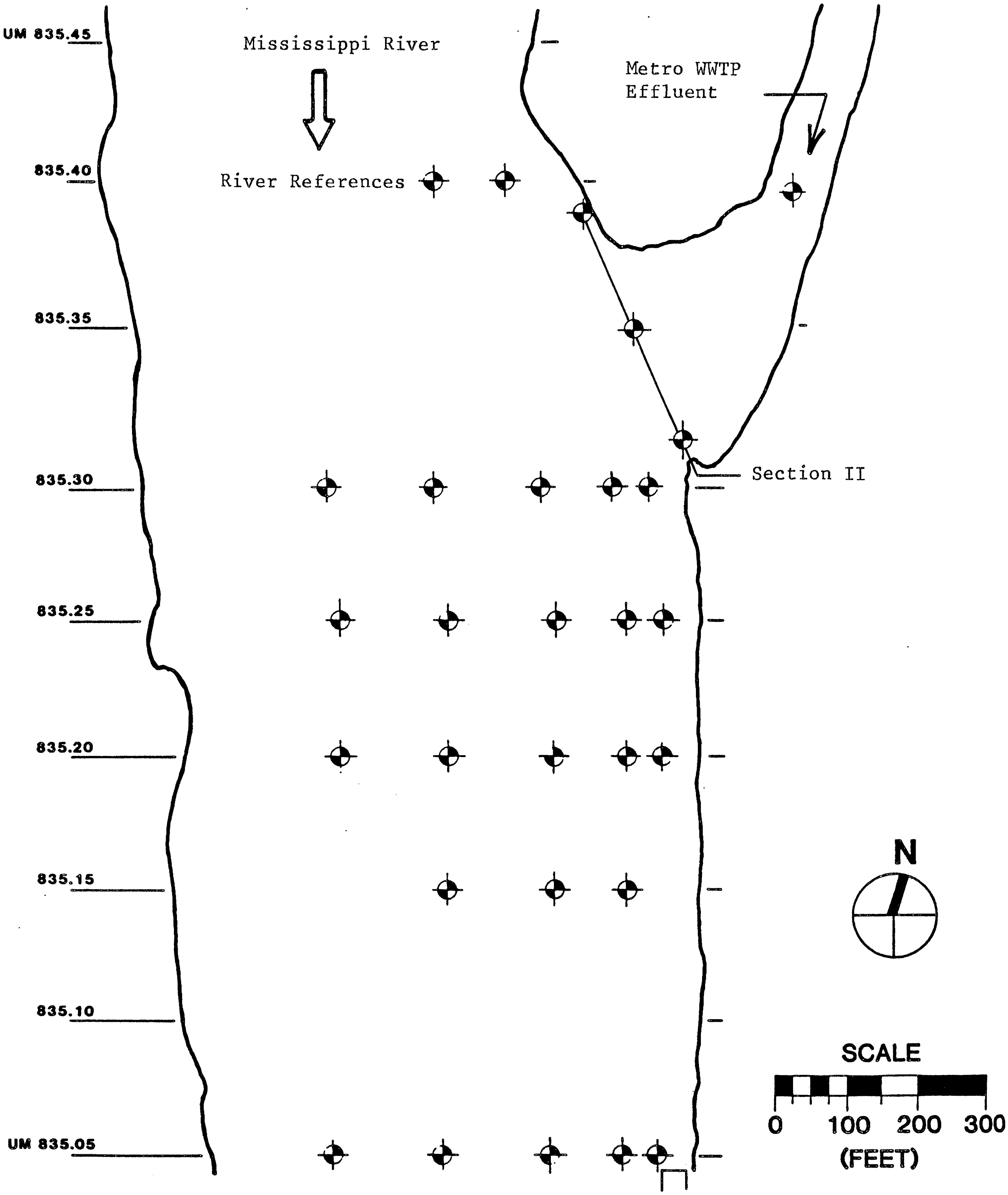



Fig. IV-1. Sampling sites for the 1983 Metro WWTP mixing zone surveys. Not all sites were sampled for each survey date. Up to eleven sites were used across Section II.

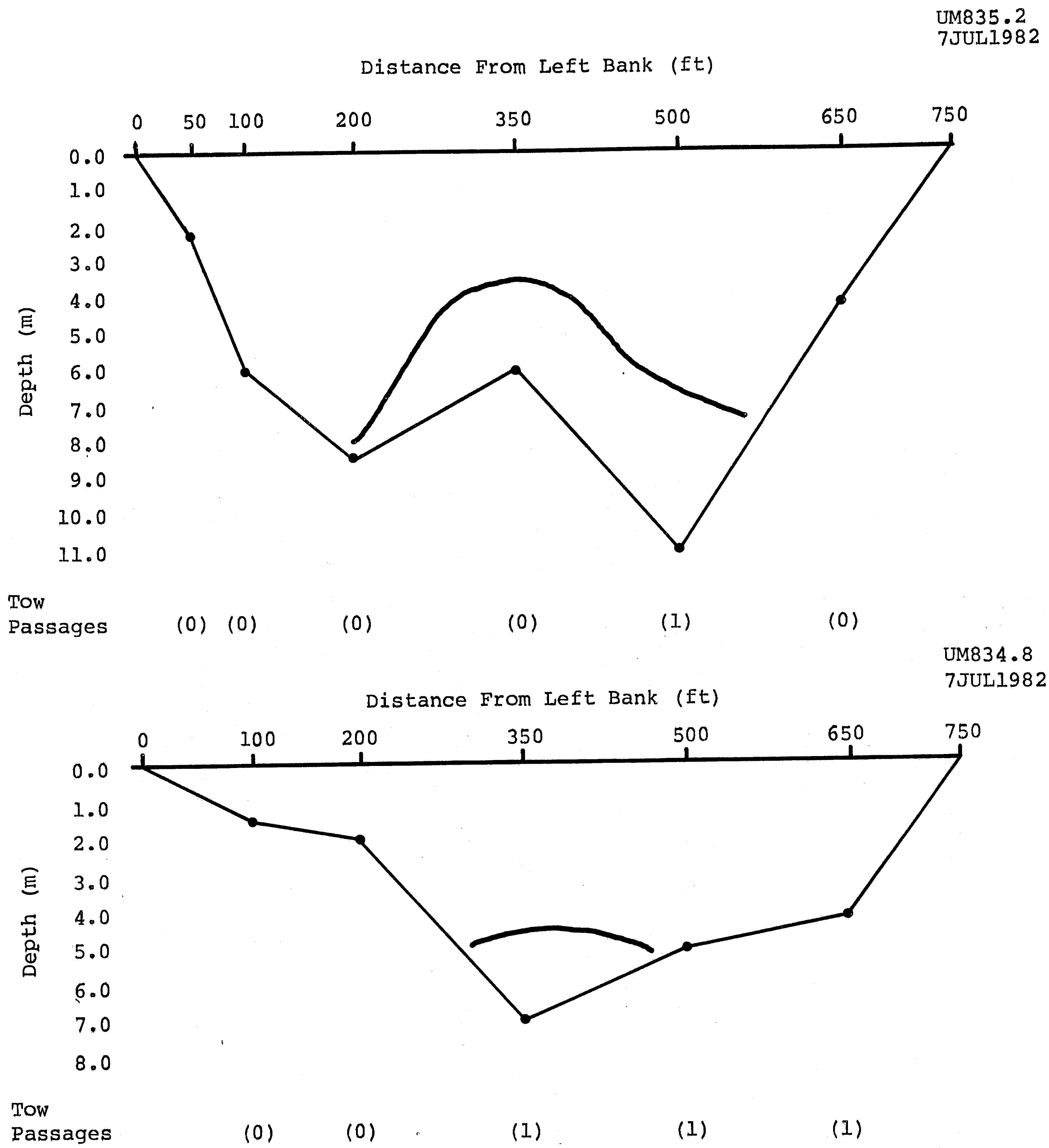
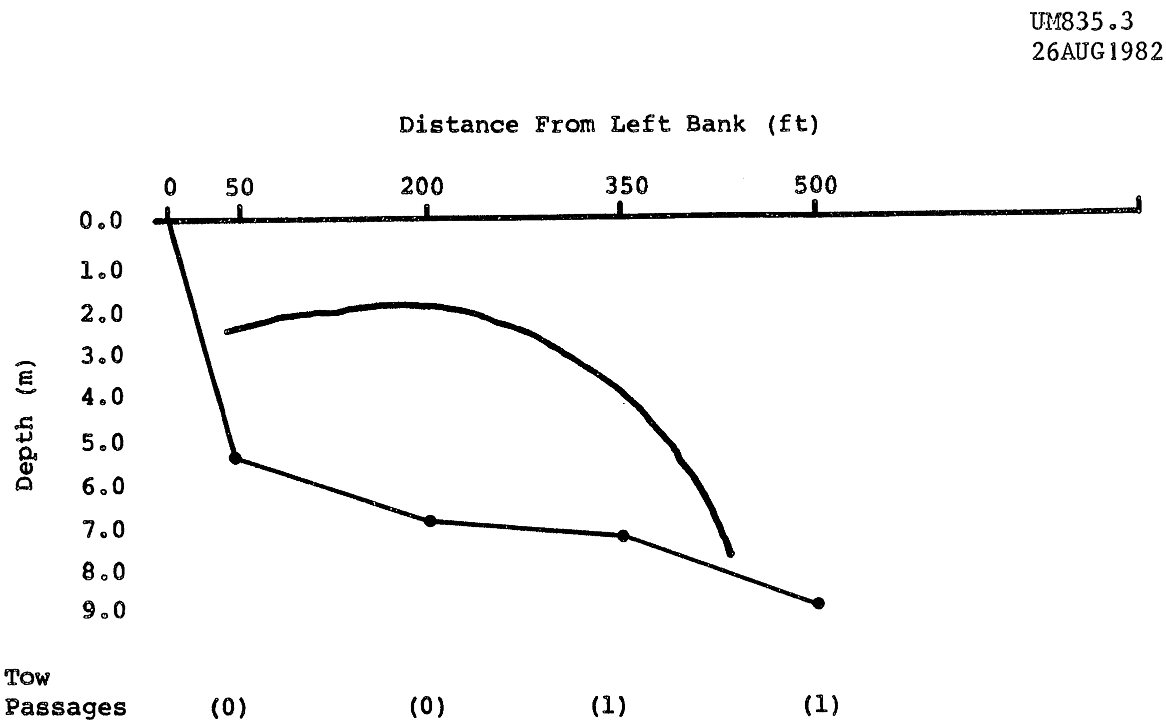



Fig. IV-2. Estimated shape of the effluent plume 700 feet from the outlet (UM 835.2) and 2500 feet from the outlet (UM 834.8) on 7 July 1982. The reduced size downstream indicates considerable mixing between stations. $Q_r$ = 11,100 cfs.



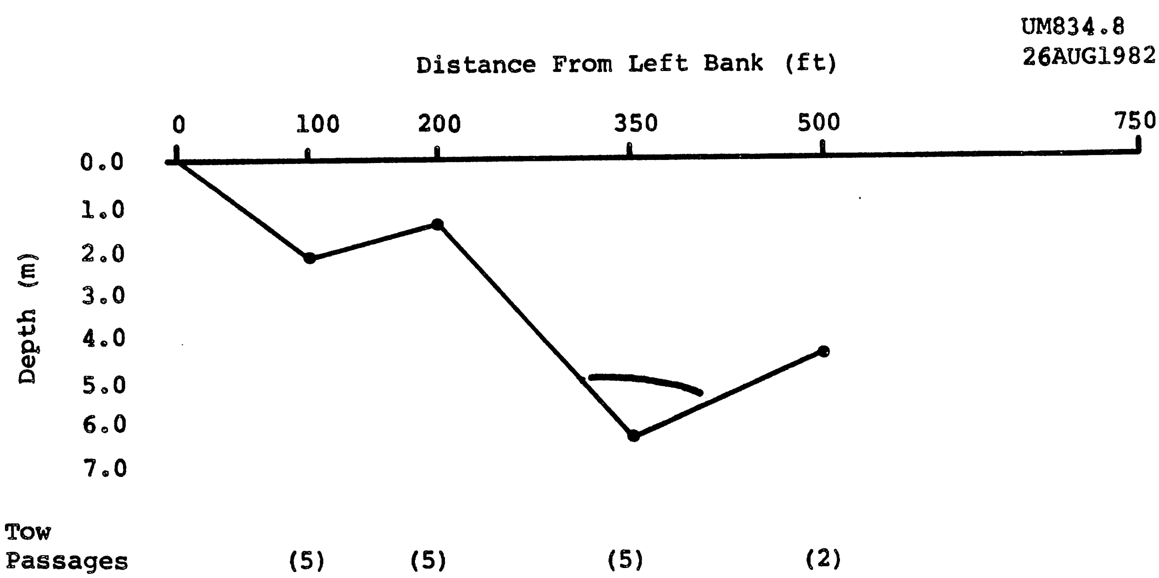
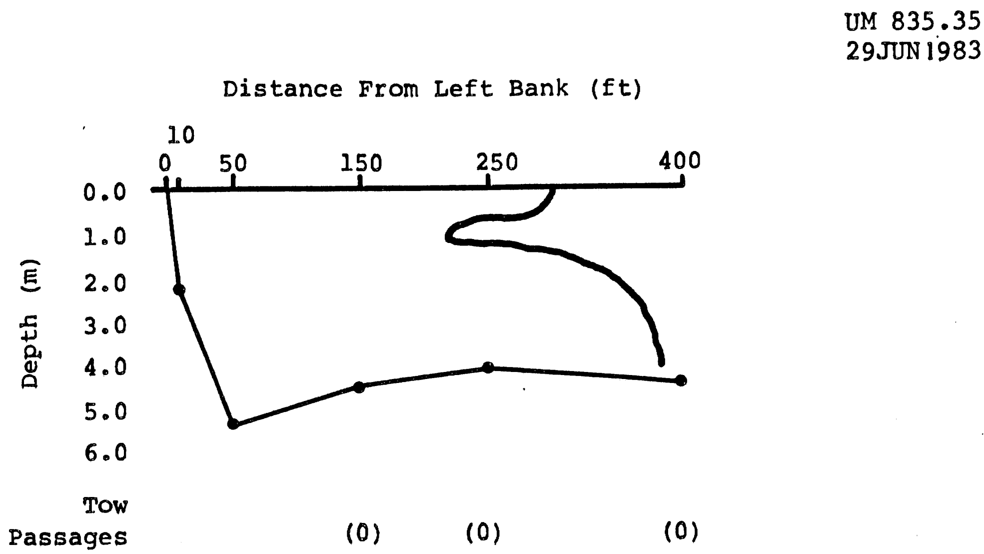




Fig. IV-3. Estimated shape of the effluent plume 300 feet from the outlet (UM 835.3) and 2500 feet from the outlet (UM 834.8) on 26 August 1982. The size of the downstream plume is reduced due to heavy barge traffic. $Q_r$ = 4,700 cfs.



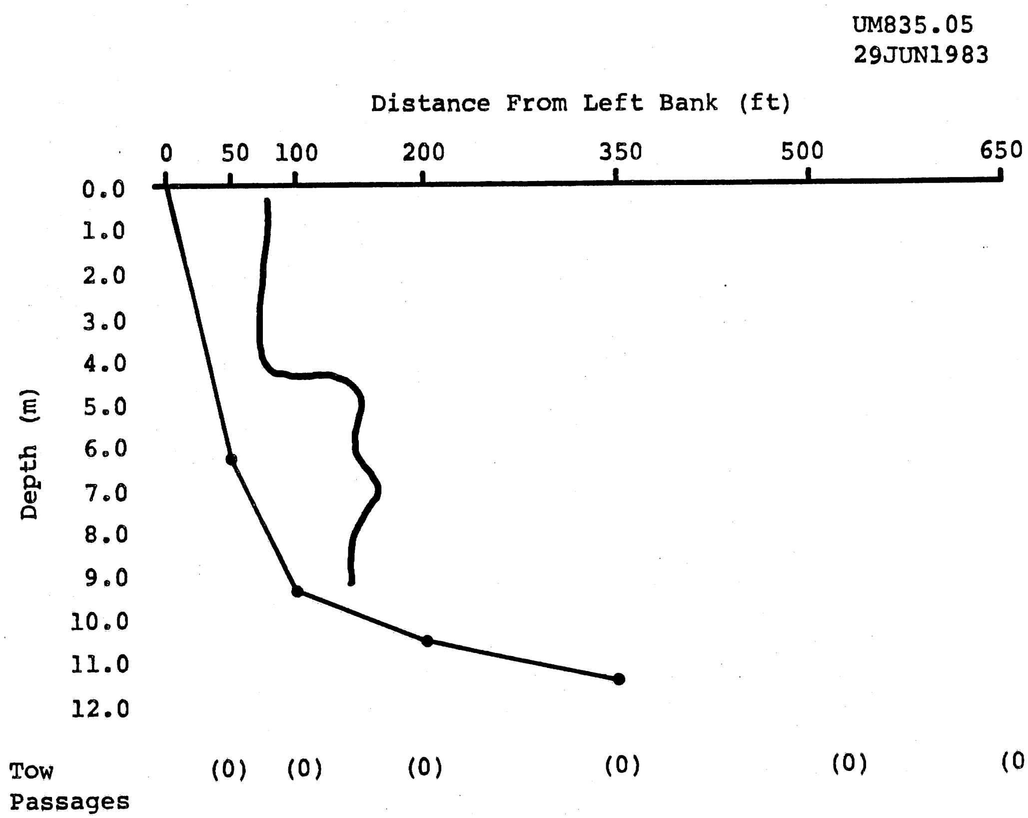




Fig. IV-4. Estimated shape of the effluent plume in the diffuser (835.35) and 1300 feet downstream from the outlet (835.05) on 29 June 1983. The high river flow rate (35,600 cfs) caused a strong shearing action in front of the outlet resulting in the destruction of stratification by UM 835.05.

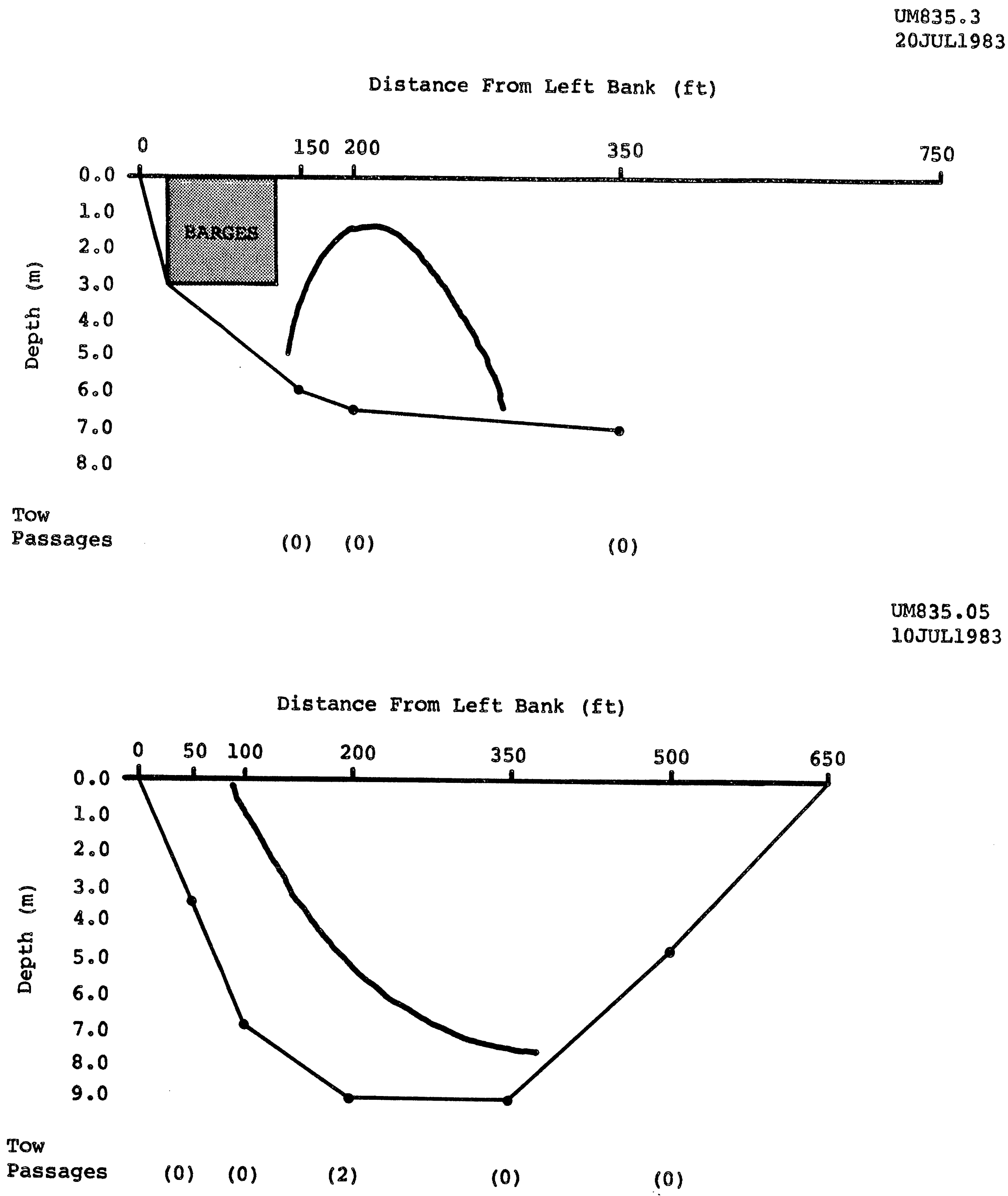
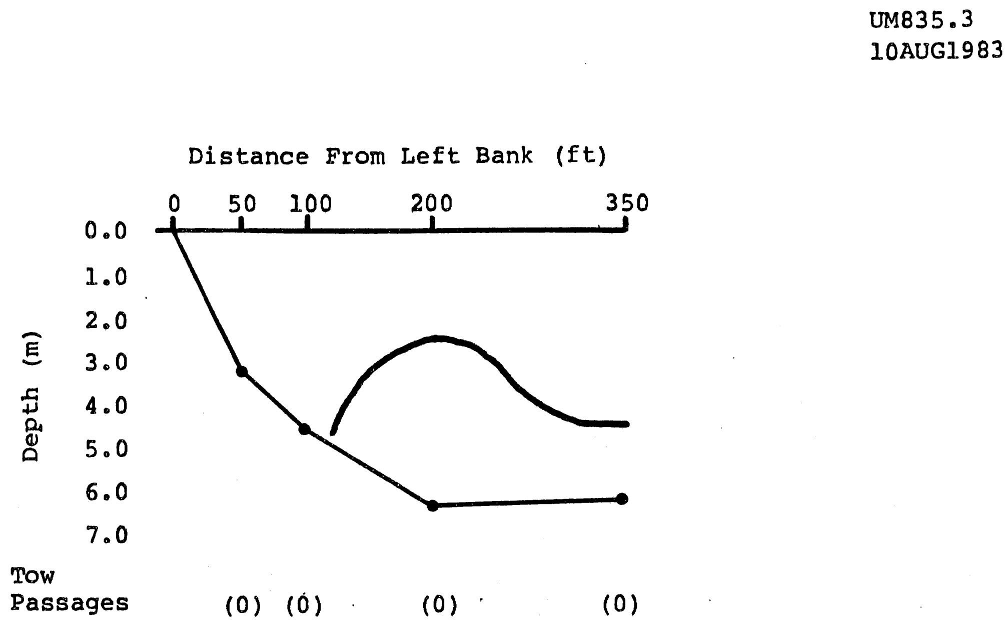



Fig. IV-5. Estimated shape of the plume 300 feet from the outlet (UM 835.3) and 1300 feet from the outlet (835.05) on 20 July 1983. The initial well formed plume at UM 835.3 is distorted at UM 835.05 due to barges moored along the bank as well as moving barge traffic. $Q_r$ = 21,700 cfs.



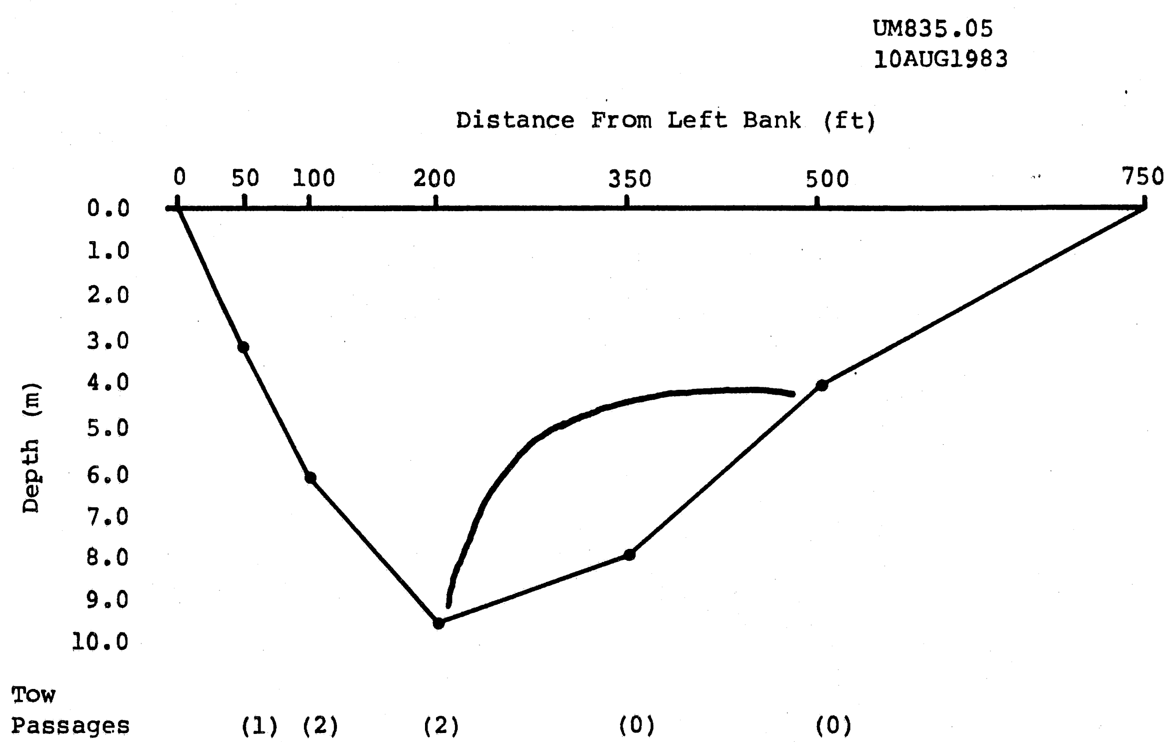
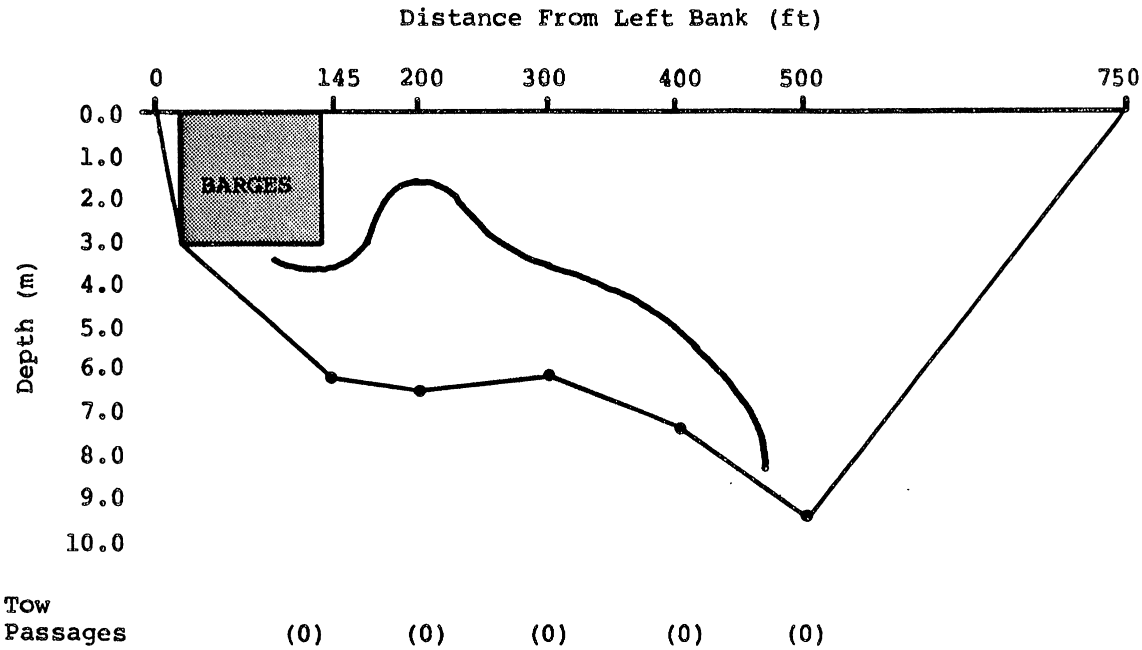




Fig. IV-6. Estimated shape of the plume 300 ft from the outlet (835.3) and 1300 feet from the outlet (UM 835.05) on 10 August 1983. The initial, strongly stratified plume at UM 835.3 is evident at UM 835.05 although the plume shape has been distorted due to barge traffic. Under undisturbed conditions, the plume is expected to extend across the entire channel bottom. $Q_r$ = 10,900 cfs.

UM835.3
24AUG1983




UM835.2
24AUG1983

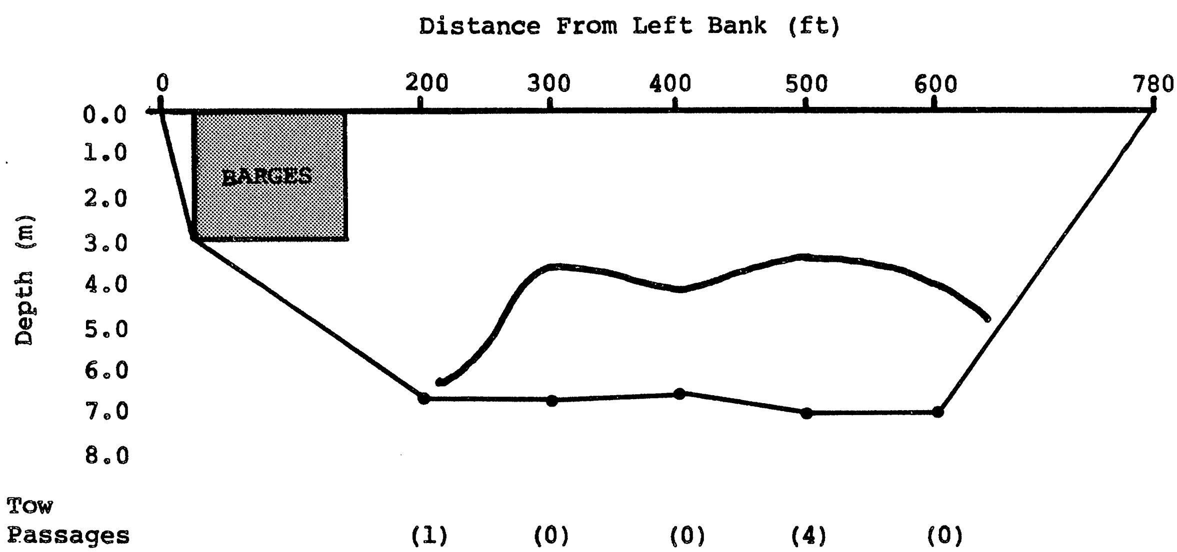



Fig. IV-7. Estimated shape of the plume 300 feet from the outlet (UM 835.3) and 700 feet from the outlet (UM 835.2) on 24 August 1983. At UM 835.3, the plume is strongly stratified and plunging into the river channel. At UM 835.2, the plume is a well formed stratified flow although the left side of the stratified flow has been disturbed by barge traffic. $Q_r$ = 7,260.

was expected possibly with some upstream spreading. Instead, the spreading was less extensive than for 24 August 1983 with a flow rate of 7200 cfs. Because of the low flow rate and long travel time, only two profiles were unaffected by barge traffic and most were affected by three or more passages. Only the two unaffected profiles showed a strongly stratified condition at river mile 835.3 and no significant vertical stratification was found downstream.

Figure IV-8 presents a plot of the estimated edge of plume for each survey date. The edge of the plume in each case is the average edge for all five parameters measured. The diagram illustrates the strong relationship between the extent of transverse spreading and the river flow rate. For the 7200 cfs flow rate on 24 August, the plume quickly spreads across the channel and further spreading is prevented by the shape of the river channel. For a flow rate of 10,600 cfs, the plume spreading is not as rapid, but completely crosses the channel before the plume reaches river mile 835.05. At a flow rate of 21,700 cfs, the plume just reaches the far side of the channel bottom at river mile 835.05 (see Fig. IV-5); at 35,600 cfs, the transverse spreading is not significant with the plume restricted to the near bank by the high river velocity (see Fig. IV-4).

At flow rates below 7000 cfs the underflow can be expected to spread very rapidly across the river bottom, and at much lower flow rates than 7000 cfs even upstream, forming an "arrested sewage water wedge" near the river bottom.

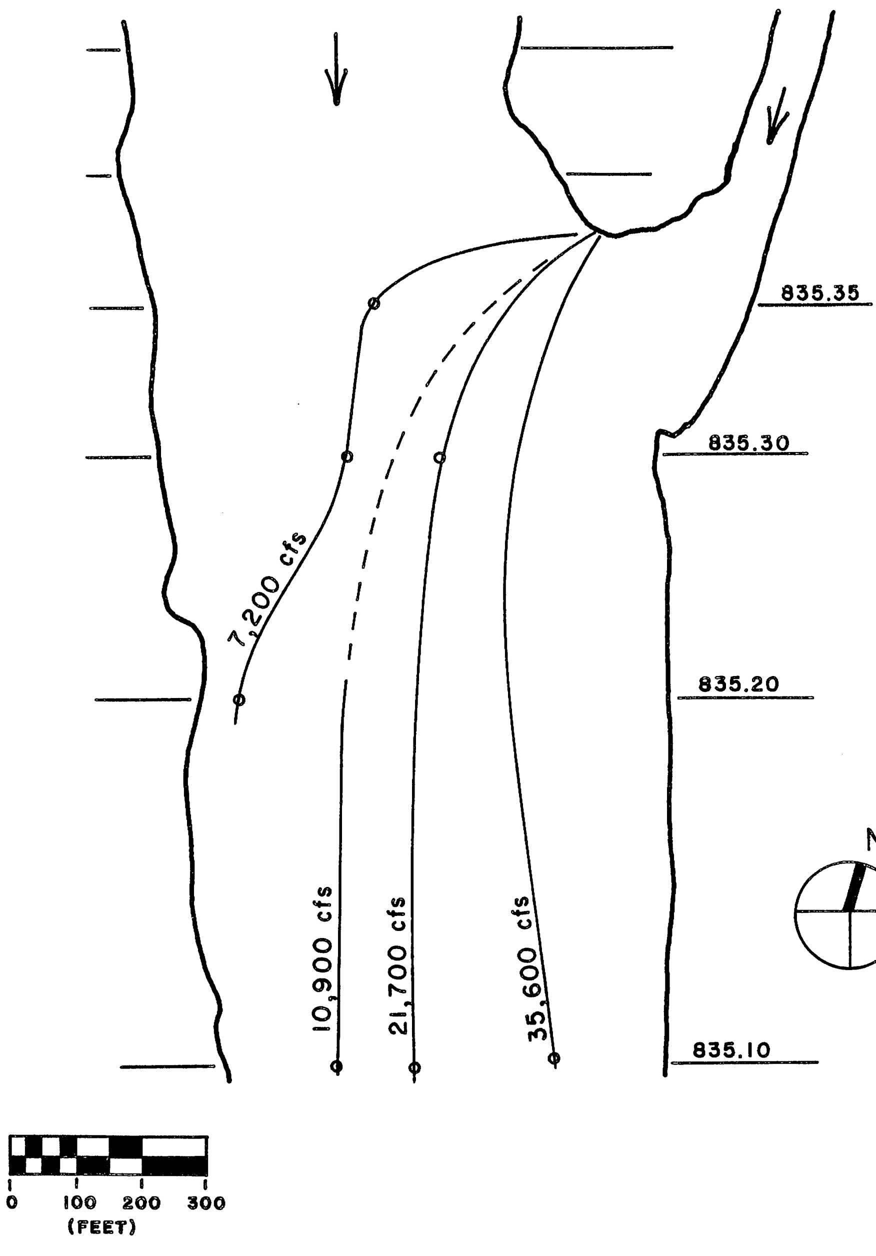



Fig. IV-8. Estimated edge of plume. Figures along the bank give river miles. Figures on lines indicate river flows. Plant discharges varied from 347 to 396 cfs.

# V. DILUTION

The river flow rate affects not only the extent of transverse spreading but also the extent of dilution. To determine dilution, the data was transformed into normalized excess concentrations using the same method as discussed in Sections III.

Isopleths of average dimensionless excess concentration at one meter depth and at the bottom are presented in Figs. V-1 through V-5 for five survey dates. The actual concentration isopleths and isotherms were presented in SAFHL External Memorandum No. 189, "Water Quality in the Nearfield of the Metro Wastewater Effluent Mixing Zone: Graphical Representation of 1983 Data." The figures indicate that the plunging phenomenon is present in the diffuser regardless of the river flow rate. At flow rates above 30,000 cfs the underflow is quickly diluted and remains close to the near bank spreading transversely as a two-dimensional vertically well mixed plume. At lower flow rates the underflow spreads transversely across the river bottom. A three-dimensional process of horizontal spreading and vertical mixing of the stratified underflow takes place. At river flow rates below 10,000 cfs under plunging effluent conditions, the vertical stratification continues downstream to the end of the survey stations at river miles 835.05. Beyond river mile 835.05, further dilution is due to vertical mixing of the underflow.

The two step mixing process of effluent plunging in the diffuser and transverse flow and mixing in the river is illustrated in Figs. V-6 and V-7. The dimensionless excess concentration in the effluent plume is plotted against distance downstream. Figure V-6 uses the maximum excess concentration and Fig. V-7 uses the average excess concentration in the plume. The plume's edge is again defined as 95 percent of well mixed concentration ($C_o$). Both figures illustrate the same mixing phenomenon. From the beginning of the diffuser to the mouth of the diffuser (Section II), the effluent is not in direct contact with the river current and mixing occurs due to plunging and energy dissipation within the diffuser. The degree of mixing decreases with increased river stage and volume of river water within the diffuser.

From the mouth of the diffuser at Section II to the first river station at mile 835.3, the effluent enters the river and comes in direct contact with the cross current from the river. Rapid mixing occurs from the shear effect of the river current. Mixing is much stronger at high flow rates and decreases considerably at lower river flow rates where underflow occurs. For the average concentration in the plume, the data can be approximated by a single line from Section II to river mile 835.05 for flow rates greater than 10,600 cfs. Below 5000 cfs (26 July 1982) the mixing from the cross current is very weak which may be due to the sinking of the effluent underflow into the river channel rather than to the effect of the river cross flow.

From river mile 835.3 to 835.05, mixing by turbulence induced by bed shear continues. The effluent plume travels downstream and spreads transversely in the case of underflow at low river flow rates.

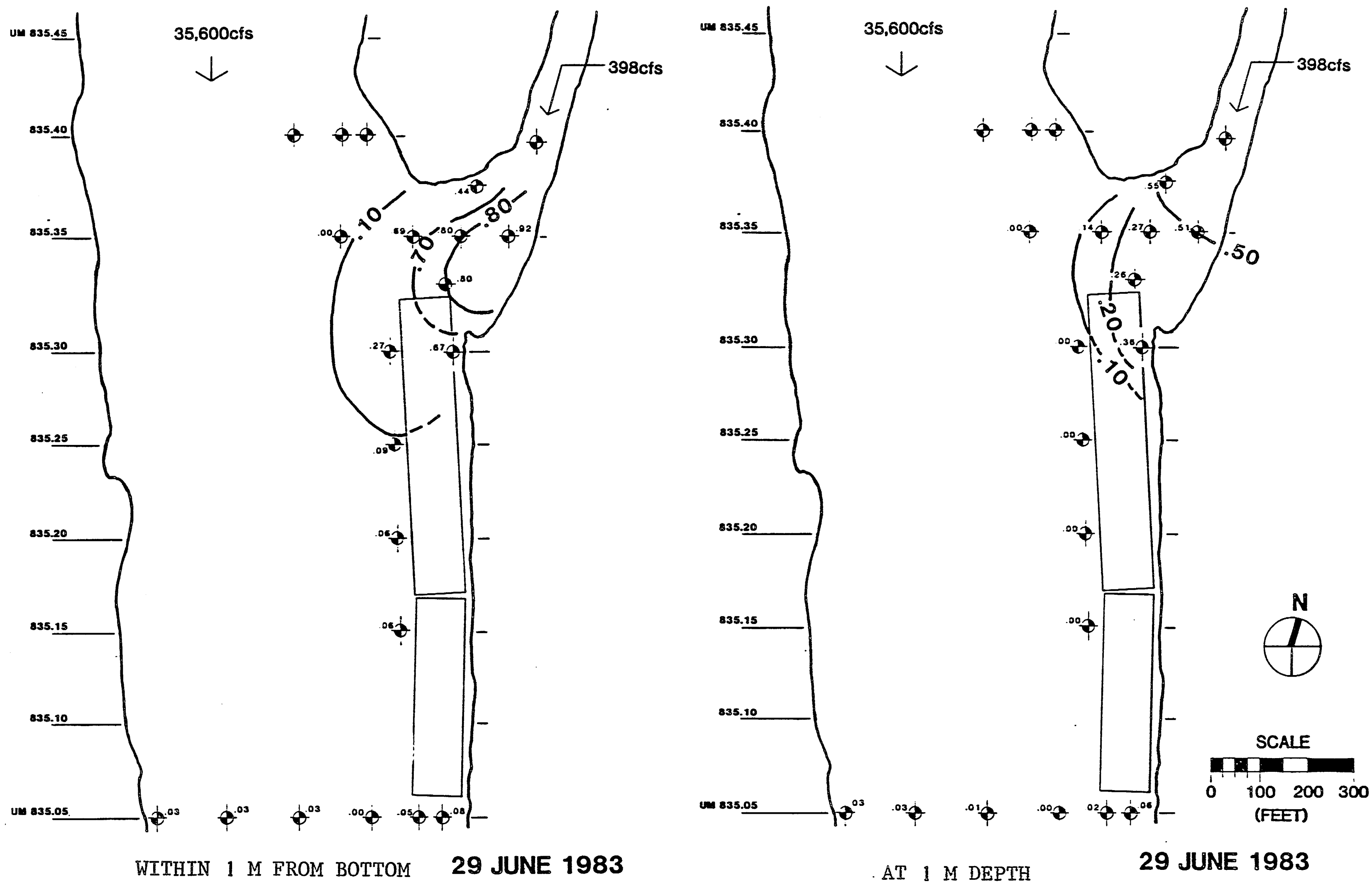
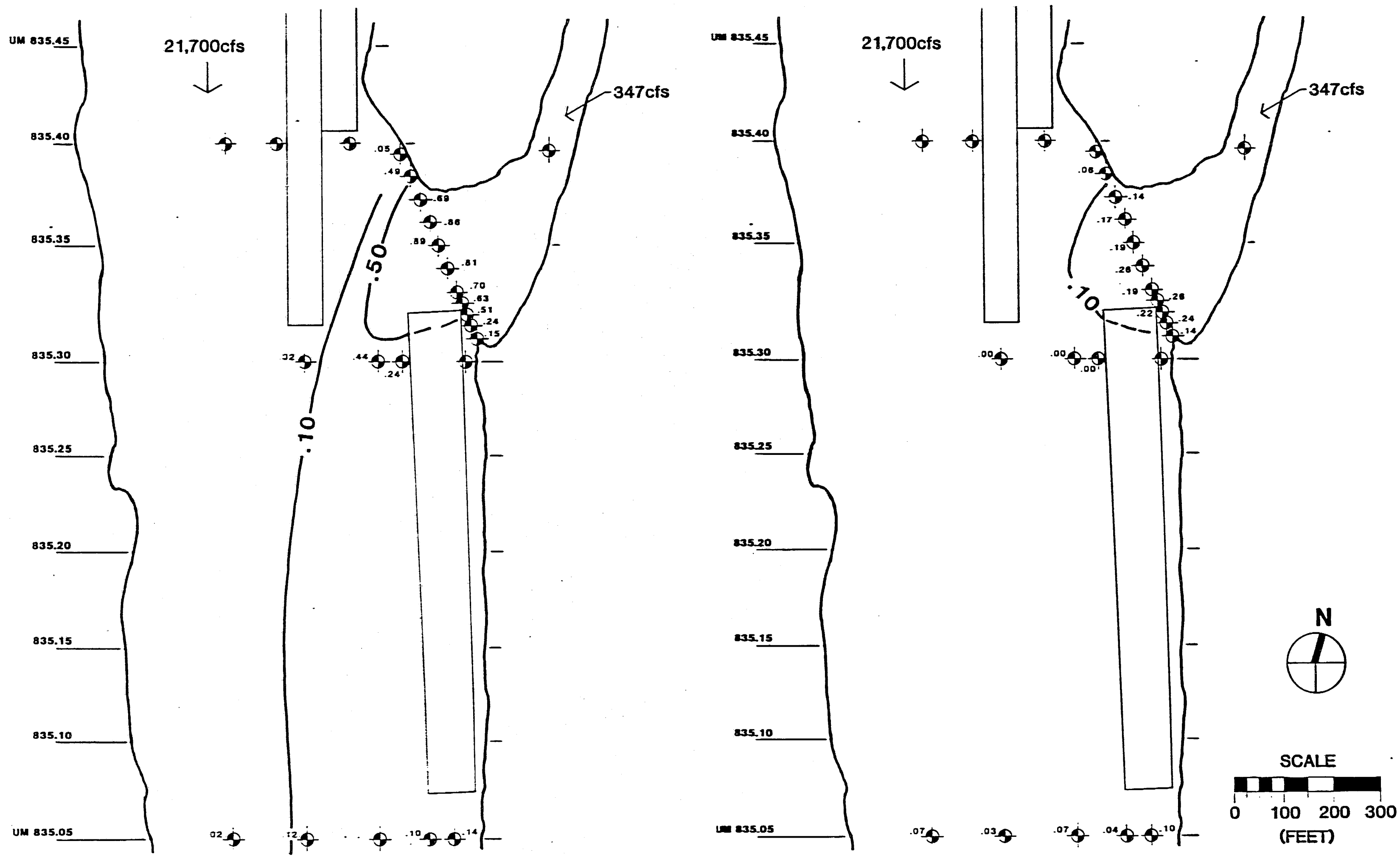



Fig. V-1. Mixing of the Metro WWTP effluent sinking plume with the Mississippi River. Normalized excess concentrations at 35,600 cfs river flow and effluent densimetric Froude number of 1.40 are given.




WITHIN 1 M FROM BOTTOM **20 JULY 1983**

AT 1 M DEPTH **20 JULY 1983**

Fig. V-2. Mixing of the Metro WWTP effluent sinking plume with the Mississippi River. Normalized excess concentrations at 21,700 cfs river flow and effluent densimetric Froude number of 1.51 are given.

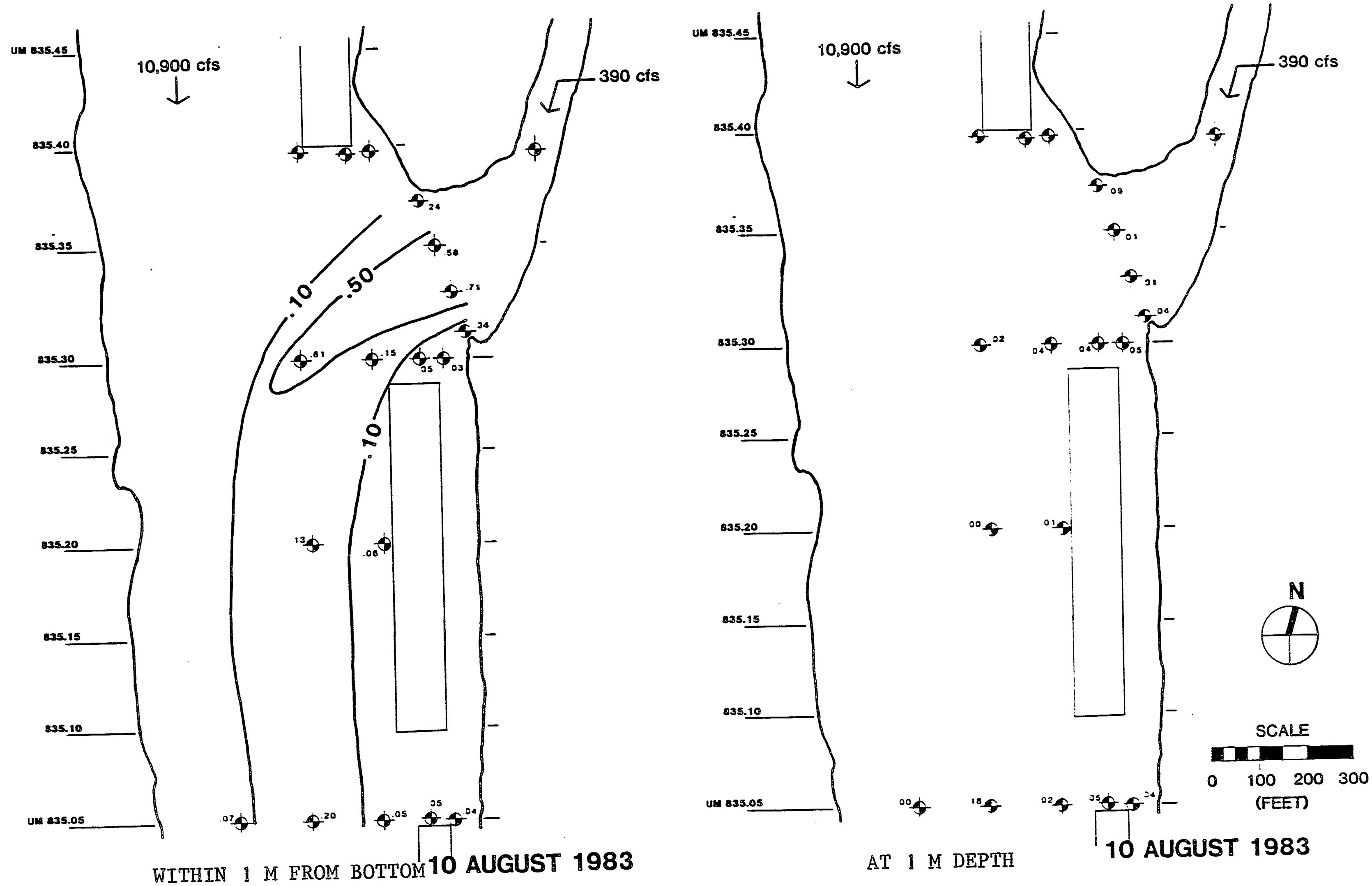



Fig. V-3. Mixing of the Metro WWTP effluent sinking plume with the Mississippi River. Normalized excess concentrations at 10,900 cfs riverflow and effluent densimetric Froude number of 2.56 are given.

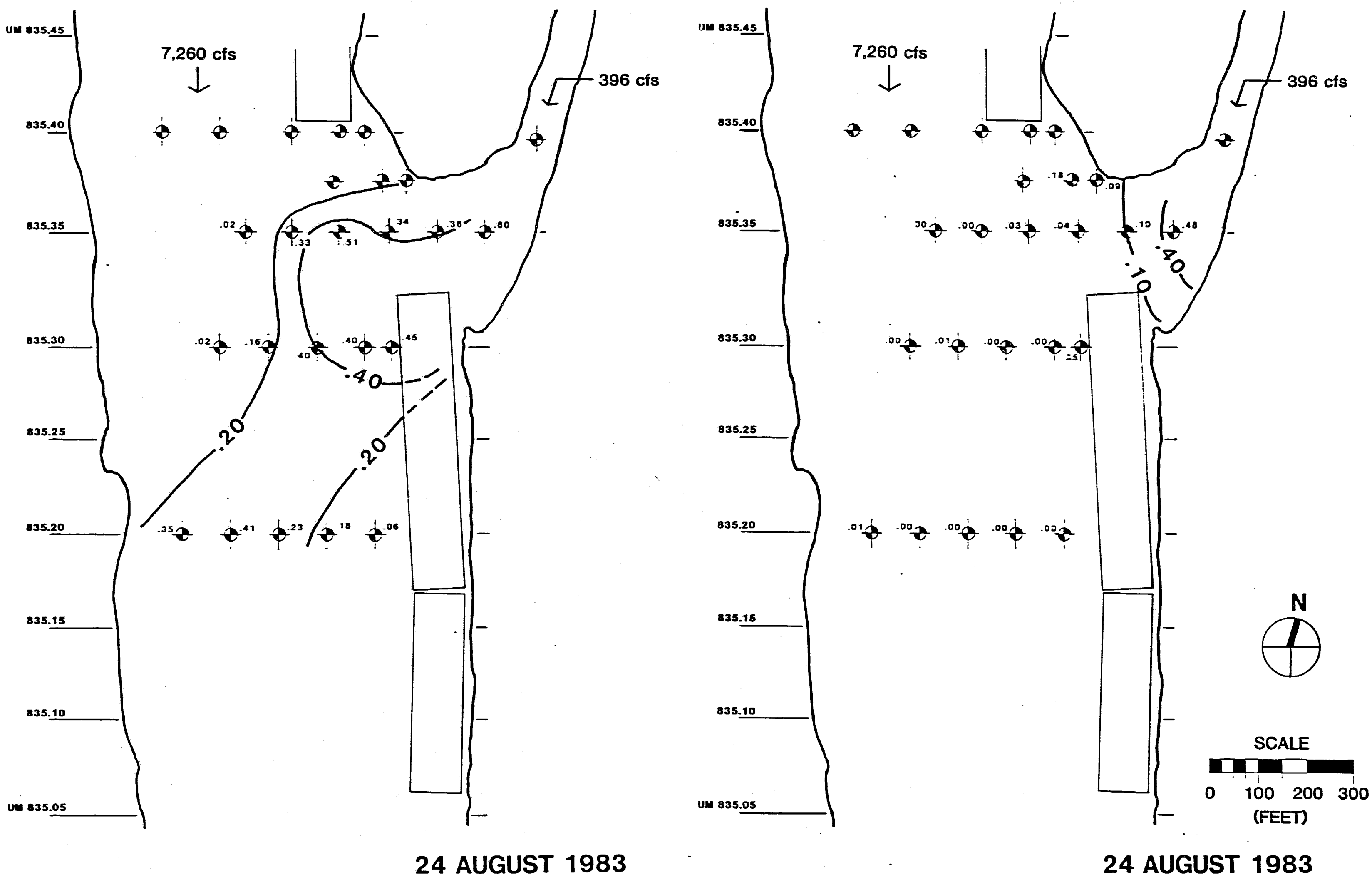
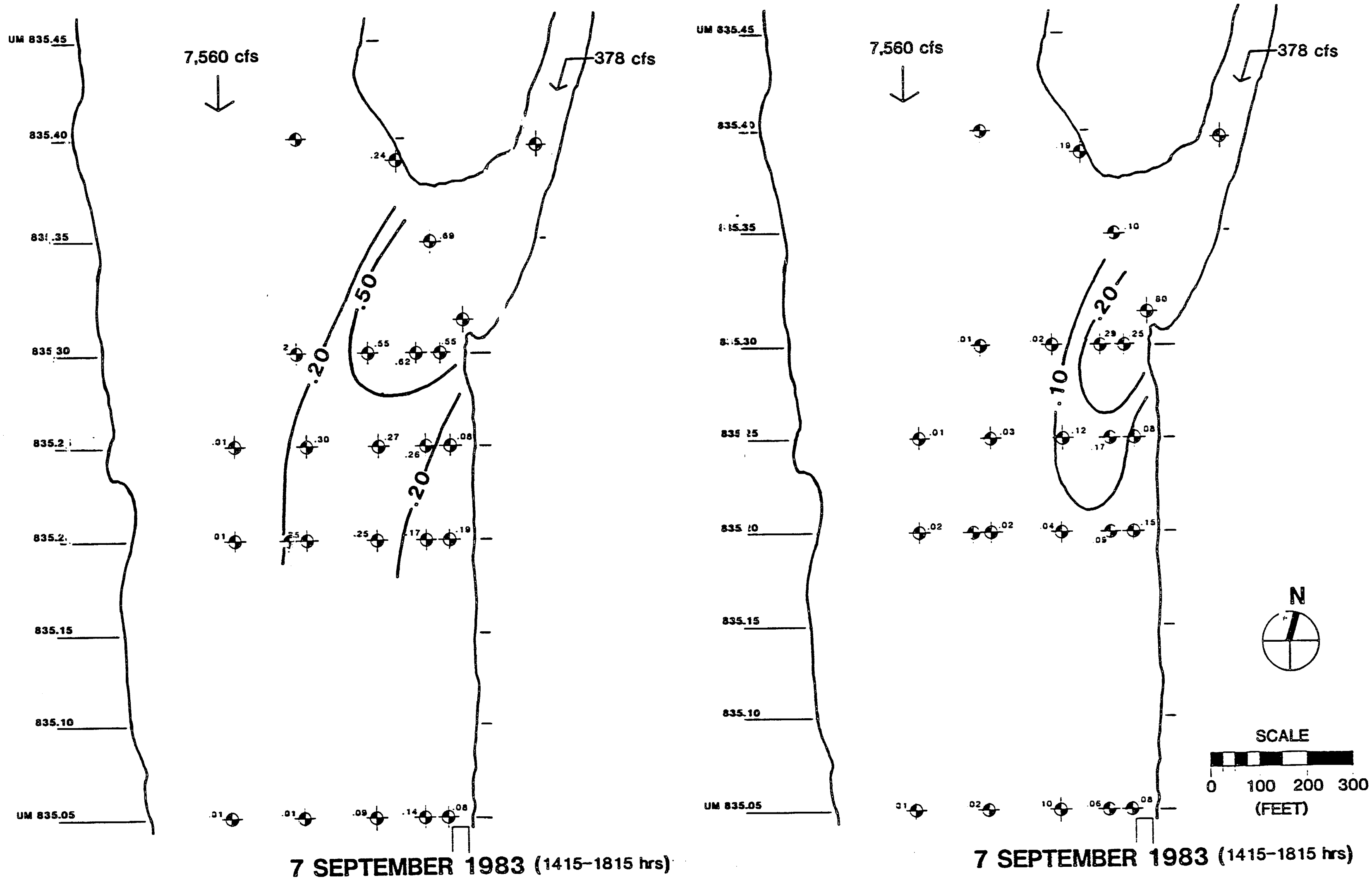



Fig. V-4. Mixing of the Metro WWTP effluent sinking plume with the Mississippi River. Normalized excess concentrations at 7,260 cfs river flow and effluent densimetric Froude number of 3.39 are given.




WITHIN 1 M FROM BOTTOM　　　　　AT 1 M DEPTH

Fig. V-5. Mixing of the Metro WWTP effluent plume of nearly neutrally buoyant conditions with the Mississippi River. Normalized excess concentrations at 7,560 cfs river flow and effluent densimetric Froude number of 4.90 are given.

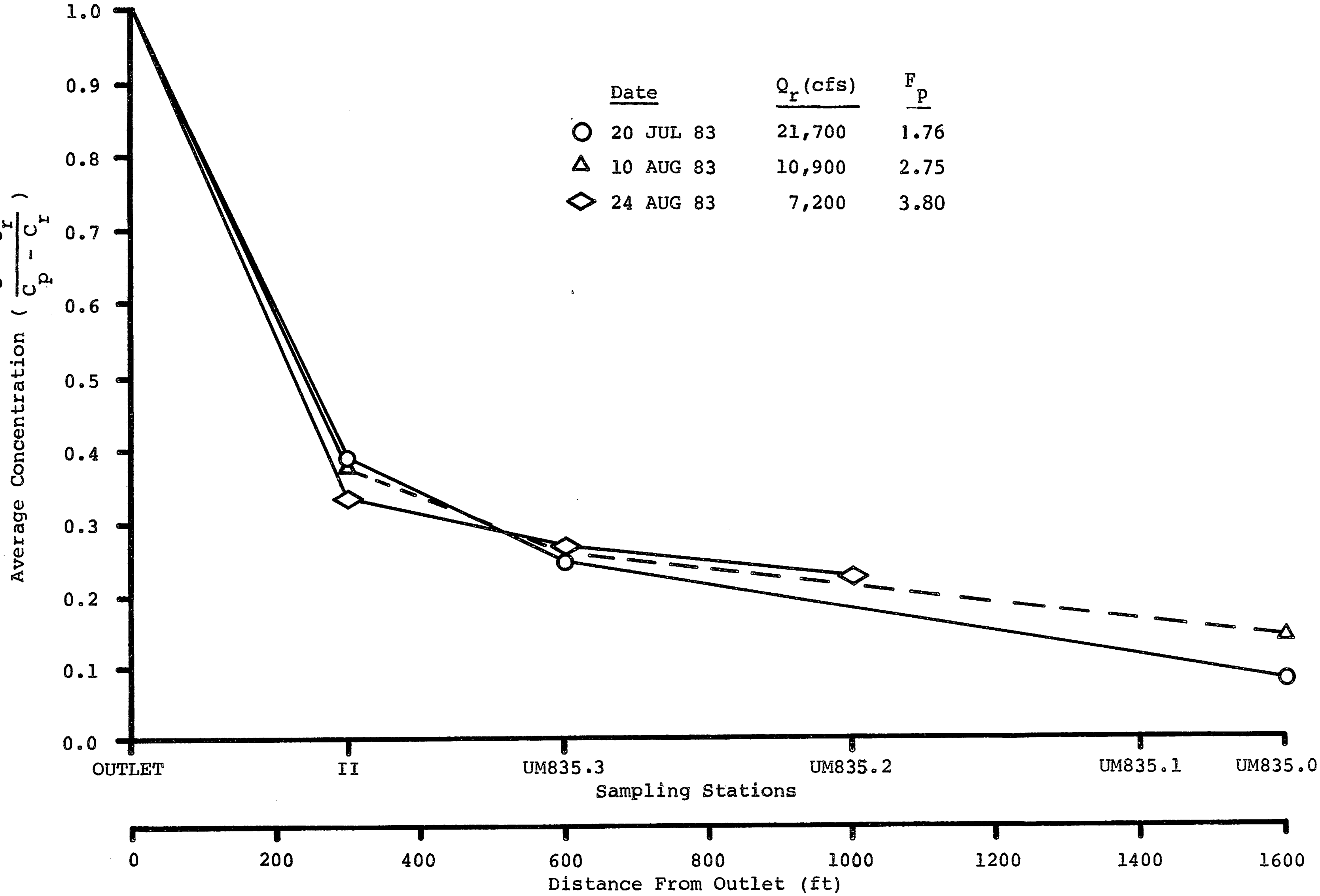



Fig. V-7. Decreasing average excess concentration within the effluent plume with distance downstream from the outlet.

By river mile 835.05, the plunging effluent can be characterized as either vertically well mixed with horizontal turbulent diffusion (above approximately 30,000 cfs river flow) or horizontally stratified with vertical turbulent diffusion (when river flow is below approximately 10,000 cfs). Between 10,000 and 30,000 cfs, either condition could occur depending on the strength of the plunging (densimetric Froude number). Because only one survey was done between 10,000 and 30,000 cfs, the effect of the densimetric Froude number could not be evaluated.

## VI. INITIAL CONDITION FOR 2-D VERTICAL MIXING FARFIELD MODEL

In the modeling of the summer Metro WWTP effluent, the flow region has been divided into three reaches: plunging flow, nearfield, and farfield. The plunging flow reach is contained within the diffuser for all flow rates. The nearfield is defined as the river reach influenced by the outlet conditions of the effluent. The farfield reach extends from the downstream end of the nearfield to the end of the mixing zone. The length of the farfield depends on the conditions at the end of the nearfield and the dilution criteria used to define the limit of the mixing zone.

### 1) Definition and Delineation of the Nearfield

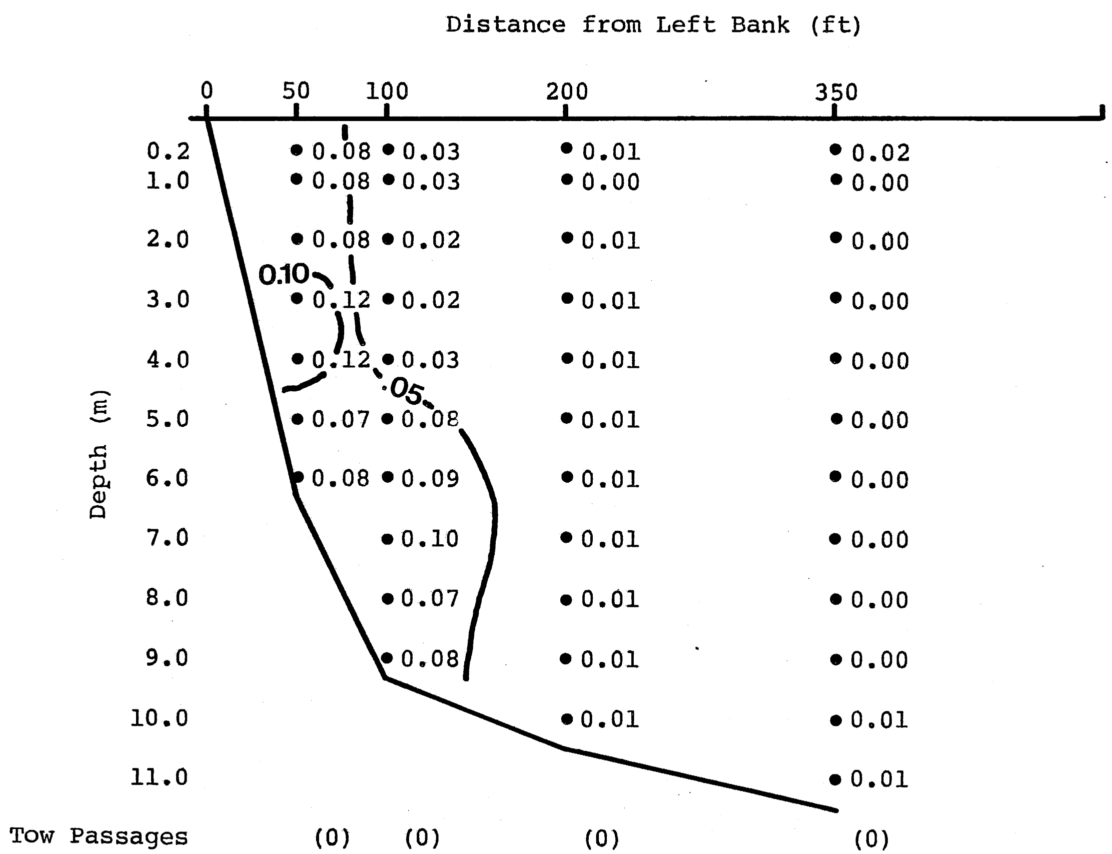
Traditionally, the nearfield has been defined as the region of flow affected by the outlet conditions. In most cases, the nearfield is quite short and limited to the region immediately downstream of the outlet. For a plunging flow, however, the nearfield must be extended downstream to a point where the stratified flow is no longer spreading transversely or has become established across the entire channel bottom.

The extended nearfield is required for two reasons. First, the transverse spreading under a density gradient between the river and effluent is a component of the outlet conditions. Second, a two dimensional farfield model can be applied in the case of either plunging or nonplunging flows if an extended nearfield is used.

The result is a broader definition of a nearfield reach. The nearfield becomes the portion of river in which the flow becomes either vertically stratified or vertically well mixed. The farfield becomes the region where advective mixing of the effluent is no longer significant and mixing is by either vertical or horizontal diffusion. The broader definition is consistent with the traditional definition, but includes a transverse spreading reach due to both outlet velocity and outlet density.

During the summer months, the nearfield may become either vertically stratified or vertically well mixed depending on the river flow rate and densimetric Froude number. For river flow rates in excess of 30,000 cfs, the stratified flow at the diffuser mouth is vertically mixed by the shear flow of the river, and the Froude number effect is negligible. The effluent plume quickly becomes vertically well mixed and downstream mixing is due to horizontal diffusion. Figure VI-1 illustrates the vertically well mixed condition at section 835.05 on 29 June 1983. The plume is largely homogeneous for a small portion of slightly higher concentration. The higher concentration is considered to be due to channelling of the effluent between moored barges and the shore.

At river flow rates below 10,000 cfs and Froude numbers less than 6.0, the effluent plunges from the diffuser and spreads transversely along the river bottom. For all low flow cases observed during the 1983 survey, a




29 June 1983

UM 835.05

$Q_p$ = 398 cfs

$Q_r$ = 35,600 cfs

$F_p$ = 1.65

Fig. VI-1. Dimensionless excess concentration distribution at cross section UM 835.05 on 29 June 1983.

stratified flow was established across the entire channel by UM 835.05 in the absence of barge traffic. For illustration, the concentration distribution in the plume at UM 835.05 on 10 August and at UM 835.2 on 24 August are presented in Figures VI-2 and VI-3, respectively.

For river flow rates between 15,000 and 30,000 cfs, the nearfield condition may vary from either vertically stratified or vertically well mixed depending on the densimetric Froude number. Only one survey was taken between 15,000 and 30,000 cfs and the nearfield condition is presented in Figure VI-4. The concentration pattern is neither vertically well mixed nor stratified, but the flow in this case is heavily influenced by moored barges and barge traffic. Consequently, a determination of nearfield conditions cannot be made for river flow rates of 10,000 to 30,000 cfs from the 1983 survey. Figure VI-5 summarizes the currently available information.

As the flow rate decreases, the transverse spreading is more pronounced. The effluent spreads across the channel more rapidly resulting in a shorter nearfield for the same densimetric Froude number. During the 1983 survey data was not taken continuously, but only at discrete points. Consequently, the limit of the nearfield can only be approximated from the data. On 20 July, a stratified flow condition was established by UM 835.05 for a flow rate of 21,700 cfs. On 10 August, a stratified flow was also established by UM 835.05 at a river flow rate of 10,900 cfs, but the data collected was insufficient to determine if the stratified flow was established at some point before UM 835.05. At a lower flow rate of 7,260 cfs on 24 August, the stratified flow was established by UM 835.20, but was not established by UM 835.30. Consequently, the nearfield can be estimated to be at UM 835.2 on 24 August at 7260 cfs river flow and at 835.05 on 20 July at 21,700 cfs river flow. On 10 August, the limit of the nearfield can be assumed to be between UM 835.20 and UM 835.05.

The length of the nearfield is also dependent on the densimetric Froude number. However, the data is insufficient to estimate the effect of Froude number. Only one survey was performed for each flow rate which prohibits the estimation of Froude number effect for a constant flow rate. Densimetric Froude numbers calculated for the concrete lined portion of the outlet channel varied from 1.65 to 4.23 (Table III-4).

The river mile at which the nearfield/farfield boundary is located has been added in Fig. VI-5.

## 2. Effect of Barges on the Nearfield

Barges affect the effluent plume by being moored downstream of the discharge site and by turbulent mixing of the water column during barge passages. Barges moored along the river often extend upstream partially obstructing the mouth of the diffuser (29 June, 20 July, 24 August). If the barges are loaded, the bottom of the barges will be very close to the bottom of the river along the shore and a portion of the effluent will flow between the barges and shore with very little mixing. The channelled effluent enters the river downstream of the line of barges causing an unusually high concentration in the river downstream of the barges (Figs. VI-1 and VI-4). The result is a distorted profile and an extended

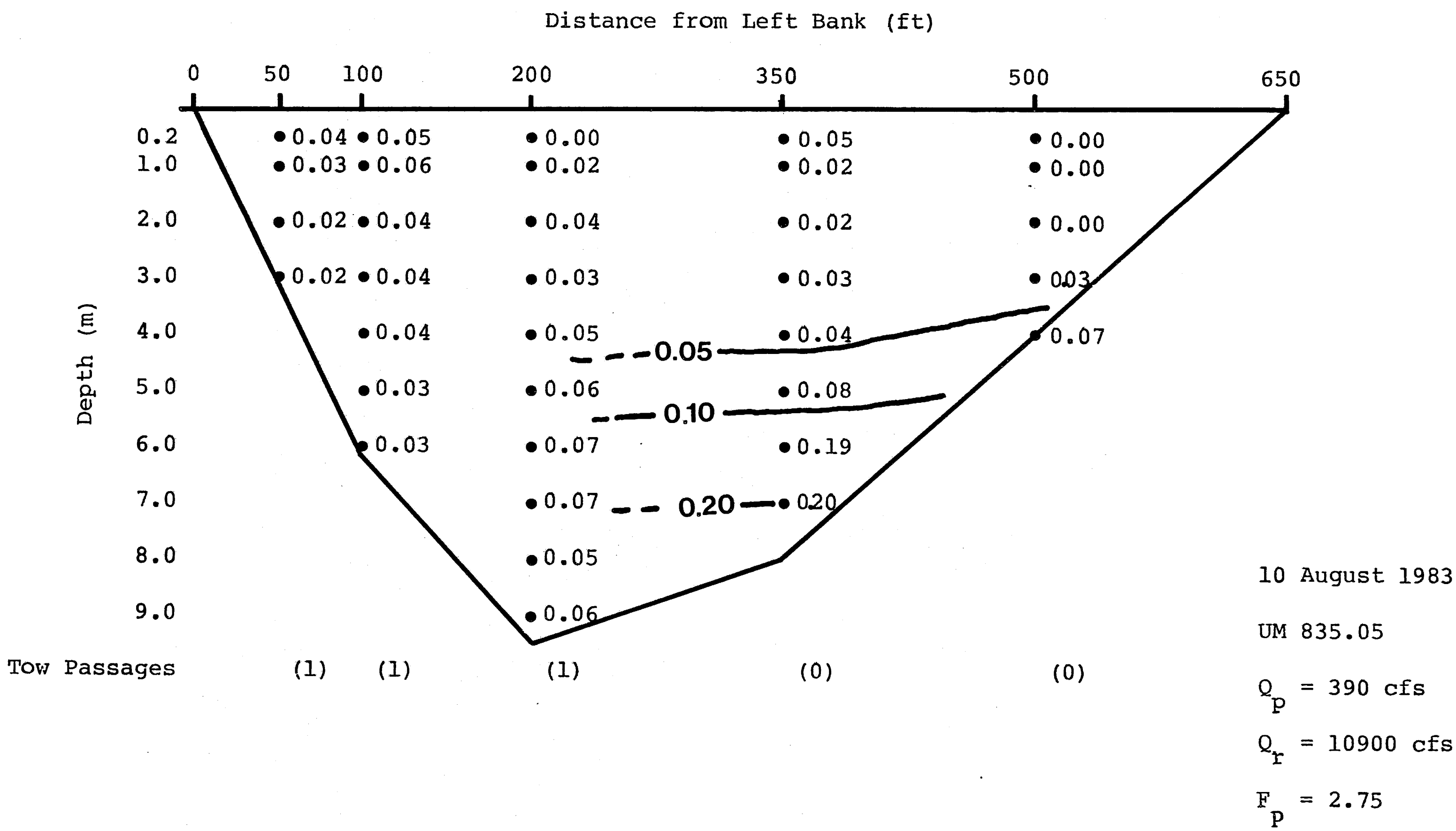



Fig. VI-2. Dimensionless excess concentration distribution in cross section UM 835.05 on 10 August 1983.

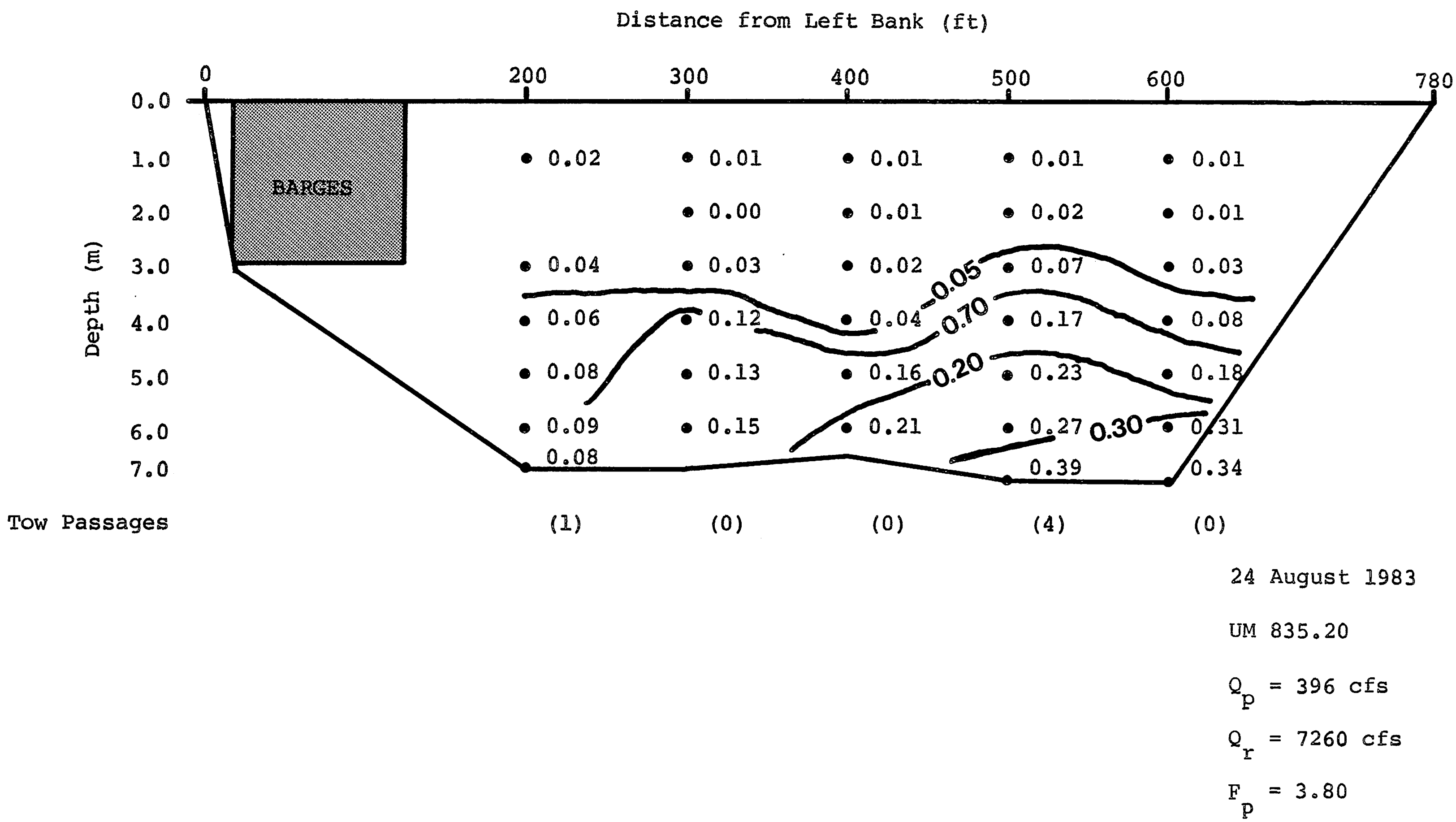



Fig. VI-3. Dimensionless excess concentration distribution in cross section UM 835.20 on 24 August 1983.

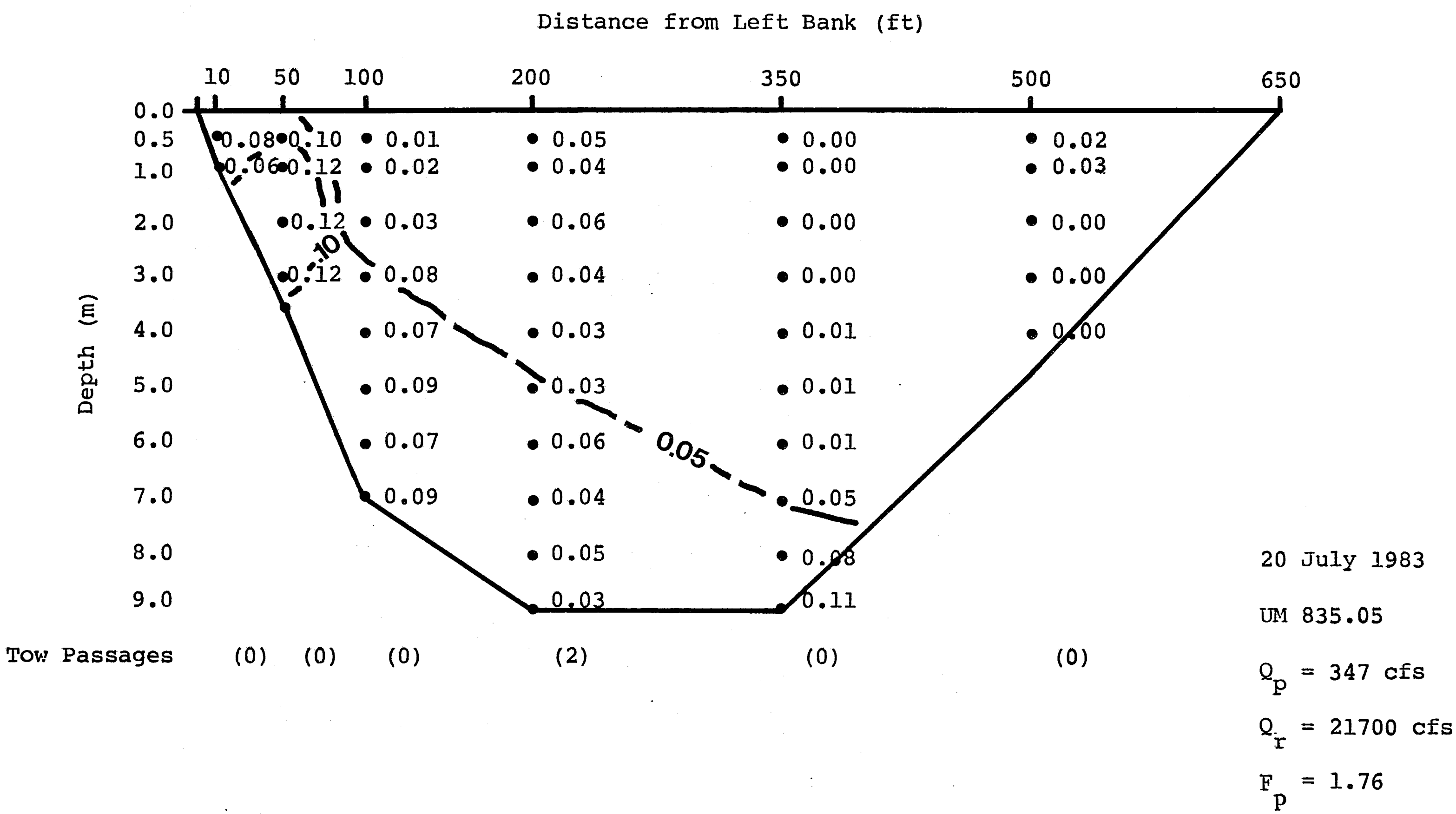



Fig. VI-4. Dimensionless excess concentration distribution in cross section UM 835.05 on 20 July 1983.

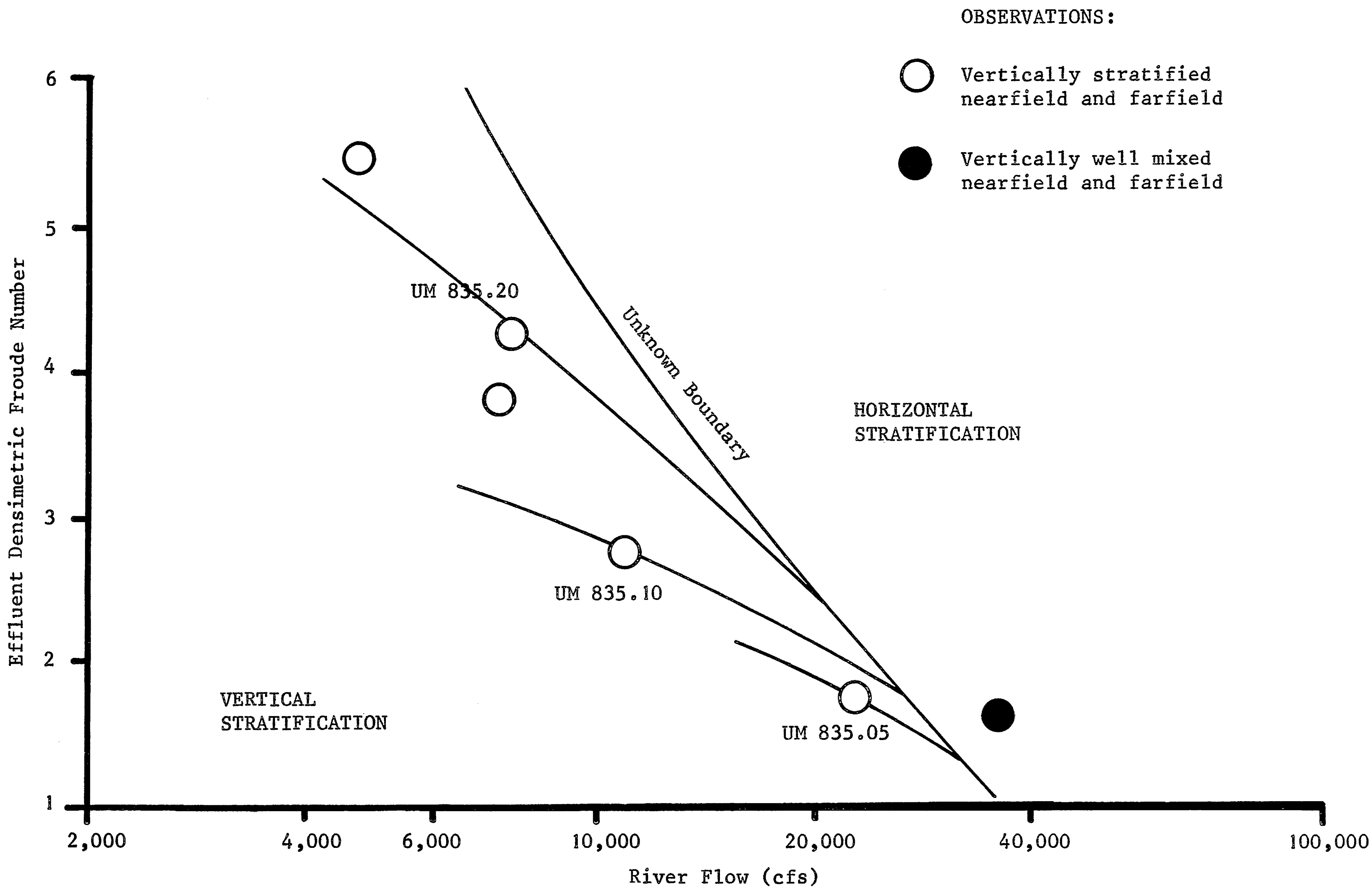



Fig. VI-5. Observed flow regimes in nearfield and farfield.

nearfield reach in which the channelled effluent either mixes vertically or plunges into the river channel. The effect of the moored barges on the nearfield was not specifically investigated during the 1983 survey and only qualitative results can be given.

Moving barge traffic has a much more pronounced and better understood effect on the mixing of the effluent plume. A detailed discussion of the effect of barge passages is present in SAFHL External Memorandum No. 186, "Mixing of Wastewater Effluents by Barge Tows in the Upper Mississippi and Minnesota Rivers." The effect of a barge passage is most clearly illustrated in Fig. VI-2. The stratified flow condition observed 350 feet from the left bank is expected to extend across the entire channel. However, the profiles taken at 50 feet, 100 feet, and 200 feet were all disturbed by barge passages and a stratified flow condition could not be observed. It is expected that the passage of barges completely mixes the water column throughout most of the channel depending on towboat size, draft of barges, number of barges abreast, and the speed of the towboat and barges.

The time for reestablishment of the stratified flow condition depends on the distance of the section from the mouth, the river velocity, and the extent of surging from the outlet due to the barge passage. The travel time to the section as determined from distance and river velocity is not a reliable measure of the time required for a fully mixed condition to become restratified. In general, the nearfield will develop a stratified flow only if barges pass at time intervals longer than the travel time to the end of the nearfield. On 20 July, the travel time to UM 835.05 was estimated at 14 min and on 24 August the travel time to UM 835.20 was estimated at 24 min. The maximum barge passage frequency observed during the survey was one barge every 23 min on 7 September, but barge frequency is reduced in late evening and early morning. Consequently, the nearfield mixing by barge passages is insufficient to prevent stratified flow in the nearfield. It has a more significant effect in the farfield where the travel time is longer and the concentration gradients are weaker.

## 3. Parameter Estimation for Vertical Mixing Farfield Model

The flow conditions at the end of the nearfield are characterized by a maximum concentration, a standard deviation of the vertical concentration profile, and the average concentration within the plume. The maximum concentration occurs at the bottom in an undisturbed profile. For the survey data of 1983, the maximum concentration decreased with increasing flow rate, even though the initial Froude number increased. The maximum concentration flow rate relationship is plotted in Fig. VI-6 for 20 July, 10 August, and 24 August. The maximum concentration at the end of the nearfield is strongly influenced by the river flow rate with decreasing maximum concentration for increasing river flow rate.

The standard deviation of the vertical concentration profile describes the distribution of the concentration from a maximum near the bottom to near ambient river conditions at the surface. The standard deviation is calculated from

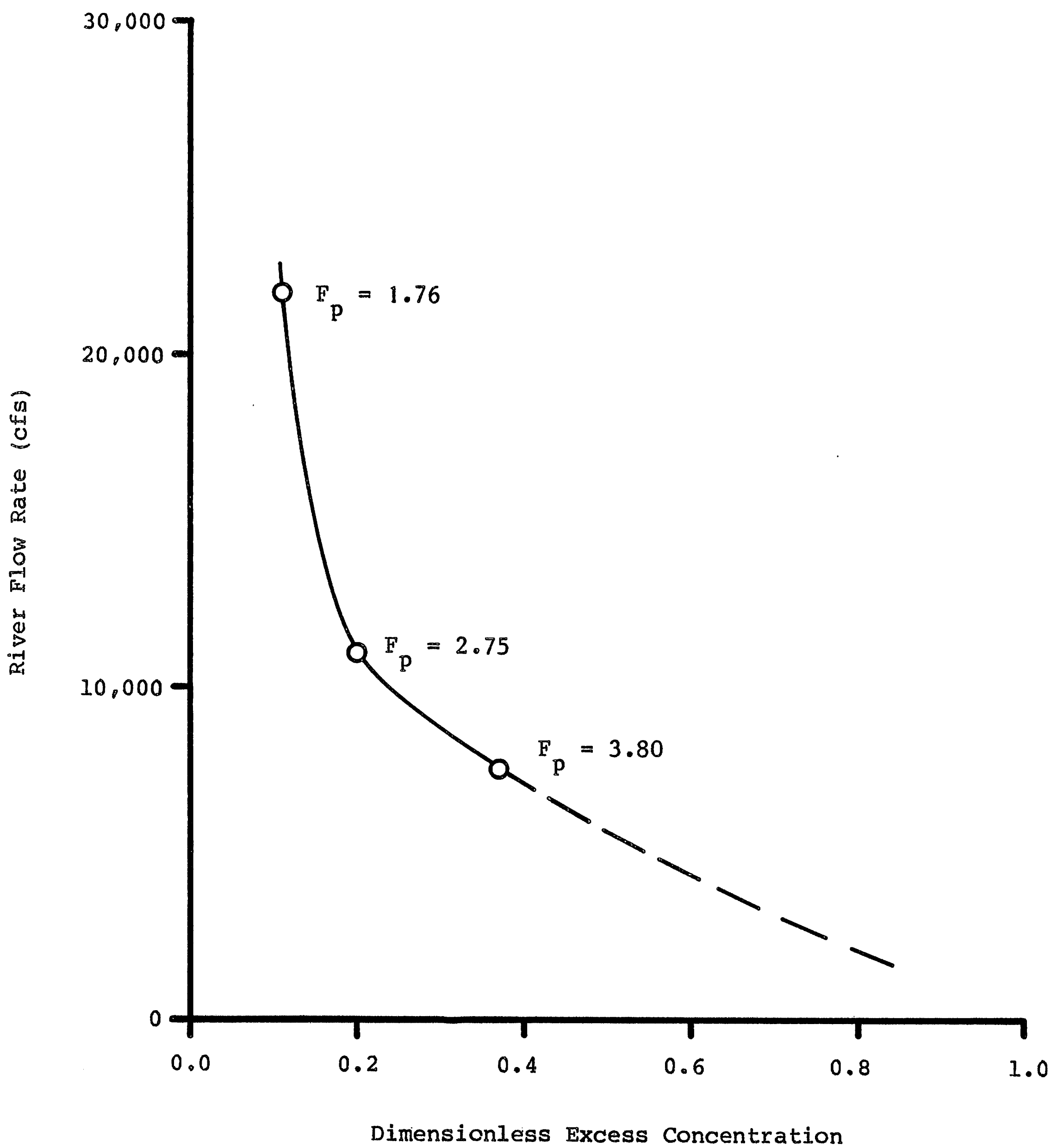



Fig. VI-6. Maximum dimensionless excess concentration at the end of the nearfield in relation to river flow rate.

$$\sigma_z = \left( \frac{\Sigma C(z)^2}{\Sigma C} \right)^{1/2} \qquad (6)$$

where $z$ is the distance from the channel bottom and $C$ is the concentration at depth $z$. The summation is over the entire water column.

The standard deviation calculation assumes that the concentration is normally distributed in the water column. The standard deviation at the end of the nearfield for 20 July, 10 August, and 24 August are presented in Table VI-1. On 20 July and 10 August, the profile is disturbed by barge passages and only one undisturbed profile was used in the calculation. The single profile used for the data of 20 July was taken too soon after the barge passage; a fully stratified flow was not yet reestablished.

The average concentration in the plume at the end of the nearfield was calculated by

$$C = \frac{\Sigma C_i A_i}{\Sigma A_i} \qquad (7)$$

where $C_i$ is the concentration in subarea $A_i$. The summation is over the entire portion of the cross section under the plume whose boundary is defined as 95 percent of the fully mixed concentration. The computation assumes a uniform flow velocity in the entire cross section. Data for 20 July, 10 August, and 24 August were used despite the barge disturbed profiles. The data follows the same trend as the maximum concentration with an increasing average concentration with decreasing flow rate. The results are plotted in Fig. VI-7.

The average temperature and total dissolved solids in the plume are used to determine the average density in the plume which is used to calculate local, cross-sectional densimetric Froude number of the plume ($F_{OD}$). This densimetric Froude number can be used to estimate the vertical diffusion coefficient (Schiller and Sayre, 1975). The densimetric Froude number and the vertical diffusion coefficient for 20 July, 10 August, and 24 August are presented in Table VI-2. The computed vertical diffusion coefficient is compared to the previous estimates (Stefan, 1982) in Table VI-3. In a vertical mixing model, the vertical diffusion coefficient and the concentration distribution determine the rate of vertical mixing and, ultimately, the length of the farfield.

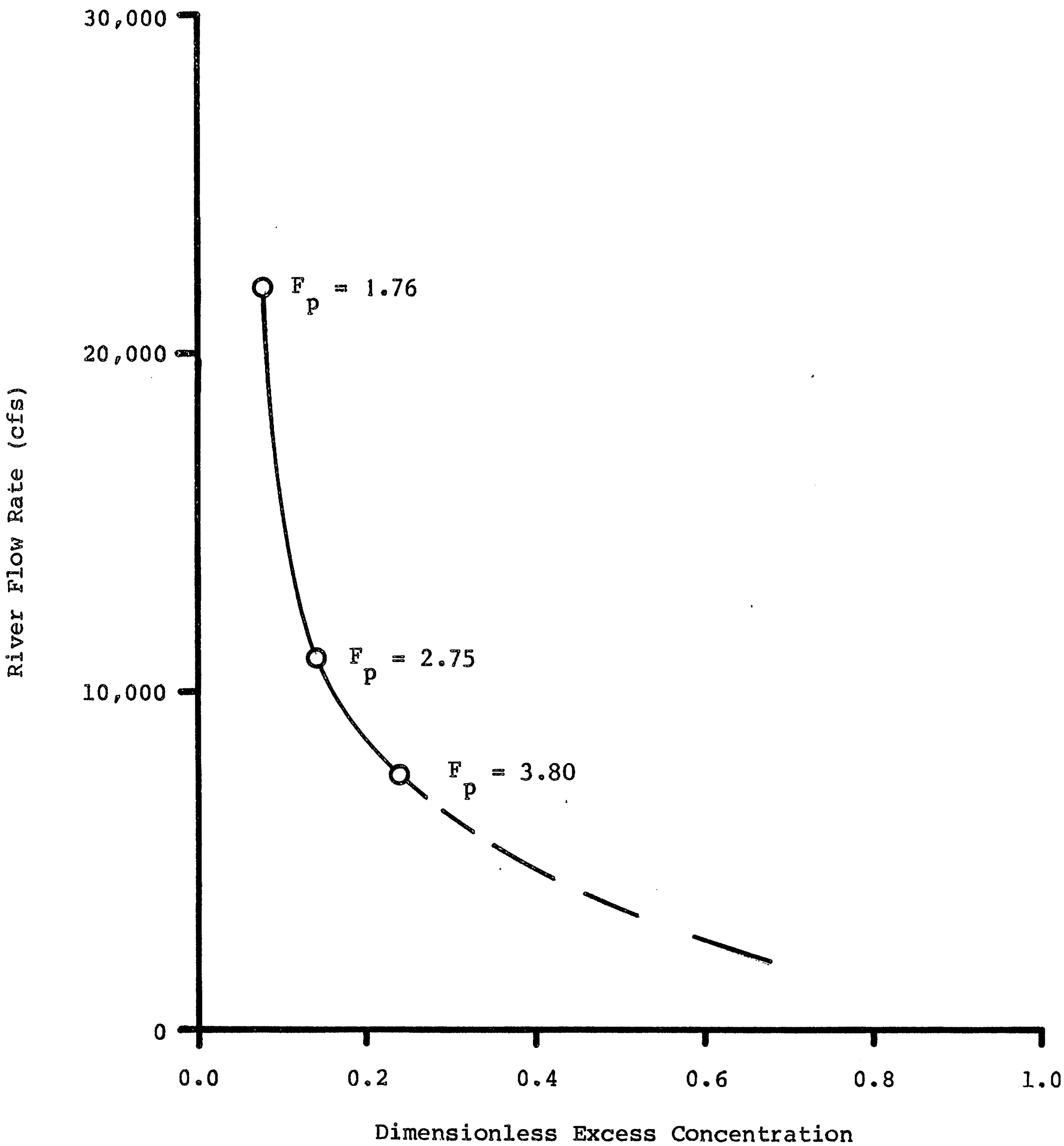



Fig. VI-7. Average dimensionless excess concentration in the effluent plume at the end of the nearfield in relation to river flow rate.

TABLE VI-1. VERTICAL STANDARD DEVIATION OF THE CONCENTRATION DISTRIBUTION FOR DATA FROM THE 1983 METRO WWTP SURVEY

| Date | River Flow Rate | Effluent Densimetric Froude Number | Distance to End of Nearfield | Vertical Standard Deviation at End of Nearfield |
|---|---|---|---|---|
| | (cfs) | | (ft) | (ft) |
| 20 July 1983 | 21,700 | 1.76 | 1600 | 2.1 |
| 10 August 1983 | 10,900 | 2.75 | 1300 | 3.5 |
| 24 August 1983 | 7,200 | 3.80 | 800 | 1.9 |

TABLE VI-2. DENSIMETRIC FROUDE NUMBER OF THE UNDERFLOW ($F_{OD}$), AND CORRESPONDING VERTICAL DIFFUSION COEFFICIENT AT UM 835.05 ON 20 JULY 1983 AND 10 JULY 1983 AND AT UM 835.2 ON 24 JULY 1983

| Date | $F_{OD}$ | $\frac{D_v}{u_* H}$ | $Q_r + Q_p$ |
|---|---|---|---|
| | | | (cfs) |
| 20 July 1983 | 4.89 | .035 | 22050 |
| 10 Aug 1983 | 2.18 | .018 | 11290 |
| 24 Aug 1983 | 1.68 | .013 | 7660 |

TABLE VI-3. COMPARISON OF VERTICAL DIFFUSION COEFFICIENTS FOR VARIOUS FLOW RATES FROM THE 1982 AND 1983 SURVEYS

| Discharge | Date | $\frac{D_v}{u_* H}$ | $D_v$ |
|---|---|---|---|
| | | | ($ft^2/s$) |
| 22,000 | 20 July 1983 | .035 | .07 |
| 20,000 | Estimated | .030 | .06 |
| 11,000 | 10 August 1983 | .018 | .019 |
| 10,000 | Estimated | .017 | .016 |
| 7,500 | 24 August 1983 | .013 | .010 |
| 5,000 | Estimated | .008 | .004 |

# VII. PREDICTION OF MIXING ZONE LENGTHS FOR VERTICALLY STRATIFIED FARFIELD CONDITIONS

Given the river flow, plant discharge and river and effluent temperature and dissolved solids contents in both, the estimation of the total mixing zone length for summer conditions can proceed in the following way:

**Nearfield**

1. Calculate effluent and river water density and the effluent densimetric Froude number (see e.g. Table III-4).

2. Determine if the nearfield and farfield flow will be vertically stratified or not (Fig. VI-5).

3. If it is horizontally stratified, refer to St. Anthony Falls Hydraulic Laboratory Project Report No. 214 for analysis.

4. If flow is vertically stratified, estimate the length of nearfield (Table VI-1 can help).

**Virtual Nearfield**

5. Estimate maximum concentration ($C'_m$) of sewage layer at the end of nearfield (Fig. VI-6).

6. Calculate the dimensionless concentration ratio $C/C_o$ at the end of the nearfield, where $C$ is the maximum excess concentration and $C_o$ is the well-mixed excess river concentration

$$C = C'_m |C_p - C_r|$$

$$C_o = \left| \frac{(C_p - C_r)Q_p}{Q_p + Q_r} \right| \tag{8}$$

7. Referring to Fig. V-3 in Report No. 214 determine the dimensionless distance to a virtual source on the bottom of the river $x' = x'_{near}$ from the curve called "left bank" (applies here to river bottom). (See Appendix B for figures and tables from Report No. 214.)

Farfield

8. Calculate the dimensionless length of the farfield $x'_{95} - x_{near}$ or $x'_{90} - x'_{near}$. The subscripts 95 and 90 mean that the effluent water is diluted to within 95% or 90% of the well mixed conditions, respectively. $x'_{95} = 0.4$ and $x'_{90} = 0.3$ from Fig. V-3 in Report No. 214.

9. Calculate the densimetric Froude number $F_{OD}$ at the end of the nearfield and find the vertical dimensionless diffusion coefficient $D_V/u_*H$ (Fig. VI-1 in Report No. 214).

10. Estimate $u_*H$ at the given river flow rate (Table VI-3 in Report No. 214) and find the dimensional vertical diffusion coefficient $D_V$.

11. Calculate the dimensional length of the farfield as

$$x_{far} = \left(x'_{95} - x'_{near}\right) \frac{U_* H^2}{D_v} \qquad (9)$$

12. Calculate total length of the mixing zone as

$$x_{total} = x_{near} + x_{far} \qquad (10)$$

A much simplified estimate of the length of the farfield which entirely ignores dilution in the nearfield can be made using the vertical diffusion coefficient, the given velocity and mean depth (Stefan, 1982). The farfield length for a 90 percent dilution of the plume is given by

$$X_{90} = \frac{0.3 u_* H^2}{D} \qquad (11)$$

The diffusion coefficient, flow parameters, and mixing length for 20 July, 10 August, and 24 August are presented in Table VII-1. The results indicate a strong effect of river flow rate as both the velocity and the vertical diffusion coefficient decrease with decreasing flow rate. Mixing zone length for very low flow rates would have to be extrapolated well below the minimum flow condition observed.

Estimates of the mixing zone length under vertical mixing are considerably less than the mixing zone lengths obtained for lateral diffusion in a horizontal mixing model (Stefan, 1982).

Sample computations are given in Table VII-2. A travel-time/distance diagram showing computed mixing zone lengths (in the absence of navigation) is given in Fig. VII-1.

Towboats and barges, particularly loaded barges, produce much vertical mixing and thereby reduce the length of the farfield shown in Fig. VII-1.

TABLE VII-1. ESTIMATES OF THE TOTAL MIXING ZONE FROM THE FIELD SURVEYS OF 20 JULY, 10 AUGUST, AND 24 AUGUST 1983.

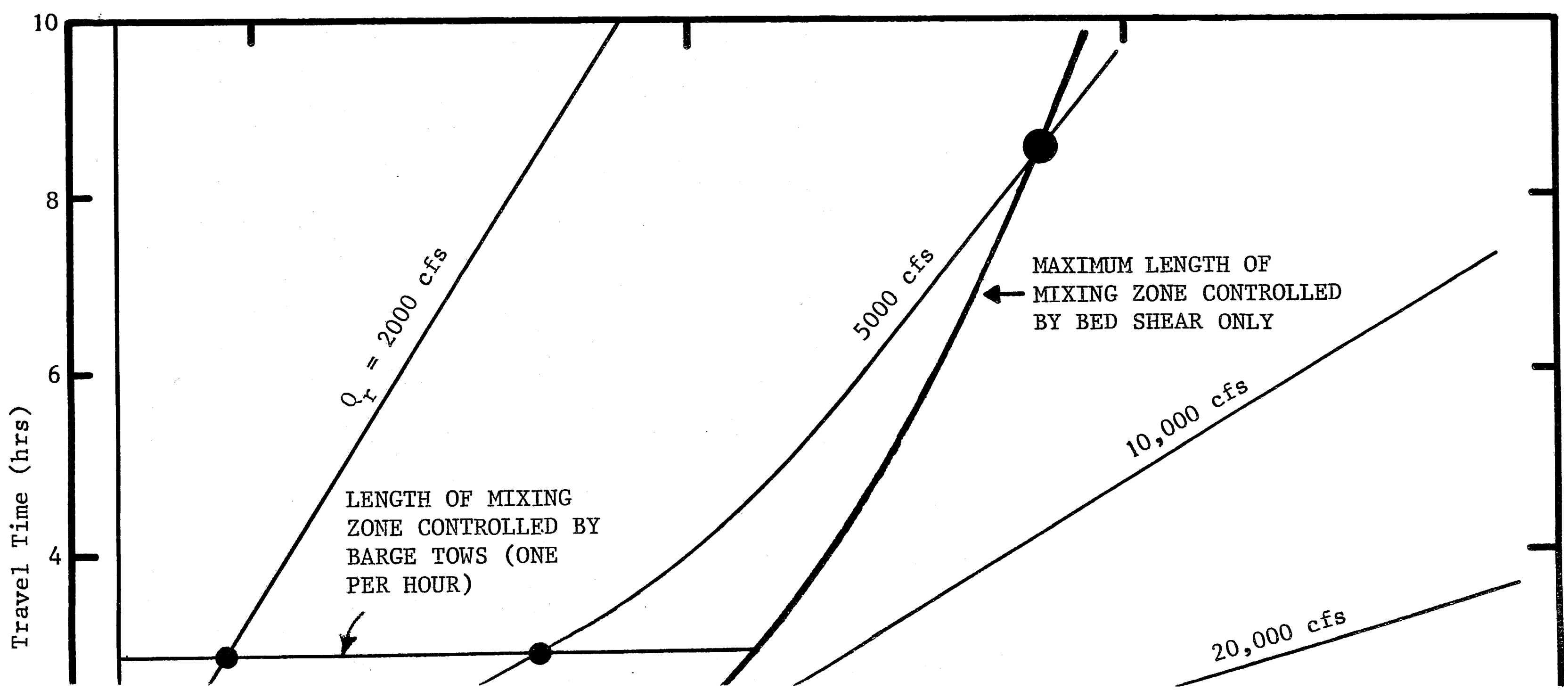
| Date: | 10 July 1983 | 10 August 1983 | 24 August 1983 |
|---|---|---|---|
| Q (cfs) | 22,000 | 11,000 | 7,500 |
| B(ft) | 810 | 810 | 810 |
| H(ft) | 15.4 | 14.7 | 14.5 |
| S (-) | 37.6 $(10^{-6})$ | 11.2 $(10^{-6})$ | 5.5 $(10^{-6})$ |
| $u_* \left(\frac{ft}{s}\right)$ | 0.137 | 0.0728 | .0507 |
| Nearfield (ft) | 1,600 | 1,300 | 800 |
| Farfield (ft) | 1,700 | 3,100 | 4,200 |
| Total (ft) | 3,300 | 4,400 | 5,000 |

For 20 July and 10 August the inital farfield conditions are taken at station 835.05 and on 24 August the initial farfield conditions are evaluated at station 835.2. Distances for each station are from Fig. I-1 or IV-8.

To quantify this effect is still difficult. It has been established by field counts that one to two towboats with barges per hour pass the metro outfall site during a typical summer day. Their effect on mixing depends primarily on the blocking ratio (ratio of cross-sectional area of the barge tow below the water surface and the cross-section area of the river) and the draft/depth ratio (draft of the barges to river depth). Without detailed information available at this time it is estimated from available observations that three towboat/barge passages are sufficient to mix a river cross section fairly completely. With a frequency of one barge tow/hour, it can therefore be expected that on a typical day the farfield of the mixing zone will not extend much more than three hours travel time from the outlet.

TABLE VII-2. SAMPLE CALCULATIONS FOR LENGTH OF THE MIXING ZONE FOR A VERTICALLY STRATIFIED FARFIELD

| | | | | | | |
|---|---|---|---|---|---|---|
| $Q_r$ | (cfs) | 20,000 | 10,000 | 7,500 | 5,000 | 2,000 |
| $Q_p$ | (cfs) | 400 | 400 | 400 | 400 | 400 |
| $H_p$ | (ft) | 5.2 | 4.5 | 4.3 | 4.2 | 4.1 |
| $U_p$ | (ft) | 0.75 | 1.13 | 1.18 | 1.21 | 1.25 |
| $T_r$ | (°F) | 80 | 80 | 80 | 80 | 80 |
| $T_p$ | (°F) | 70 | 70 | 70 | 70 | 70 |
| $\rho_r$ | (kg/m$^3$) | 0.996637 | 0.996637 | 0.996637 | 0.996637 | 0.996637 |
| $\rho_p$ | (kg/m$^3$) | 0.998000 | 0.998000 | 0.998000 | 0.998000 | 0.998000 |
| $F_p$ | (-) | 1.56 | 2.54 | 2.71 | 1.81 | 1.94 |
| $x_n$ | (ft) | 2500 | 1300 | 800 | 700 | 600 |
| $C'_m$ | (-) | 0.2 | 0.3 | 0.6 | 0.7 | 0.8 |
| $C_{excess}$ | (°F) | 2.0 | 3.0 | 6.0 | 7.0 | 8.0 |
| $C_{D_{excess}}$ | (°F) | 0.20 | 0.38 | 0.51 | 0.74 | 1.67 |
| $(C/C_o)_{excess}$ | | 10.0 | 7.89 | 11.8 | 9.45 | 4.80 |
| $x'_n$ | (-) | 0.0031 | 0.0051 | 0.0023 | 0.0036 | 0.014 |
| $\rho_{OD}$ | (mg/m$^3$) | .996933 | .997077 | .997491 | .997623 | .99752 |
| $H_r$ | (ft) | 15.3 | 14.7 | 14.5 | 14.4 | 14.3 |
| $U_r$ | (ft/s) | 1.63 | 0.846 | 0.643 | 0.432 | 0.174 |
| $F_{OD}$ | (-) | 4.26 | 1.85 | 1.02 | 0.94 | 0.24 |
| $D_v/u_*H$ | (-) | 0.032 | 0.014 | 0.008 | 0.007 | 0.002 |
| $u_*$ | (ft/s) | 0.127 | 0.0667 | 0.0507 | 0.0341 | 0.0138 |
| $D_v$ | (ft$^2$/s) | 0.062 | 0.014 | 0.0059 | 0.0034 | 0.00039 |
| $x_{far95}$ | (ft) | 2442 | 5157 | 9113 | 10,443 | 35,216 |
| $x_{total95}$ | (ft) | 3950 | 6450 | 9900 | 11,150 | 35,800 |
| Previous Estimates | | | | | | |
| | Table VII-1 (ft) | 3300 | 4400 | 5000 | | |
| | Report 214 Table VII-1 (ft) | 4200 | 4200 | | 6800 | 16,500 |


10
8
6
4
Travel Time (hrs)
$Q_r$ = 2000 cfs
5000 cfs
10,000 cfs
20,000 cfs
MAXIMUM LENGTH OF
MIXING ZONE CONTROLLED
BY BED SHEAR ONLY
LENGTH OF MIXING
ZONE CONTROLLED BY
BARGE TOWS (ONE
PER HOUR)

REFERENCES

Riley, Michael and Stefan, Heinz. "Mixing of Wastewater Effluents by Barge Tows in the Upper Mississippi and Minnesota Rivers," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, External Memorandum No. 186, March, 1984.

Roach, Michael, Yuling, Chen, Riley, Michael, Farrell, Gerard, and Stefan, Heinz. "Water Quality in the Nearfield of the Metro Wastewater Effluent Mixing Zone: Graphical Representation of 1983 Data," St. Anthony Falls Hydraulic Laboratory, University of Minnesota, External Memorandum No. 189, February, 1984.

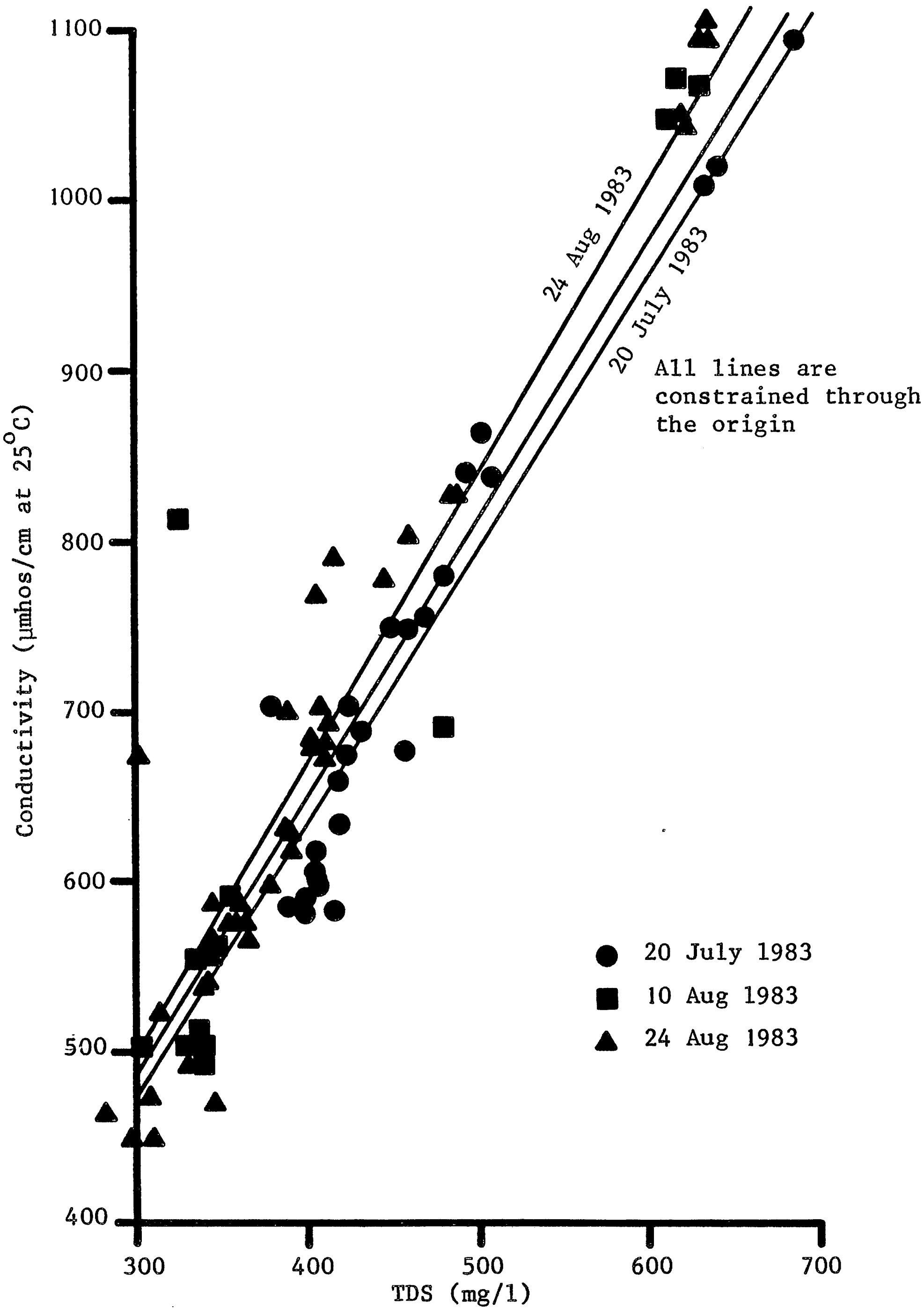
Schiller, E. J. and Sayre, W. W. "Vertical Temperature Profiles in Open Channel Flow," Journal Hydraulic Division, ASCE, Vol. 101, No. HY6, June 1975.

Stefan, Heinz G. "Mixing of the Metro Wastewater Treatment Plant Effluent with the Mississippi River below St. Paul," by Heinz G. Stefan, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, Project Report No. 214, November, 1982.

Stefan, Heinz, Durland, Gary, Farrell, Gerard, Riley, Michael, Chen, Yuling, Roach, Michael. "Water Quality Data for the Metro Wastewater Treatment Plant Effluent Mixing Zone in the Mississippi River below St. Paul, Minnesota, from June 29 to September 22, 1983, St. Anthony Falls Hydraulic Laboratory, University of Minnesota, External Memorandum No. 185, December, 1983.

# APPENDIX A

## Relationship between Measured TDS (mg/ℓ) and Measured Specific Conductance (μmhos/cm)



Conductivity (μmhos/cm at 25°C)
1100
1000
900
800
700
600
500
400
300
400
500
600
700
TDS (mg/1)
24 Aug 1983
20 July 1983
All lines are constrained through the origin
20 July 1983
10 Aug 1983
24 Aug 1983

TDS AND CONDUCTIVITY

| Date | Location | Depth | Cond. | TDS |
|---|---|---|---|---|
| 1983 | | | | |
| 20 Jul | Ref | | 861 | 502 |
| | | | 838 | 507 |
| | | | 838 | 493 |
| | Section II | 5 m | 754 | 468 |
| | | | 778 | 479 |
| | | | 828 | 485 |
| | | | 823 | 484 |
| | | 4 m | 729 | 451 |
| | | | 749 | 460 |
| | | 3 m | 687 | 432 |
| | | | 657 | 417 |
| | | | 675 | 422 |
| | | | 701 | 425 |
| | | | 702 | 378 |
| | | | 749 | 449 |
| | 835.3 | 3 m | 634 | 419 |
| | | 4 m | 598 | 383 |
| | | | 674 | 403 |
| | | 4 m | 638 | 418 |
| | | 6 m | 618 | 406 |
| | | | 674 | 456 |
| | | | 584 | 388 |
| | 835.05 | 9 m | 583 | 388 |
| | | 8 m | 583 | 409 |
| | | | 605 | 403 |
| | | 7 m | 597 | 406 |
| | | | 592 | 399 |
| | | 6 m | 597 | 405 |
| | | | 582 | 414 |
| | | | 582 | 397 |
| | | | N = 30 | N = 30 |
| | | | $\overline{C}$ = 684 | $\overline{TDS}$ = 432 |

TDS AND CONDUCTIVITY (Cont'd)

| Date | Location | Depth | Cond. | TDS |
|---|---|---|---|---|
| 1983 | | | | |
| 10 Aug | Ref | | 1071 | 604 |
| | | | 1071 | 626 |
| | | | 1071 | 620 |
| | | | 1067 | 633 |
| | | | 1067 | 627 |
| | | | 1048 | 611 |
| | | | 1048 | 613 |
| | | | 1048 | 615 |
| | Section II | 4 m | 814 | 325 |
| | | 2 m | 492 | 338 |
| | | | 502 | 402 |
| | 835.3 | 6 m | 591 | 355 |
| | | | 691 | 480 |
| | | 5 m | 586 | 358 |
| | | 4 m | 503 | 336 |
| | | | 564 | 347 |
| | | 3 m | 502 | 338 |
| | | | 502 | 329 |
| | | | 553 | 351 |
| | | | 512 | 335 |
| | | | N = 15 | N = 15 |
| | | | $\bar{C}$ = 667 | $\overline{TDS}$ = 410 |

TDS AND CONDUCTIVITY (Cont'd)

| Date | Location | Depth | Cond. | TDS |
|---|---|---|---|---|
| 1983 | | | | |
| 24 Aug | Ref | | 1044 | 623 |
| | | | 1044 | 624 |
| | | | 1049 | 620 |
| | | | 1094 | 636 |
| | | | 1094 | 632 |
| | | | 1105 | 635 |
| | 835.35 | 1 m | 789 | 414 |
| | | 2 m | 829 | 484 |
| | | 3 m | 779 | 445 |
| | | | 617 | 391 |
| | | | 681 | 411 |
| | | | 564 | 344 |
| | | | 469 | 345 |
| | | 4 m | 829 | 489 |
| | | | 671 | 301 |
| | | | 671 | 410 |
| | | | 565 | 365 |
| | | | 492 | 329 |
| | | 5 m | 802 | 457 |
| | | | 585 | 361 |
| | | | 449 | 309 |
| | | 6 m | 676 | 404 |
| | | | 449 | 298 |
| | 835.3 | 4 m | 464 | 281 |
| | | | 587 | 343 |
| | | | 524 | 312 |
| | | 5 m | 698 | 386 |
| | | | 628 | 388 |
| | | | 555 | 343 |
| | | | 472 | 308 |
| | | 6 m | 767 | 405 |
| | | | 693 | 412 |
| | | | 704 | 406 |
| | | | 575 | 352 |
| | 835.2 | 5 m | 544 | 341 |
| | | | 575 | 363 |
| | | | 538 | 339 |
| | | 6 m | 575 | 357 |
| | | | 597 | 376 |
| | | | 529 | 386 |
| | | 7 m | 683 | 402 |
| | | | N = 41 | N = 41 |
| | | | $\overline{C}$ = 687 | $\overline{TDS}$ = 410 |

APPENDIX B

Tables and figures from Report No. 214 required for the prediction of mixing zone lengths for vertically stratified farfield conditions.

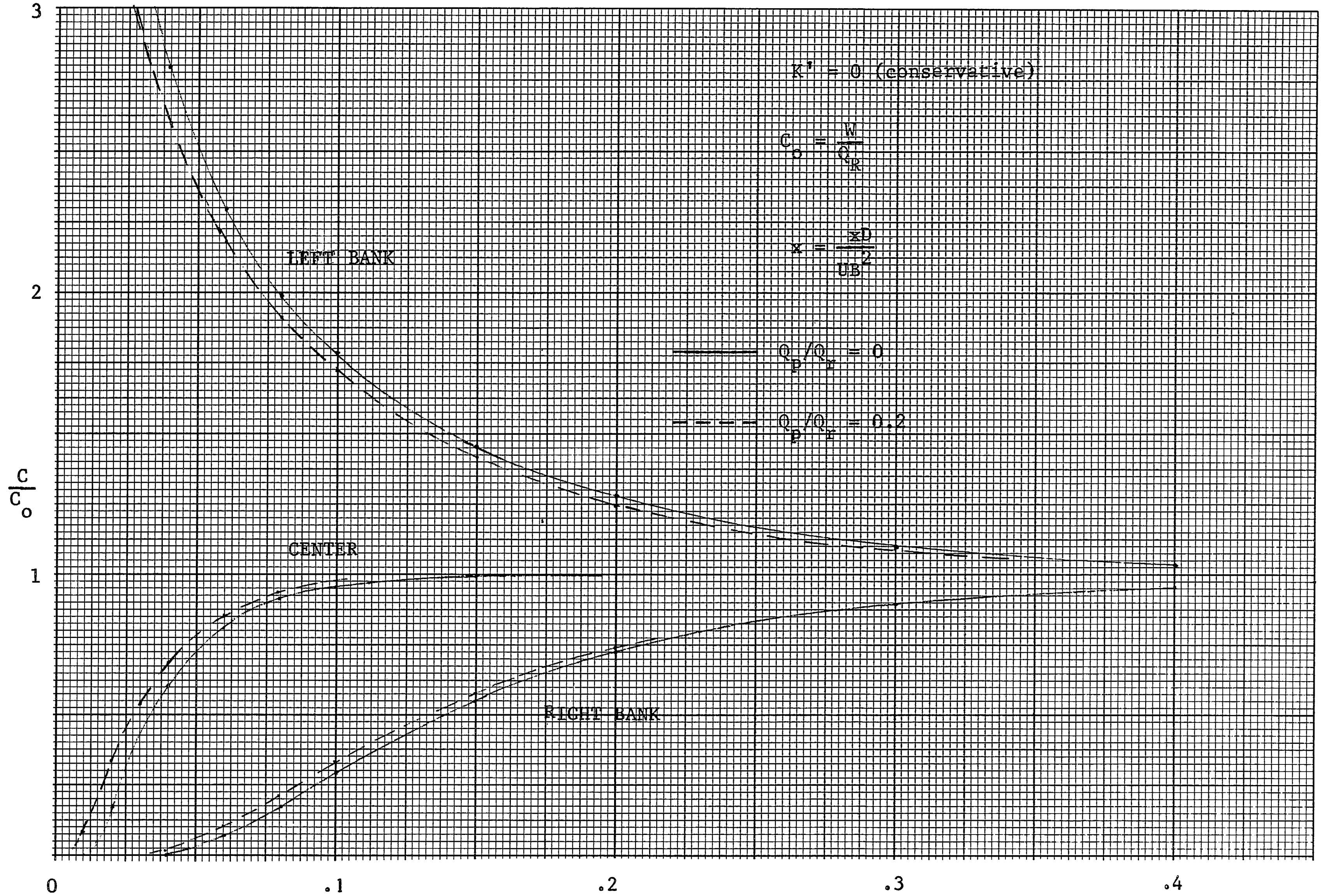



Fig. V-3. Normalized concentration versus distance - conservative substance. Transverse mixing zone model.

TABLE VI-3. Mississippi River Mean Flow Parameters Between Metro WWTP Outlet at UM 835.3 and UM 828 and Transverse Turbulent Diffusion Coefficients

| | River Flow Rate $Q_r$ (cfs) | | | | |
|---|---|---|---|---|---|
| Parameter | 20,000 | 10,000 | 5,000 | 2,000 | 1760 |
| WSEL at outlet | 688.2 | 687.5 | 687.3 | 687.2 | 687.2 |
| H(ft) | 15.3 | 14.7 | 14.4 | 14.3 | 14.3 |
| B(ft) | 804 | 804 | 804 | 804 | 804 |
| U(ft/s) | 1.63 | 0.846 | 0.432 | 0.174 | 0.153 |
| S(-) | $31.8*10^{-6}$ | $9.04*10^{-6}$ | $2.41*10^{-6}$ | $0.395*10^{-6}$ | $0.306*10^{-6}$ |
| $u_*$(ft/s) | .127 | .0667 | 0.0341 | 0.01376 | 0.0121 |
| $D_h(ft^2/s)$ | 2.02 C | 1.02 C | 0.51 C | 0.205 C | 0.180 C |
| $D_r(\psi)(ft^5/s^2)$ | 802 Cψ | 195 Cψ | 47.7 Cψ | 7.60 Cψ | 5.9 Cψ |
| $Q_rB/u_*H^2$(ft) | 500,000 | 514,000 | 523,000 | 525,000 | 525,000 |

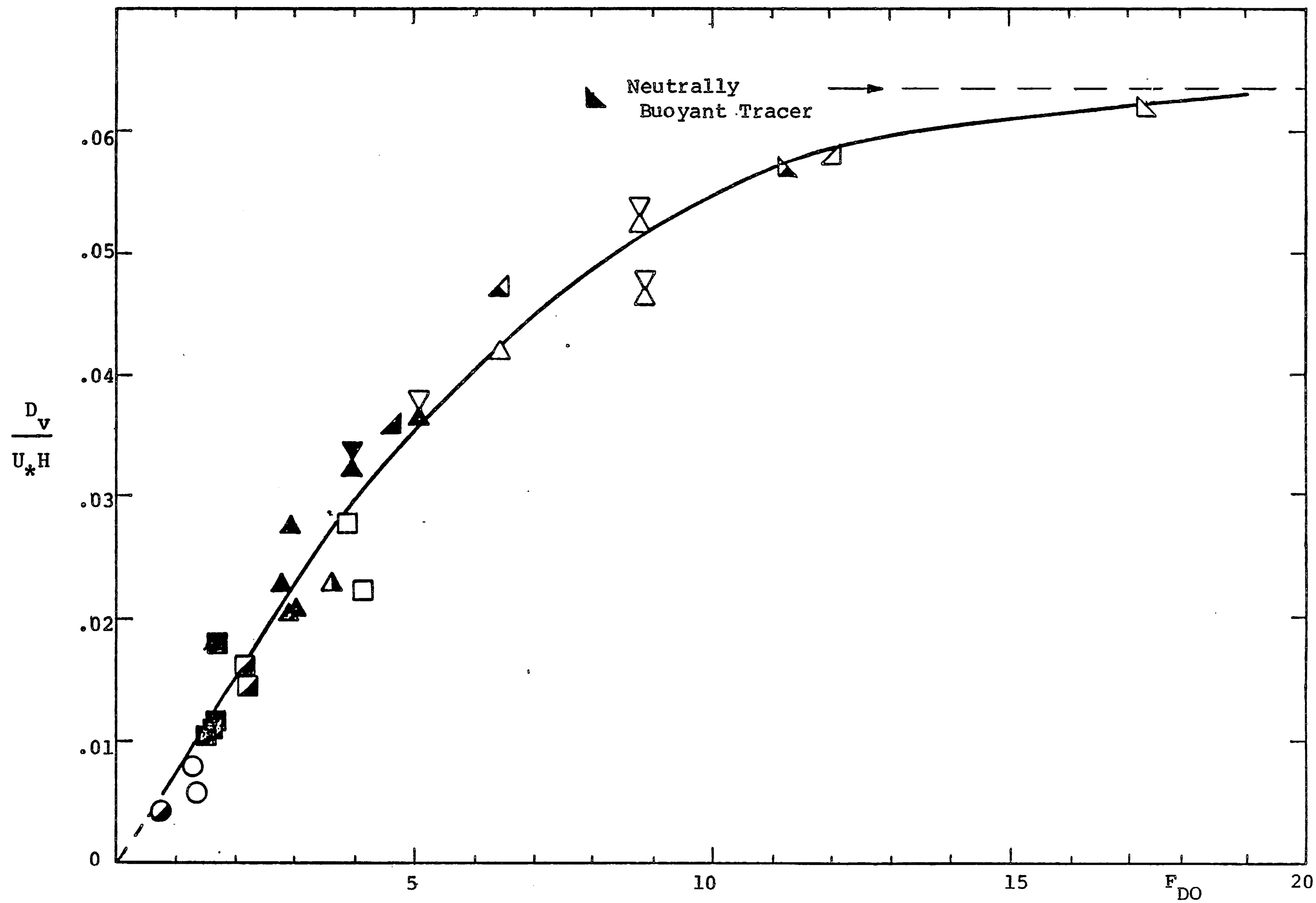



Fig. VI-1. Average values of $D_v/u_*H$ vs. $F_{DO}$. (After Schiller & Sayre, 1973.)
(Symbols are for different experiments.)