To the Graduate Council:

I am submitting herewith a thesis written by John Henry Hoover entitled "Longitudinal Dye Dispersion in Nottely Dam Tailwater." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the Master of Science degree, with a major in Environmental Engineering

Bruce A. Tschantz, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

LONGITUDINAL DYE DISPERSION IN NOTTELY DAM TAILWATER

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

John Henry Hoover
May 1998

DEDICATION

This thesis is dedicated to

Jessica Frances

and

Tara Lynn,

may you help to make the world a better place.

ACKNOWLEDGMENTS

I wish to express my appreciation to Vahid Alavian, Chris Cox, Jim Smoot, and Bruce Tschantz, who opened a window of opportunity for me in 1992. Without their intuitive judgment, my studies in Environmental Hydraulics at the University of Tennessee would not have been possible. I will always appreciate the opportunity they gave me.

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Most importantly, this thesis project would not have been possible without the support and prayers of my dedicated wife, Karin, who has enough confidence in me to suffice for both of us. To Jessica and Tara, I dedicate this work to you, in appreciation for your loving acceptance during my many hours of absence.

ABSTRACT

A dye tracing experiment was successfully conducted over a distance of 5.3 miles on the Nottely River below Nottely Dam, in northern Georgia and western North Carolina. The purpose of the experiment was to determine the longitudinal dispersion coefficient, which gives insight into the distribution, assimilation, and behavior of soluble contaminants that may be introduced into the river.

The dye test used a slug injection of Rhodamine WT fluorescent dye in the tailrace of Nottely Dam during fixed steady-state turbine operation. Two downstream sampling stations were set up 3.8 miles apart to collect dye samples every three minutes. Both sampling stations used three intakes, which separated the river into three lateral theoretical streamtubes of approximately equal discharge. Each of six intakes for the high-level test consisted of an intake hose and continuous feed mini-pump. Periodic grab samples were obtained at varying depths to assure uniform mixing in the vertical direction. Within 24 hours after the tests, laboratory analysis of the samples was completed.

Also included in the field study was surveying of river channel cross sections at eleven locations, with streamflow measurements at two of the cross sections. By knowing the streamflow, velocity, and dye concentration with respect to time, the longitudinal dispersion coefficient (E_x) can be determined by solving the one-dimensional dispersion equation. E_x for the high-level Nottely tailwater dye test was 360 ft^2/sec. If E_x were based only on empirical equations found in literature, the best estimate was 390 ft^2/sec (Fischer and List, 1979). Therefore, the empirical equation by

Fischer and List, when compared with experimental results, was concluded to provide a good estimate of the longitudinal dispersion coefficient for the Nottely Dam tailwater. The reason is because the Fischer/List equation is highly dependent on velocity, which used reliable velocity data acquired during the channel surveying phase of this thesis project. Because the Fischer/List equation directly used velocity, and is nonlinear, the equation emulated essential features of the one-dimensional advection-dispersion equation.

Results from the high-level study were compared with a companion low-level study. The low-level test used only one intake at each of the two sampling stations. Using only the center sampling intake (i.e., low-level study), E_x for the Nottely tailwater was 203 ft^2/sec. The significant difference (43 percent) between the high-level and low-level test results indicated that a low-level test was not worth the slight cost savings (relative to a high-level study).

Similar observations during companion tests on the White River in the Ozark Mountains indicated multiple streamtubes should be used. Consequently, for dispersion studies, this thesis concludes that it is advisable to use at least three intakes at each sampling station. However, if multiple sampling intakes can not be used, guidelines are provided for the use and interpretation of low-level (less expensive) test results. A procedure is also provided for estimating the effect on longitudinal dispersion due to different steady-state discharges.

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NOMENCLATURE

A	cross section area
C	concentration
c_k	advective velocity
d	channel depth
D	hydraulic depth
E_x	longitudinal dispersion coefficient
F	Froude number
K	flow dispersion coefficient
L	reach length
l	distance from point of maximum velocity to bank
M	weight of active dye ingredient
Q	steady-state turbine discharge
Q_{vol}	discharge volume
P	wetted perimeter
R	hydraulic radius
R^2	least-squares coefficient of determination
S	channel slope
S_p	plotted slope of $C_{\max}$ versus $t_p^{-0.5}$
t	time
t_{d}	time of passage at downstream station
t_{p}	time of peak concentration

t_u time of passage at upstream station

u channel velocity

u_{tt} dye time of travel velocity

V_{dye} volume of dye

W channel top width

x distance downstream in longitudinal direction of flow

Y stage height

γ_w specific weight of water

σ^2 variance

ν kinematic viscosity of water

ABBREVIATIONS

ASCE	American Society of Civil Engineers
cfs	cubic feet per second
DO	dissolved oxygen
EST	Eastern Standard Time
ft	feet
GA	Georgia
gm	grams
LA	Louisiana
lb	pound
MD	Maryland
mg	milligram
min	minute
NC	North Carolina
NE	Nebraska
IA	Iowa
IN	Indiana
L	liter
NRM	Nottely River Mile
OR	Oregon
PA	Pennslyvania
ppb	parts per billion

sec	second
TN	Tennessee
TVA	Tennessee Valley Authority
TX	Texas
USCOE	United States Army Corps of Engineers
USGS	United States Geological Survey
WA	Washington
WY	Wyoming

1. INTRODUCTION

Background

There is growing interest in the recreational use of hydroplant tailwaters. Hydropower relicensing requirements frequently require a minimum constant discharge to sustain the aquatic habitat during periods of no hydroelectric power generation. Anglers quickly discover that if the discharge is also aerated, the year-round, cool release temperatures of Appalachian hydroplants make an ideal trout habitat. Often, with the increased recreational opportunities, come increased tourism and development, which increase the potential introduction of stream pollutants and the need to understand the assimilation of soluble contaminants. Consequently, many hydroplant tailwaters require computerized water quality models to simulate the turbulent mixing and fate of pollutants.

Purpose

Regardless of the software selected, all models require a high level of data input (meteorology, hydraulics, pollutant loadings, etc.) Often, the most difficult modeling task is acquiring the input data, including a realistic longitudinal dispersion coefficient (E_x). Longitudinal dispersion occurs when the molecules of a waterborne constituent (contaminant, tracer, etc.) randomly scatter, disperse, or diffuse, while still being transported in the same general direction (downstream). Field studies are often required to satisfy model input needs because dispersion characteristics are dependent upon the site-specific hydraulic parameters of the channel or tailwater, which can vary widely from project to project and region to region. Although several empirical equations are available in literature to estimate E_x, the expected accuracy is only "within a factor of four or so" (Fischer, 1979). Therefore, the purpose of this dye tracing experiment is to determine the longitudinal dispersion coefficient, which gives insight into the distribution and behavior of soluble contaminants in unique tailwater conditions (below dams located in mountainous regions). Little data is available or published for this condition.

Scope

This research focused on the waterborne dispersion characteristics of a hydroplant tailwater located in the Blue Ridge Mountains of northern Georgia and western North Carolina. A dye tracer experiment was used as a basis for this research to physically model the longitudinal dispersion characteristics of the Nottely Dam tailwater. The dam is located on the Nottely River, 61 miles east of Chattanooga, Tennessee, in Union County, Georgia. The length of the test reach was 5.3 miles.

Approach

The dye tracer experiment utilized an instantaneous slug injection of Rhodamine WT fluorescent dye. The test was performed during fixed, steady-state flow conditions. The experiment used two dye sampling stations along the Nottely River, with three water sampling intakes each, which required separating the river into three lateral theoretical streamtubes of approximately equal discharge. Also included in the field study was surveying of river channel cross sections at eleven locations that included streamflow measurements at two of the cross sections. Since the streamflow, velocity, and dye concentration with respect to time were known, the longitudinal dispersion coefficient could be solved by using the one-dimensional dispersion equation.

Site Selection

The Nottely Dam tailwater was selected because of its potential for sustaining a cold water fishery. A trout habitat on the Nottely River may be possible because the Tennessee Valley Authority (TVA) can now inject air (when needed) into the turbine to improve the dissolved oxygen (DO) content of the discharge. Another attribute is that Nottely Dam now maintains an instantaneous minimum discharge of 50 cfs. Thus, the tailwater's aquatic habitat has been improved greatly, which may lead to increased recreational use and development, and the likely need for a validated contaminant transport model.

Two other TVA sites that also have oxygen injection capability, minimum flow augmentation, and year-round, cool release temperatures were seriously considered. Tims Ford Dam tailwater on the Elk River in middle Tennessee, and Blue Ridge Dam tailwater on the Ocoee River in northern Georgia, both would have been good selections. However, the Tims Ford generation schedule was unfavorable due to dam repairs. The Blue Ridge Dam tailwater was not selected because a town (Copperhill, TN) may have been affected by a dye test, which would have made test coordination more difficult.

2. LITERATURE REVIEW

The literature review for this thesis started with a computerized search of the Environmental Abstracts database for citations on Rhodamine WT dye tracer and dispersion. Although only a few listings of the first search were relevant, three available bibliographies led to other sources. Those new sources then led again to many additional references. Continuing this cyclic search pattern provided a plethora of documents. The highlights of those documents are presented in this chapter.

Textbooks

From the literature review, it was learned that a pioneer in the field of diffusion, dispersion, and mixing is Hugo B. Fischer. Generally, his numerous papers (Fischer, 1967, 1968, 1969) were summarized in the textbook, Mixing in Inland and Coastal Waters (Fischer and List, 1979). Another textbook frequently used for self-teaching in this thesis was Principles of Surface Water Quality Modeling and Control (Thomann and Mueller, 1987).

Mixing in Inland and Coastal Waters (Fischer and List, 1979)

This was the first reference found in the literature review that identified the field of "environmental hydraulics". With the advent of the personal computer, environmental analysis of various hydraulic works can be simulated with computer models. Some examples of processes in environmental hydraulics are hydrologic transport, buoyant plumes, stratified density flow, fate and transport studies, and sedimentation/erosion.

Hydrologic transport processes involve the physical flow of natural water bodies, which cause pollutants or natural substances to be transported and mixed, or exchanged, with other media. Included among hydrologic transport processes in a natural water environment are:

Advection - Transport by an imposed flow-induced current system, as in a river.

Convection - Vertical transport induced by hydrostatic instability, such as the flow over a heated plate, or below a chilled water surface in a lake.

Diffusion (molecular) - The scattering of particles by random molecular motion.

Diffusion (turbulent) - The random scattering of particles by turbulent motion.

Shear - The advection of fluid at different velocities at different depths due to turbulence.

Dispersion - The scattering of particles by the combined effects of shear and transverse diffusion.

Detailed dispersion theory is described in a later chapter of this thesis, but in general terms, an important aspect of the dispersion process in the longitudinal direction (downstream) is described by a coefficient (E_x). The units of E_x are area per time, which describes how fast the tracer spreads out with respect to time. Fischer's equation to estimate E_x is:

$$E_x = \frac{0.011\,(\bar{u})^2\,W^2}{\bar{d} \times u^*} \qquad (1)$$

where E_x= longitudinal dispersion coefficient (ft^2/sec)
$\bar{u}$ = mean velocity of channel (ft/sec)
W = channel top width (ft)
$\bar{d}$ = mean channel depth (ft)
u^*= shear velocity (ft/sec) = $\sqrt{gRS}$

g = acceleration of gravity (ft^2/sec)
R = hydraulic radius (ft)
S = channel slope (ft/ft)

However, Equation 1 is an empirical equation that only provides approximate results. When compared with field observations, the results agree "within a factor of four or so" (Fischer and List, 1979).

Principles of Surface Water Quality Modeling and Control (Thomann and Mueller, 1987)

This textbook arose out of the need for dissemination of the fundamentals and principles which underlie the mathematical modeling techniques used to analyze the quality of surface waters. The growing use of computers in the 1980s led to a growing field called water quality modeling. The book helps beginning modelers as well as those more seasoned veterans who may occasionally need a quick reference to the theory or general approach. Thomann's discussion of conservative and nonconservative constituents (substances) is of interest to understand more about water quality modeling.

A conservative pollutant does not decay due to chemical or biological degradations. Such substances may include, for example, total dissolved solids or chlorides. A nonconservative pollutant degenerates with time due perhaps to chemical reactions, bacterial degradation, radioactive decay, or exposure to ultraviolet light. Examples of nonconservative contaminants are radioactive isotopes and volatile chemicals.

Thomann's textbook provided another estimate of the longitudinal dispersion coefficient (McQuivey and Keefer, 1974). The equation is based on 18 streams and nearly 40 time of travel studies for rivers with flows ranging from 35 to 33,000 cfs and slopes from 0.00015 to 0.0098 ft/ft.

$$E_x = 0.058 \frac{Q}{S \overline{W}} \qquad (2)$$

where E_x = longitudinal dispersion coefficient (ft^2/sec)
Q = steady-state flow (cfs)
S = channel slope (ft/ft)
$\overline{W}$ = mean top width of channel (ft)

Other Textbooks

Four other textbooks were occasionally used to refresh the author's knowledge of open channel hydraulics. All four references are valuable assets to an engineer's personal water resource library. The citations are Chapra (1997), Chaudhry (1993), Chow and Maidment (1987), and Graf (1984).

Government Publications

There are two federal agencies that provide water resource services. The United States Geological Survey (USGS) is part of the United States Department of Interior. The other agency is the United States Army Corps of Engineers (USCOE). Several manuals on river dye tracer tests have been published by the two agencies and are noted as follows:

Measurement of Time of Travel and Dispersion in Streams by Dye Tracing (USGS, 1982b)

This manual is for the application of fluorescent dyes and tracing techniques used to provide a means for measuring the time of travel and dispersion characteristics of steady and gradually varied flow in streams. The manual describes methods of measuring time of travel of water and waterborne solutes by dye tracing. The fluorescent dyes, measuring equipment used, and the field and laboratory procedures are also described. One requirement of proper field procedure advises that dye concentrations at water-user withdrawal points should not exceed 10 ppb. Methods of analysis and presentation to illustrate dispersion characteristics of streams are provided by the manual.

The manual also discussed "level of study" in the context of explaining that dye studies may be conducted at different levels of completeness, depending on the objectives of the investigation, policy considerations, staffing, and financial constraints. If, for instance, only time-of-travel data are needed, the data requirements would be considerably less than when dispersion data are needed. The primary difference between a high-level and low-level study is that in any high-level study, the dye cloud should be measured at several points across each sampling section to better account for the entire tracer mass and to ensure the completeness of lateral dispersion. Conversely, a low-level study only tracks measurements of the dye cloud concentration in the center of flow.

Determination of Stream Reaeration Coefficients by Use of Tracers (USGS, 1989)

This detailed, high-level procedure describes how to perform reaeration measurements on streams using dye and gas tracers injected concurrently to simulate oxygen absorption. Because the dye test results are used as a base case for the more elaborate reaeration calculations, this procedure requires that the dye test results be computed with a corresponding high-level of accuracy. This can be accomplished by paying close attention to dye mass conservation and the percentage of dye mass recovered in each streamtube. For a successful dye dispersion test, enough of the dye plume tail must be captured such that the minimum dye concentration is ≤ 2 percent of the peak concentration. In order to achieve a high-level of dye mass accountability, it is also important to know the relative flow in each streamtube. Therefore, the discharge distribution across the channel at each sampling station must be carefully measured and documented. If the discharge and concentration time history are known for each streamtube, the mass of dye exiting the test reach can be computed by using the flow weighted contribution of each streamtube.

Fluorometric Techniques for Tracing Reservoir Inflows (USCOE, 1984)

Although this instruction report traced inflows through a reservoir, the same field practices can be applied to a river. Similar to the USGS manual (USGS, 1982b), the USCOE instructional report presented Rhodamine WT characteristics and discussed fluorometer operation. The most valuable information provided was a procedure on how to dilute Rhodamine WT dye from a 20 percent stock solution down to concentrations of 24 ppb and 0.48 ppb. The dilution scheme is necessary for fluorometer calibration. The theoretical sections of the report were simply presentations of previous work done by Fischer and List (1979) and Kilpatrick (1970).

The instruction report also discussed dye toxicity. Rhodamine WT has generally been thought to have a very low toxicity level. Parker (1973) showed that Rhodamine WT had no harmful effects on the development of silver salmon, Donaldson trout, and

Pacific oyster eggs. Smart and Laidlaw (1977) also cite the unpublished work of Donaldson, who reported no traumatic effects for subcutaneous injections or oral feedings of the dye in laboratory rats.

Methods for Predicting Dispersion Coefficients in Natural Streams (USGS, 1968)

Dye tracing dispersion studies were conducted in the Green and Duwamish Rivers (WA) by Hugo B. Fischer. The results of these studies provided a basis for several sections of his later textbook (Fischer and List, 1979). The study reach was a lowland, tidally-influenced estuary. Although the study reach is much flatter than typical Appalachian streams, the report is very useful because it combines the theory presented in Fischer's textbook (Fischer and List, 1979) with the practical how-to steps presented in the USGS publication (USGS, 1982b).

Journal Articles

Dosage Requirements for Slug Injections of Rhodamine BA and WT Dyes (Kilpatrick, 1970)

Simulation studies of waste dilution, thermal pollution, and dispersion tests in rivers involve the slug injection of specific amounts of fluorescent dye. One requirement in planning a dye tracing experiment is to determine how much dye to inject. If an insufficient amount of dye is used, the test is a failure. However, if too much dye is injected, expensive material is wasted and downstream water intakes could be affected. Kilpatrick retrieved results for 85 dye tests and developed a regression equation to help estimate the amount of dye required for a test. His equation provides an estimated volume of Rhodamine WT (20 percent solution) typically required to produce a concentration of 1 ppb at a given distance downstream.

$$V_{dye} = 0.00034\left(\frac{Q \times L}{\bar{u}}\right)^{0.93} \tag{3}$$

where V_{dye} = gallons of Rhodamine WT (20 percent solution) required to achieve 1 ppb
Q = discharge in reach (cfs)
L = length of reach (miles)
$\bar{u}$ = mean channel section velocity (ft/sec)

The Effect of Bends on Dispersion in Streams (Fischer, 1969)

Fischer's laboratory flume experiments indicated that bends in streams induce secondary currents that alter the rates of dispersion. Fischer's analogy is that marked fluid particles move downstream in streamlines, while at the same time exchanging among flow streamlines via molecular or turbulent diffusion. This concept may be expanded in scale by visualizing a flow made up of a number of separate streamtubes. Within a given streamtube, all the fluid particles are carried downstream at the streamtube velocity, which may vary along the stream. At the same time, marked fluid particles are continuously exchanged between adjacent streamtubes because of turbulence. A particular marked fluid particle may migrate downstream at the velocity of the streamtube in which the tracer particle happens to be.

The use of this concept in a meandering flow is illustrated by Figure 1. Fischer's laboratory experiments divided the flow into five imaginary streamtubes of equal discharge, but varying velocity and area. The widths, depths, and velocities of the

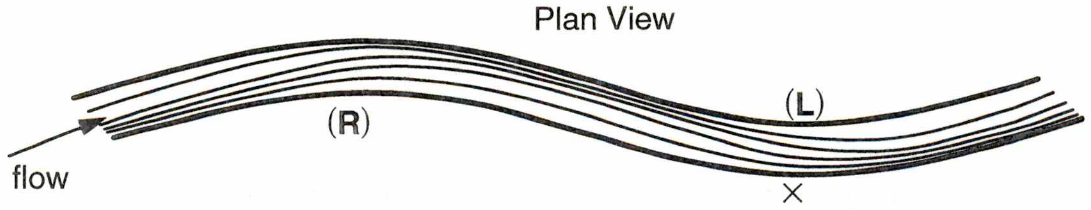


Figure 1. Schematic Division of Meandering Flow in Streamtubes of Equal Discharge

streamtubes vary in the longitudinal flow direction according to the position along the channel alignment curves. Around a curve to the left (**L**), the streamtubes are shifted to the right (× – outside) bank, where the velocities and depths are greater; around a curve to the right (**R**), the opposite is true.

Fischer determined the dispersion coefficient for a series of bends that alternate in direction may be much lower that that for the same series of bends all in the same direction. His work is of special interest because preliminary field studies for this thesis showed that streamtubes do indeed occur (Figure 2) in natural river flow.

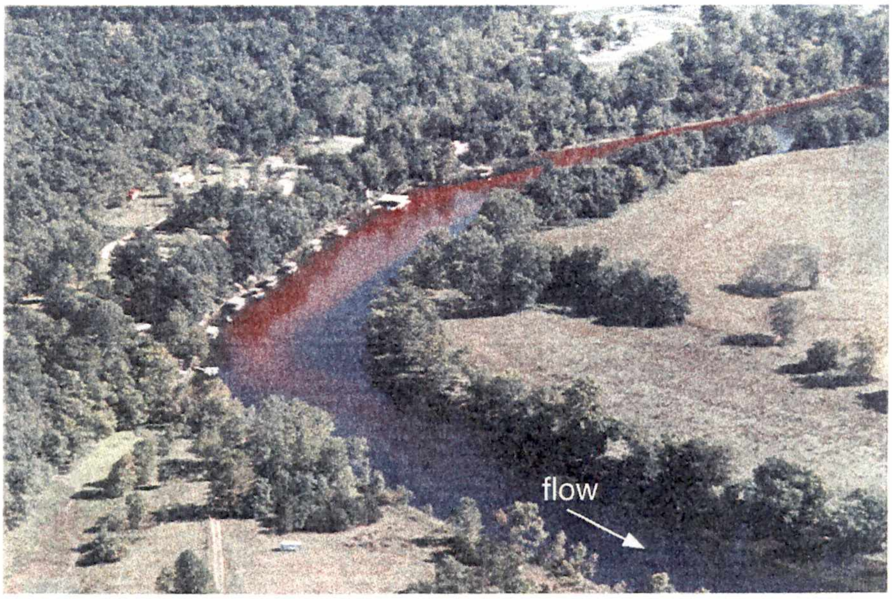


Figure 2. Meandering Flow in Norfork River Streamtubes (Hoover, 1996)

3. DISPERSION THEORY

Discussion

Longitudinal dispersion is the spreading out along the channel which occurs when a concentrated mass of pollutant is introduced into a stream. Rather than move downstream as a slug, such a mass will be distributed along the length of the stream, some parts traveling faster and some slower than the mean-flow velocity. The dispersion process of a pollutant or tracer may be described by the point-form one-dimensional advection-dispersion equation (Fischer and List, 1979).

$$\frac{\partial \overline{C}}{\partial t} = \underbrace{\left(-\overline{u}\right)\frac{\partial \overline{C}}{\partial x}}_{\substack{\textit{advection}\\ \textit{term}}} + \underbrace{E_x \frac{\partial^2 \overline{C}}{\partial x^2}}_{\substack{\textit{dispersion}\\ \textit{term}}} \tag{4}$$

where $\overline{C}$ = cross-sectional mean concentration (ppb)
$\overline{u}$ = cross-sectional mean velocity (ft/sec)
t = time (sec)
x = distance downstream in the longitudinal direction of mean flow (ft)
E_x= longitudinal dispersion coefficient (ft^2/sec)

Equation 4 says that concentration at any point along the channel is changing with time due to the downstream moving mass (– *advection term*) and the spreading out due to diffusion and turbulence (+ *dispersion term*).

Physical Factors

The longitudinal dispersion coefficient (E_x) is dependent upon site-specific hydraulic parameters of the tailwater. Some factors that influence dispersion are dead zones, eddies, channel meandering, prismatic cross section, constant depth, uniform slope, uniform roughness, velocity, discharge, flow state (laminar vs. turbulent), and obstructions, such as, trees or boulders.

Transverse Mixing

To assure adequate transverse mixing of the tracer (in terms of the distance downstream from the injection of a tracer source), Fischer showed that the one-dimensional dispersion model was found to be a good approximation if Equation 5 is satisfied.

$$L > 1.8 \frac{l^2}{R} \frac{\bar{u}}{u^*} \qquad (5)$$

where L = distance downstream from the source (ft)
l = distance from point of maximum surface velocity to bank (ft)
$\bar{u}$ = cross sectional mean velocity (ft/sec)
R = hydraulic radius (ft)
u^* =shear velocity (ft/sec)

The effective mixing length can be shortened by injecting dye at multiple points across the stream. The dye is measured and divided into a number of containers and poured simultaneously at several points along the cross section. Another method is to use a line injection. Dye is poured continuously while crossing the stream (Figure 3). To avoid dead zones or slow-moving sections, the dye should be injected in only about the central 75 percent of the flow (USGS, 1982b).

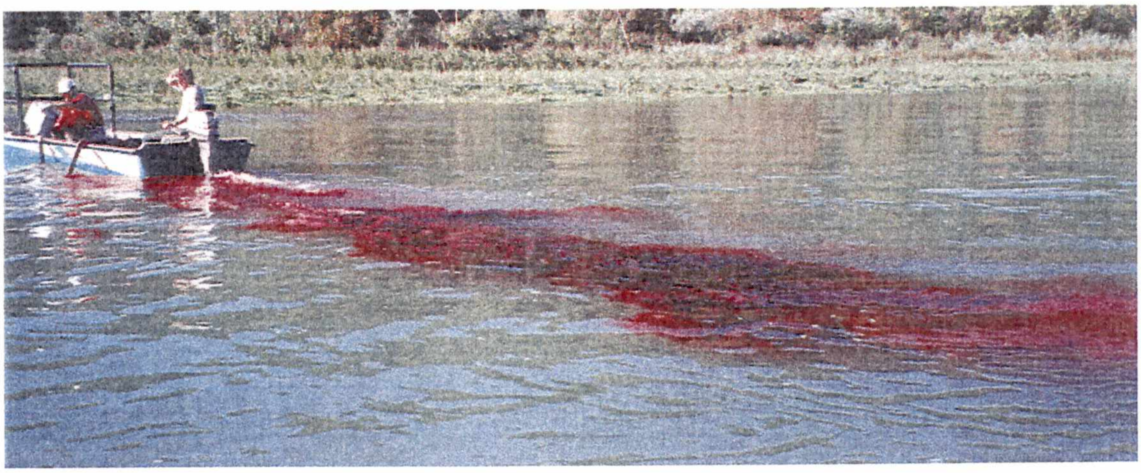


Figure 3. White River Line Injection Method (Hoover, 1996)

Applicable Equations

If a dye study is performed that uses two sampling stations, the longitudinal dispersion coefficient can be estimated from the concentration data obtained at an upstream station and a downstream station (Thomann and Mueller, 1987). Example results of observed dye concentrations versus time at two sampling stations are plotted in Figure 4.

Fischer (1968) describes the "method of moments" that can be used to estimate the dispersion in the reach. His derivation concludes that,

$$E_x = \frac{(\bar{u})^2}{2} \frac{\sigma_{td}^2 - \sigma_{tu}^2}{\bar{t}_d - \bar{t}_u} \qquad (6)$$

where E_x = longitudinal dispersion coefficient (ft^2/sec)

σ_{tu}^2 = variance of the concentration vs. time curve at upstream station

σ_{td}^2 = variance of the concentration vs. time curve at downstream station

$\bar{t}_u$ = mean time of passage at upstream station (sec)

$\bar{t}_d$ = mean time of passage at downstream station (sec)

$\bar{u}$ = cross-sectional mean velocity (ft/sec).

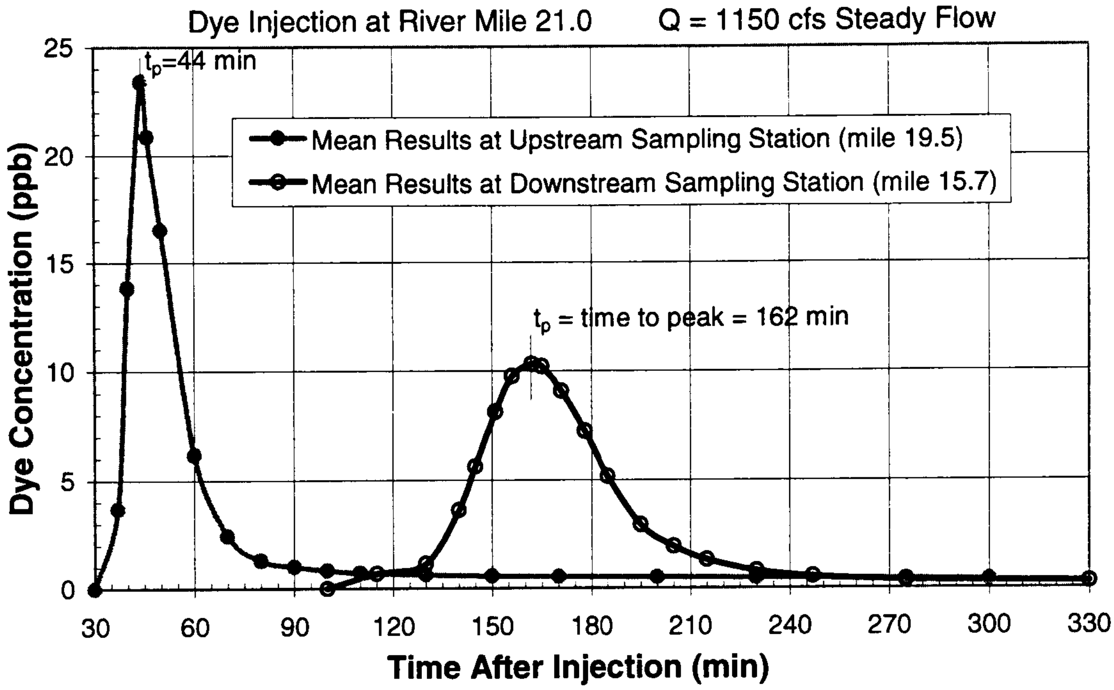


Figure 4. Example Dye Concentration vs. Time Plots

The variances are computed from

$$\sigma^2 = \frac{\int_0^{t_{0.01}} Ct^2 dt}{\int_0^{t_{0.01}} C\, dt} - \left(\bar{t}\right)^2 \tag{7}$$

where C = mean dye concentration at sampling station (ppb = mg/L^3 = μg/L)
t = time after dye injection (sec)

and the centroid times are computed from

$$\bar{t} = \frac{\int_0^{t_{0.01}} Ct\, dt}{\int_0^{t_{0.01}} C\, dt} \tag{8}$$

where $t_{0.01}$ = time (seconds) at which concentration has decreased to 1% of peak concentration.

Finally, a simple procedure is given by evaluating Equation 8 for the peak concentration of tracer or pollutant. Then, for an instantaneous slug injection of dye, the peak concentration (C_{max}) is given by Equation 9 (Thomann and Mueller, 1987).

$$C_{max} = \frac{M}{2A\sqrt{\pi E_x t_p}} = S_p \times \frac{1}{\sqrt{t_p}} \tag{9}$$

$$S_p = \frac{M}{2A\sqrt{\pi E_x}} \tag{10}$$

where C_{max} = peak concentration (ppb)
M = weight of dye injected (lb)
A = mean-cross sectional area of channel (ft^2)
E_x = longitudinal dispersion coefficient (ft^2/sec)
t_p = time of peak concentration (minutes after dye injection)
S_p = plotted slope of C_{max} versus $t_p^{-0.5}$ (ppb • $sec^{0.5}$)

The plotted slope (S_p) is determined from a plot of the observed peak dye concentrations versus $t_p^{-0.5}$. S_p is then used to estimate E_x using Equation 10. An example that illustrates how to determine S_p is shown in Figure 5. The two data points used in the example are from Figure 4.

Although this procedure by Thomann and Mueller (1987) appears simple, there is some intrinsic manipulation of units that is required. The pounds of dye injected must be "converted" to include ppb. This is done by introducing the specific weight of water (γ_w) and a multiplier of one billion parts per billion.

For example, if given that M = 2.5 lb, the equivalent volume of water that would be occupied by 2.5 lb of active dye ingredient is 0.040 ft^3.

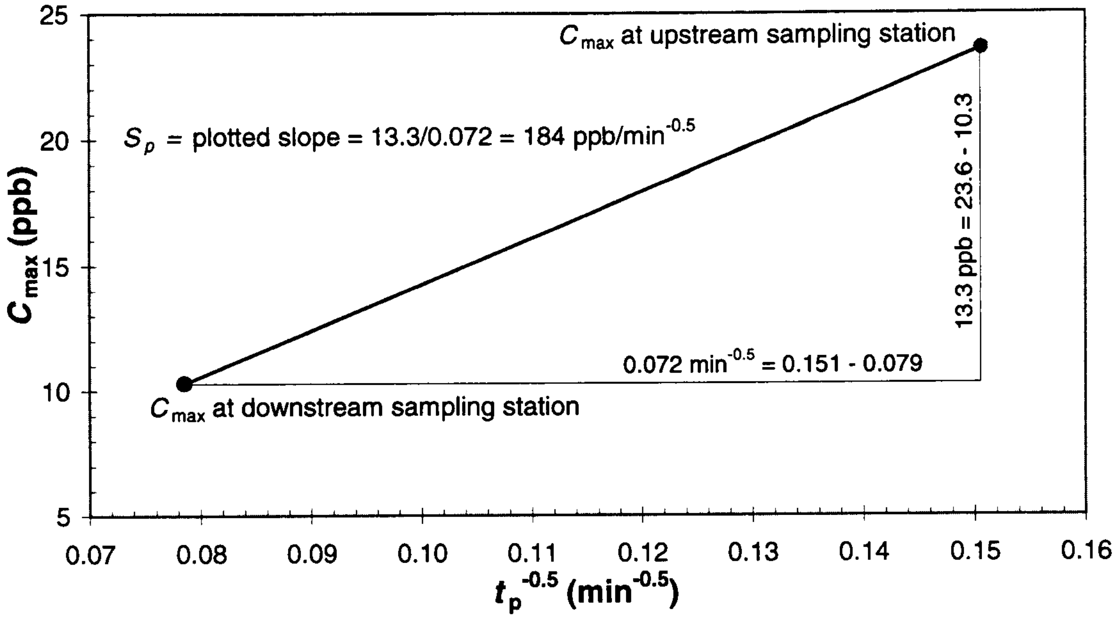


Figure 5. Example Illustrating Method of Determining Plotted Slope *(S_p)*

$$\frac{M}{\gamma_w} = \frac{2.5 \text{ lb}}{62.4 \text{ lb/ft}^3} = 0.040 \text{ ft}^3.$$

Then multiplying by one billion parts per billion,

$$0.040 \text{ ft}^3 \times \frac{\text{one billion parts}}{\text{one billion parts}} = \frac{40{,}000{,}000 \text{ ft}^3 \bullet \text{ parts}}{\text{one billion parts}}$$

which is 40,000,000 $ft^3 \bullet$ ppb.

When $ft^3 \bullet$ ppb are combined with units of other terms, the units cancel nicely to give E_x in units of ft^2/sec. Calculations that illustrate the detailed cancellation of units are shown on page 19.

$$S_p = \frac{M}{2A\sqrt{\pi}\sqrt{E_x}} = \frac{(\text{lb}) \times \dfrac{\text{one billion parts}}{\text{one billion parts}}}{\text{ft}^2 \times \sqrt{E_x \dfrac{\text{ft}^2}{\text{sec}}} \times \underbrace{\left(\dfrac{\text{lb}}{\text{ft}^3}\right)}_{\gamma_w}} = \text{ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{(\text{lb}) \times 10^9 \text{ ppb}}{\text{ft}^2 \times \sqrt{E_x \text{ ft}^2 / \text{sec}} \times \dfrac{\text{lb}}{\text{ft}^3}} = \text{ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{\text{ft}^3 \bullet \text{ppb}}{\text{ft}^2 \times \sqrt{E_x \text{ ft}^2 / \text{sec}}} = \text{ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{\text{ft} \bullet \text{ppb}}{\sqrt{E_x \text{ ft}^2 / \text{sec}}} = \text{ppb} \bullet \sqrt{\text{sec}} .$$

Solving for E_x gives

$$E_x = \left(\frac{\text{ft} \bullet \text{ppb}}{\text{ppb} \bullet \sqrt{\text{sec}}}\right)^2 = \frac{\text{ft}^2}{\text{sec}} .$$

4. PROJECT SITE DESCRIPTION

Location

Nottely Dam is shown in Figure 6 to be located on the Nottely River, 61 miles east of Chattanooga, Tennessee, in Union County, Georgia. The multipurpose, compacted rockfill and rolled earthfill dam is 184 ft high. It provides flood control, recreation, and peaking hydropower to the Tennessee Valley Authority (TVA). Typical turbine discharge during generation is 1400 cfs.

The Nottely River watershed is one of several rivers that drain the Blue Ridge Mountains in northern Georgia. The Nottely Dam tailwater (Figure 7) starts in the Chattahoochee National Forest and continues downstream 20 miles to join the Hiwassee River in western North Carolina. The reach is wooded with mountainous terrain. The channel bed downstream of Nottely Dam drops 15 feet in the first mile and 25 addtional feet in the next 4.5 miles.

Site Visit

A preliminary site visit was conducted on October 24, 1997. One purpose of the visit was to inspect the tailwater reach for accessibility. Once two potential dye sampling stations were identified, several preliminary hydraulic measurements (velocity, depth, width) were collected to help plan the test. No drinking water intakes were discovered on the river, so the USGS maximum-allowed dye concentration of 10 ppb at water-user withdrawal points was not an issue.

Figure 6. Nottely Dam Location Map

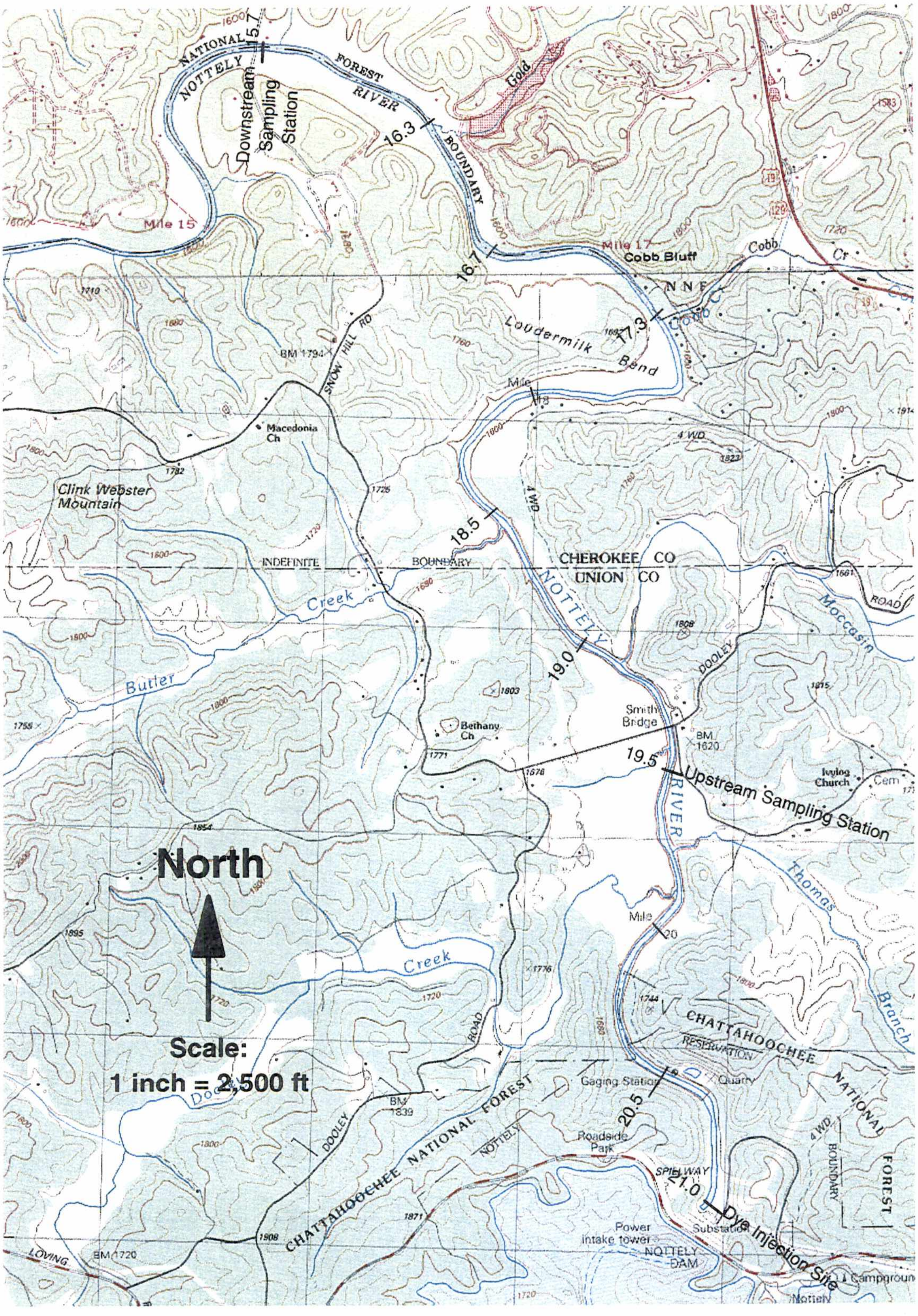


Figure 7. Nottely Dam Tailwater Map

5. DYE DISPERSION FIELD TEST

Test Preparation

The first step in planning the Nottely River dye dispersion test was to study the USGS topographic quadrangle maps (USGS, 1988 and 1990) and to make a tentative evaluation of the tailwater reach in terms of hydraulic characteristics (channel width and slope), accessibility, and affected population. Data from the maps were supplemented with information gathered during the site visit of October 24, 1997. During the site visit, several velocity and cross section measurements were obtained to help estimate tracer travel time and dosage requirements. A dye dosage of 5 liters was selected based on previous experience gained from the White River dye test (Hoover, 1996).

Next, the appropriate natural resource officials of Georgia and North Carolina were informed of plans for a dye dispersion test using Rhodamine WT below Nottely Dam (Hoover, 1997). The approval process was greatly simplified because no municipalities or potable water intakes are located on the test reach.

The final task pertained to getting necessary sampling equipment, supplies, and personnel in order. Pumps, hoses, generators, sample bottles, tag lines, boats, winches, tape measures, radios, and etc. were cleaned, inspected, maintained, and packed. Two current meters were calibrated; a Marsh-McBirney Flo-Mate 2000 and a Model 1205 Price-type "mini" current meter manufactured by Scientific Instruments, Inc. Five liters of Rhodamine WT (20 percent solution) were carefully measured and poured into jugs for transport.

Hydraulic Data

On October 27, 1997, hydraulic characteristics (velocity, depth, and width) were surveyed during steady-state turbine operation (1170 cfs) at the two sampling stations. Because drawdown of Nottely Reservoir (to achieve winter pool elevation) occurred during this period, and because of mild electric loads, steady flow for the day was forecast by the TVA generation pre-schedule. (Hourly turbine discharges are listed in Appendix A).

Velocity measurements at the two sampling stations were obtained in accordance with USGS (1982a). The primary instrument used to determine velocity was the Flo-Mate 2000. Several spot checks were made using the calibrated Price-type "mini" meter. Depth and width measurements were also were collected at nine other cross section locations denoted on the tailwater map (Figure 7).

Measurements at each cross section were obtained by first suspending a taut "tag line" of 5/8-inch diameter rope across the channel. The rope was tied-off to a tree or boulder such that the tag line was about two feet above the water surface and normal to channel flow. A ratchet winch was used to achieve rope tautness The transverse distance to the left bank was determined using a Sonin Combo Pro electronic distance measurer. The electronic Sonin target was attached to a tripod on the left bank. Each time that a depth or velocity measurement was performed, the hand-held Sonin Pro instrument was aimed at the target to provide a digital read-out of transverse distance to the left bank.

A summary of all hydraulic field data is tabulated in Appendix A. A pocket-sized tape recorder was used during the surveying to enable hands-free recording of data. Examples of the survey techniques are shown in Figures 8-9.

Dye Injection

Five liters of Rhodamine WT (stock 20 percent solution) were instantaneously injected into the Nottely Dam powerhouse tailrace on October 28, 1997 at 08:25 EST. Steady-state turbine discharge was fixed at 1150 cfs. No requests were made to TVA for special generation operations; thus, there was no rationale for selecting 1150 cfs. This discharge just happened to be the flow associated with the most efficient load condition that is typically specified by TVA River System Operations for extended periods in late October when Nottely Reservoir has not quite yet achieved winter pool elevation. The steady state fixed operation during the dye test was forecast by frequently checking the TVA generation pre-schedule. This information is available to the public by calling TVA's automated Lake Information Line at 423-632-2264. Hourly turbine discharge records for late October 1997 are shown in Appendix A.

The dye was injected using a tipping bucket apparatus invented by the author especially for use in this thesis project (Figure 10). The simple arrangement of ropes and hardware (buckets, hose clamps, pipe fittings, and slider pipe) required only one person for installation and dye injection. The apparatus is safer than injecting dye by boat because the arrangement was installed during low flow (i.e., no boat was needed to install or operate the tipping bucket apparatus).

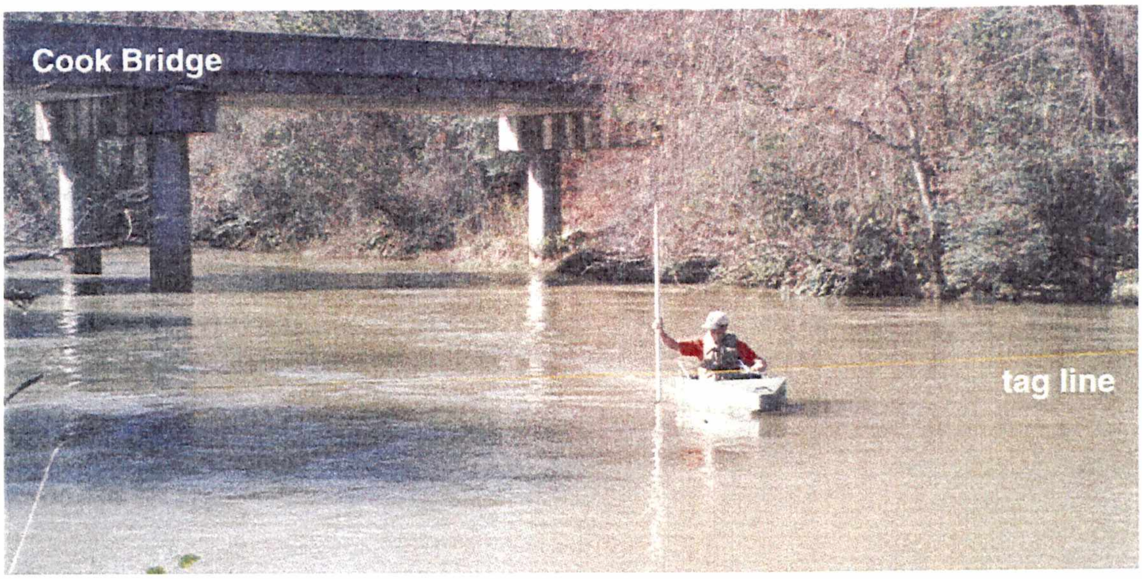


Figure 8. Depth Measurements at Downstream Sampling Station (NRM 15.7)

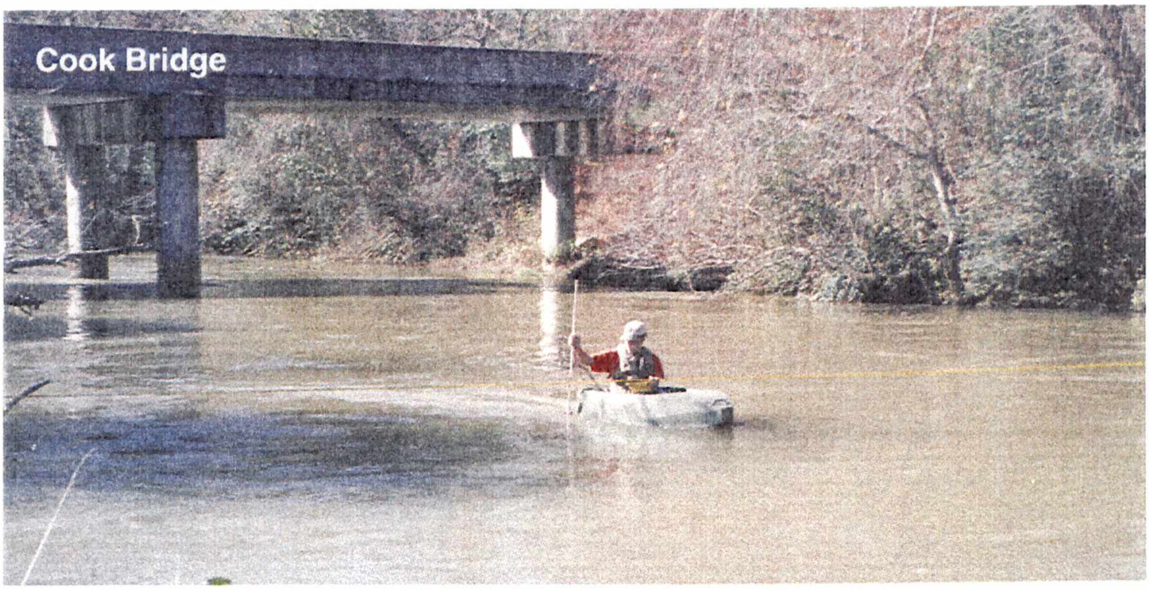


Figure 9. Velocity Measurements at Downstream Sampling Station (NRM 15.7)

Figure 10. Dye Injection Apparatus at Nottely River Mile 21.0

Two injection points were used because the mixing zone length predicted by Equation 5 indicated one point source may not be fully-mixed near the first sampling station at Nottely River Mile 19.5 (NRM 19.5). Injecting only into the central flow avoided trapping the dye in eddies. Figures 11, 12, 13, and 14 show the dye plume at four points at it progressed downstream.

Sample Collection

Dye sampling stations were set up at NRM 19.5 and NRM 15.7. Each sampling station used three intakes. The intakes were strategically placed in the channel such that each intake was located near a streamtube centroid, as shown in Figures 15-18. The intake locations were determined by computing the discharge distribution (relative to distance from the left bank) for discharge multiples of 1/6 Q, per USGS sampling procedures (USGS, 1989). The flow in each streamtube was about 385 cfs. The hydraulic data (distance, depth, and velocity) used to determine the flow in each streamtube at the two sampling stations are shown in Appendix A.

Figure 11. Instantaneous Dye Injection

Figure 12. Dye Plume 75 Seconds After Injection

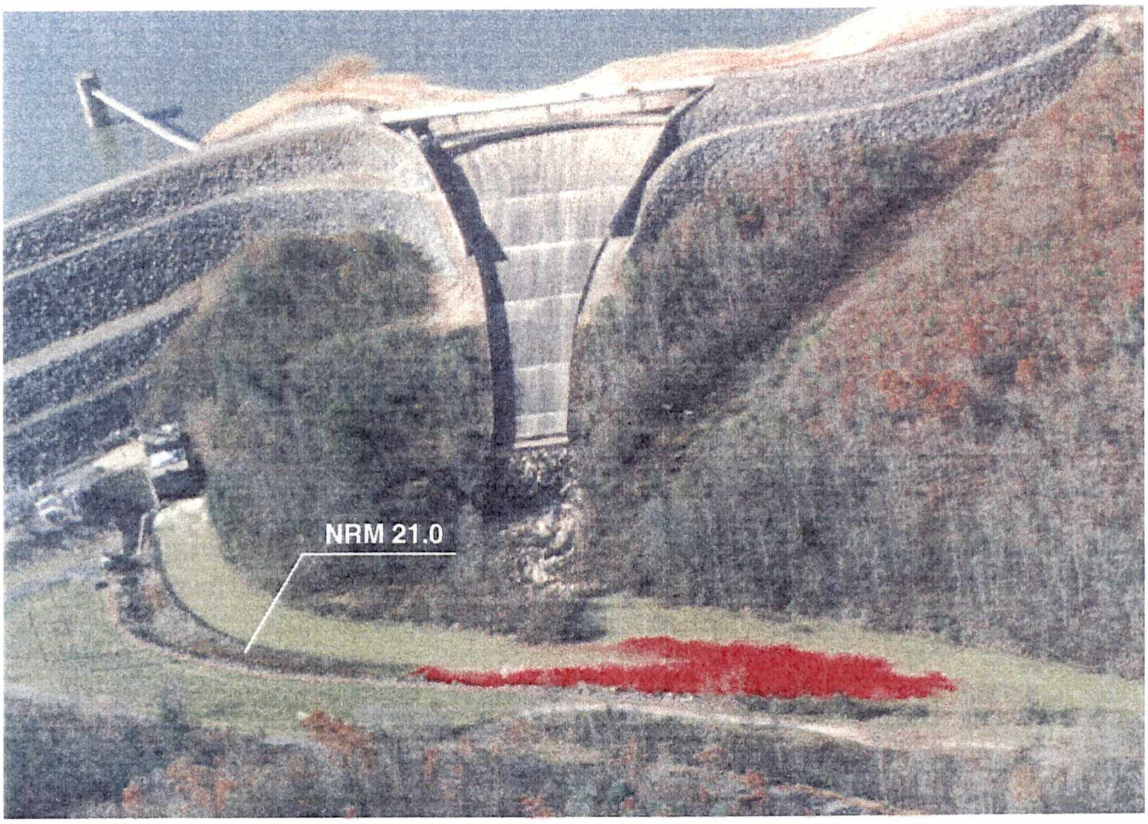


Figure 13. Dye Plume 155 Seconds After Injection

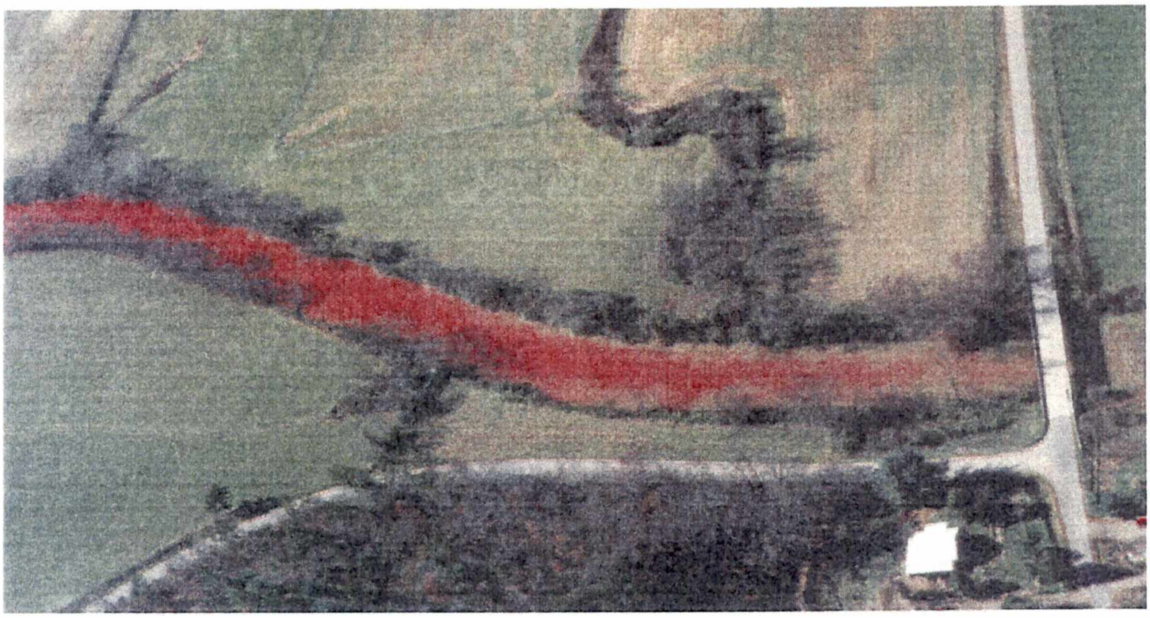


Figure 14. Leading Edge of Dye Plume at Smith Bridge (NRM 19.3)

Figure 15. Three Streamtubes of Equal Flow (approximately 385 cfs each)

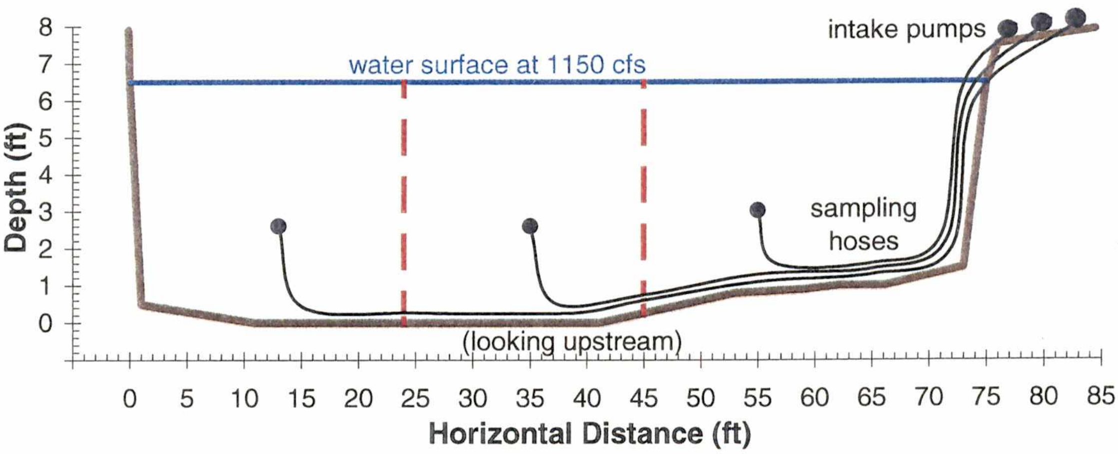


Figure 16. Schematic of Downstream Sampling Station at NRM 15.7

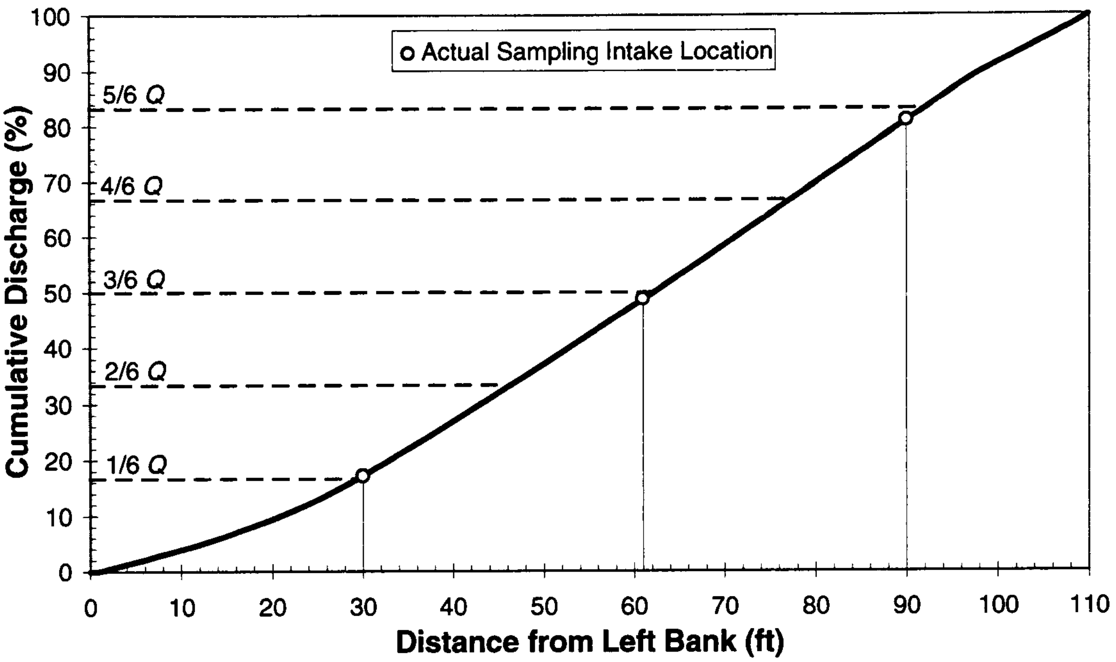


Figure 17. Discharge Distribution at Upstream Sampling Station (NRM 19.5)

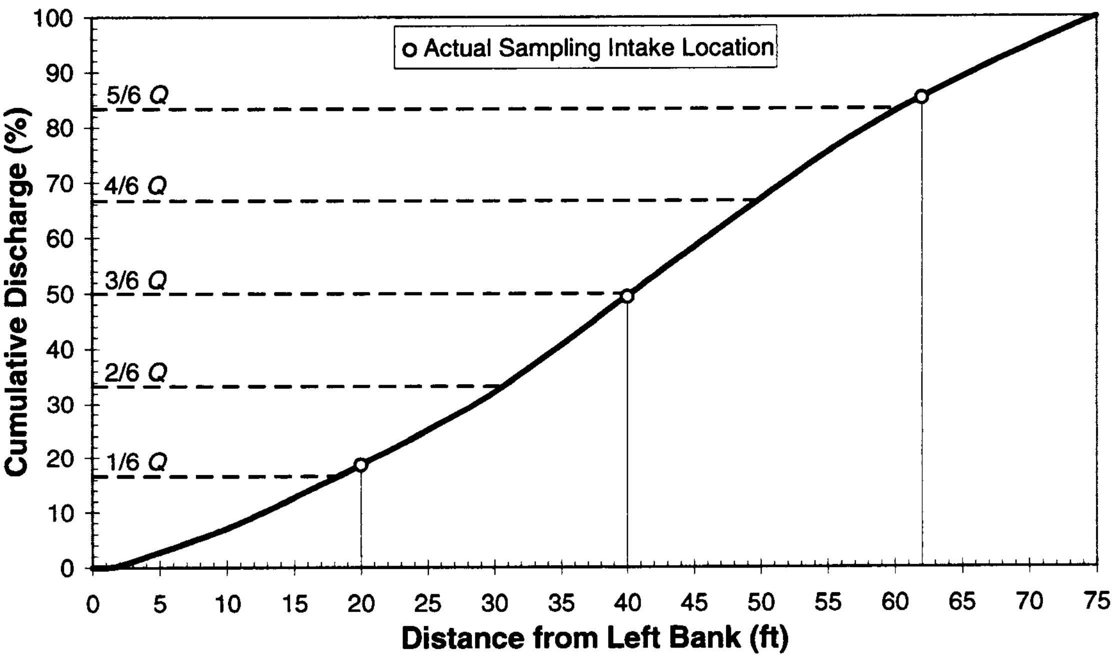


Figure 18. Discharge Distribution at Downstream Sampling Station (NRM 15.7)

Each sampling intake consisted of a mini-pump and a weighted hose. A float at the intake end of the hose was configured such that the hose intake was near mid-depth of the streamtube. The continuously operated mini-pumps provided separate, uninterrupted discharges for sampling as illustrated in Figure 19. Bottle samples were filled from the pump outlets at least every 3 minutes. The bottles were labeled and immediately boxed for transportation. Because Rhodamine WT decays if exposed to ultraviolet light, care was always taken to keep the samples in the dark.

In addition to the pumped samples, occasional grab samples were obtained at varying depths to check for uniform vertical mixing. All sampled dye data is listed in Appendix A.

Figure 19. Downstream Sampling Station at NRM 15.7

6. ANALYSIS PROCEDURES

Laboratory Analysis

Once the vials were transported to the laboratory, the samples were refrigerated to maintain river temperature equilibrium (60°F) because fluorescence varies with temperature. Meanwhile, a Turner Model 112 fluorometer was calibrated using calibration vials of 50 ppb and 5 ppb (active ingredient). The procedure (USCOE, 1984) for preparing the known samples consisted of accurately diluting 8 grams of stock 20 percent dye solution (2.264×10^8 ppb of active ingredient) with numerous doses of distilled water to obtain the calibration samples of 50 ppb and 5 ppb. The dilution doses were determined by weight using a Sentra Model 2000L digital laboratory scale. Scale accuracy was to the nearest 0.01 gram. It is estimated that the precision of each sample used for fluorometer calibration was to the nearest 0.1 ppb.

Each dye test vial was placed in the fluorometer chamber and analyzed to determine dye concentration. All laboratory analysis was completed within 24 hours after the field test was finished. The field data is listed in Appendix A.

The precision of the Model 112 flurometer is published as ± 0.1 percent (Turner Designs, 1982), so for dye mass recovery balance, the instrument precision directly affects the total percentage of dye mass recovered by $\pm$ 0.1 percent. Consequently, the resolution of the instrument has negligible effect on dye mass accountability because ± 0.1 percent is considered to be insignificant.

Data Plots

Plots of dye concentration versus time for the three streamtubes at each sampling station are shown in Figure 20. The mean peak concentrations shown in Figure 20 were computed per USGS procedures (USGS, 1989), which used the average time-to-peak and average peak concentration for each streamtube. Data plots for individual streamtubes are shown in Appendix A. Calculations are shown in Appendix B.

Slope Method

The mean peak concentrations shown on Figure 20 are used in conjunction with Equation 9 to provide an estimate of E_x.

$$C_{\max} = \frac{M}{2A\sqrt{\pi E_x t_p}} = S_p \times \frac{1}{\sqrt{t_p}} \qquad (9)$$

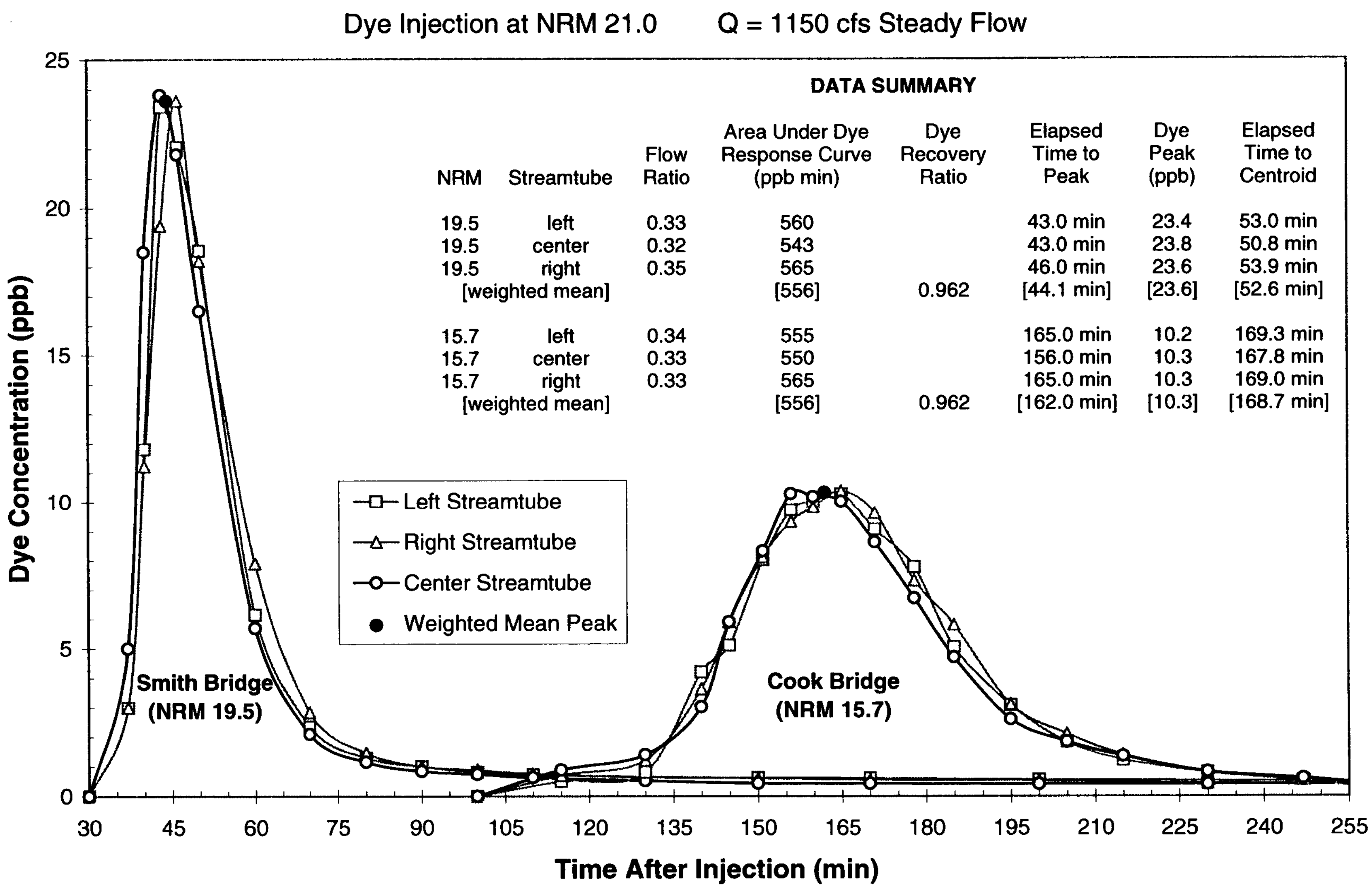
$$S_p = \frac{M}{2A\sqrt{\pi E_x}} \qquad (10)$$

where $C_{\max}$ = peak concentration (ppb)
M = weight of dye injected (lb)
A = mean cross-sectional area of channel (ft^2)
E_x = longitudinal dispersion coefficient (ft^2/sec)
t_p = time of peak concentration (minutes after dye injection)
S_p = plotted slope of $C_{\max}$ versus $t_p^{-0.5}$ (ppb • sec$^{-0.5}$)

The input used for the plotted slope method is shown in Table 1 and Figure 21.

Table 1. Input for Plotted Slope Method

	Upstream Sampling Station	Downstream Sampling Station
Location	NRM 19.5	NRM 15.7
$C_{\max}$	23.6	10.3
t_p	44 minutes	162 minutes
$t_p^{-0.5}$	0.151 (min$^{-0.5}$)	0.0786 (min$^{-0.5}$)



NRM	Streamtube	Flow Ratio	Area Under Dye Response Curve (ppb min)	Dye Recovery Ratio	Elapsed Time to Peak	Dye Peak (ppb)	Elapsed Time to Centroid
19.5	left	0.33	560		43.0 min	23.4	53.0 min
19.5	center	0.32	543		43.0 min	23.8	50.8 min
19.5	right	0.35	565		46.0 min	23.6	53.9 min
[weighted mean]			[556]	0.962	[44.1 min]	[23.6]	[52.6 min]
15.7	left	0.34	555		165.0 min	10.2	169.3 min
15.7	center	0.33	550		156.0 min	10.3	167.8 min
15.7	right	0.33	565		165.0 min	10.3	169.0 min
[weighted mean]			[556]	0.962	[162.0 min]	[10.3]	[168.7 min]

Figure 20. Dye Concentration Curves for All Three Streamtubes

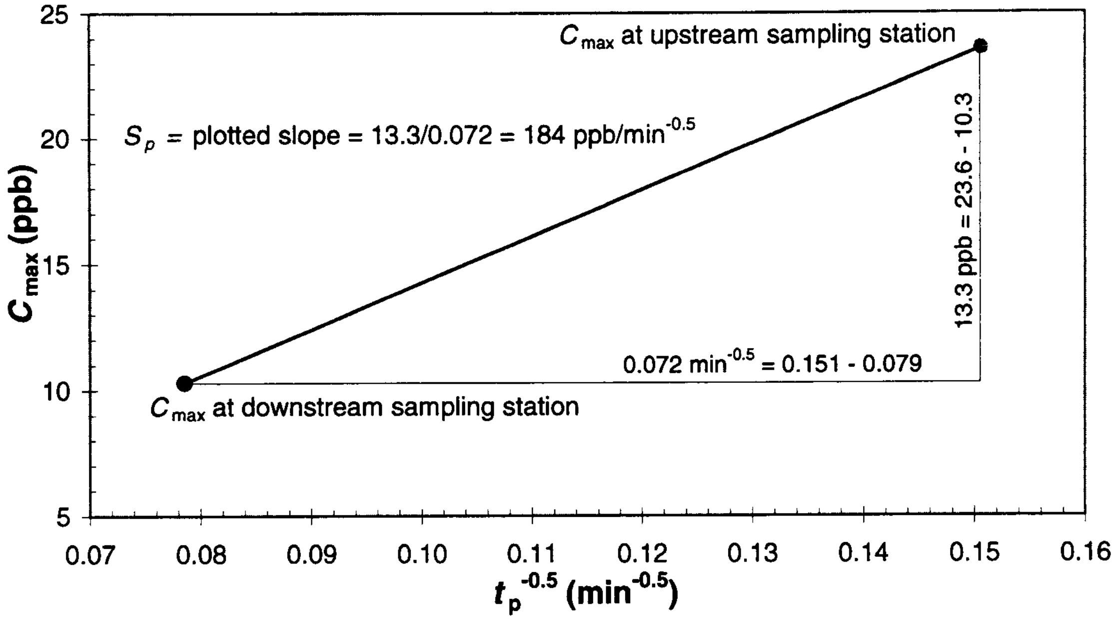


Figure 21. Plotted Slope Method

Figure 21 and the hydraulic characteristics listed in Appendix A are then used to estimate E_x. Supplemental calculations are shown in Appendix B.

$$S_p = \text{plotted slope} = 184.5\ \frac{\text{ppb}}{1/\sqrt{\text{min}}} \times \sqrt{60\frac{\text{sec}}{\text{min}}}$$

$$S_p = 1{,}429\,\text{ppb} \bullet \sqrt{\text{sec}}$$

$$A = \frac{Q}{u_{tt}} = \frac{1150\text{cfs}}{2.77\text{ ft / sec}} = 416\text{ft}^2$$

where A = cross-sectional area of channel (ft^2)

Q = steady-state flow (cfs)

u_{tt} = time-of-travel velocity (ft/sec)

Then substituting the known data into Equation 10,

$$S_p = \frac{M}{2A\sqrt{\pi}\sqrt{E_x}} = \frac{(2.5\text{lb}) \times \dfrac{\text{one billion parts}}{\text{one billion parts}}}{2 \times 416 \text{ ft}^2 \times \sqrt{\pi} \times \sqrt{E_x \dfrac{\text{ft}^2}{\text{sec}}} \times 62.4 \dfrac{\text{lb}}{\text{ft}^3}} = 1{,}429 \text{ ppb} \bullet \sqrt{\text{sec}}$$

where M = weight of dye injected (lb)

A = cross-sectional area of channel (ft^2)

E_x = longitudinal dispersion coefficient (ft^2/sec)

S_p = plotted slope of C_{max} versus $t_p^{-0.5}$ ($\text{ppb} \bullet \text{sec}^{0.5}$)

and simplifying,

$$S_p = \frac{(2.5 \text{ lb}) \times 10^9 \text{ ppb}}{2 \times 416 \text{ ft}^2 \times \sqrt{\pi} \times \sqrt{E_x \text{ ft}^2/\text{sec}} \times 62.4 \dfrac{\text{lb}}{\text{ft}^3}} = 1{,}429 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{40{,}000{,}000 \text{ ft}^3 \bullet \text{ppb}}{2 \times 416 \text{ ft}^2 \times \sqrt{\pi} \times \sqrt{E_x \text{ ft}^2/\text{sec}}} = 1{,}429 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{40{,}000{,}000 \text{ ft} \bullet \text{ppb}}{2 \times 416 \times \sqrt{\pi} \times \sqrt{E_x \text{ ft}^2/\text{sec}}} = 1{,}429 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{27{,}200 \text{ ft} \bullet \text{ppb}}{\sqrt{E_x \text{ ft}^2/\text{sec}}} = 1{,}429 \text{ ppb} \bullet \sqrt{\text{sec}}.$$

Solving for E_x gives,

$$E_x = \left(\frac{27{,}200 \text{ ppb} \bullet \text{ft}}{1{,}429 \text{ ppb} \bullet \sqrt{\text{sec}}} \right)^2 = 360 \frac{\text{ft}^2}{\text{sec}}.$$

Spreadsheet Analysis

All dye concentration plots were analyzed with a user-programmed EXCEL spreadsheet developed by Gary E. Hauser that performed trapezoidal integration of the dye concentration versus time plot (Hauser, 1996). The software ingeniously marches forward computing the area under the curve, and it simultaneously starts at the tail and marches backward also computing the area under the curve. The reason for this forward/backward progression is that at some given time point, the forward area equals the backward area. That time point is the centroid of the area under the concentration curve, which determines the time of travel. Figure 22 shows an application of this method from a similar dye study on the White River in Arkansas (Hoover, 1996).

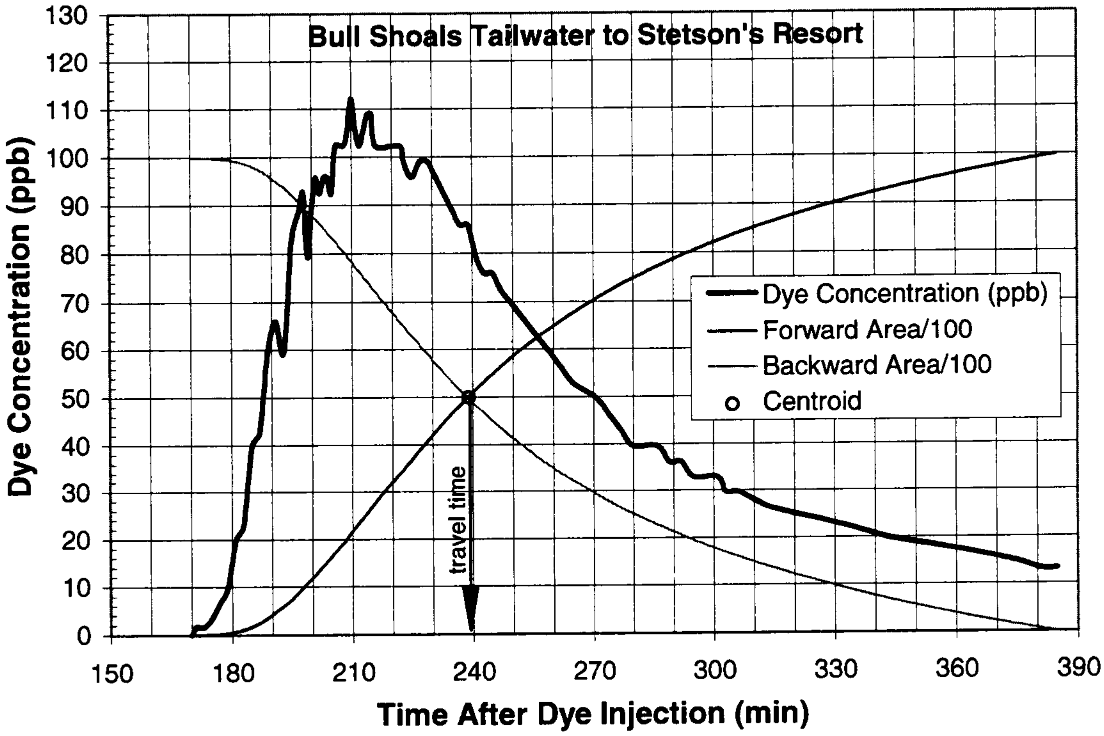


Figure 22. Dye Plume Centroid Example

7. RESULTS

Mass Balance

One characteristic that determines a successful dye study is consideration of dye mass conservation and percentage of injected dye mass recovered. Since the flow and concentration time history are known for each streamtube, the mass of dye exiting the test reach can be computed (M_{out}). By comparing M_{out} with the amount of dye injected (M_{in}), the percentage of dye mass accounted for can be determined. The percentage of dye mass recovered at the upstream sampling station (NRM 19.5) was 96.2 percent. Dye mass recovery at the downstream sampling station (NRM 15.7) was also 96.2 percent. The weighted calculations used to determine the recovery percentages are shown in Appendix B.

Due to several physical processes that typically affect dye tracing experiments, 3.8 percent of the dye injected was not conserved. The most significant reason is that some dye usually gets trapped in eddies or dead zones, only to be released slowly over many hours after the test is completed. Additional dye particles may adhere to objects in the channel, such as, gravel, sediment, roots, trees, weeds, or grass (Bencala and Rathbun, 1983). Rhodamine WT also degrades when exposed to sunlight. Some lack of recovery may also be due to possible error in the initial dye injection concentration and sampling analysis.

In accordance with USGS procedures, the observed dye concentrations at each sampling station would usually be multiplied by an adjustment factor so that complete conservation of dye mass can be theoretically achieved (USGS, 1982b). However, because the high-level data for both sampling stations happen to have the same 1.04 adjustment factor, the plotted slope used in Equation 9 will not change. Therefore, no adjustment of observed dye concentrations for the high-level study was performed.

When compared with guidelines in literature, the 96.2 percent recovery is well within acceptable limits. USCOE states that "if a large portion (i.e., greater than 10 percent) of the injected dye mass cannot be accounted for, it is difficult to defend any type of quantitative analysis that might be performed. A high percentage of dye recovery, however, is usually indicative of good field technique" (USCOE, 1984). The Monocacy River (Maryland) dye study used in the USGS dye tracing manual (USGS, 1982b) had a dye mass recovery of 95 percent. A USGS publication for reaeration studies on the Wabash River had a dye mass recovery of 96 percent (Crawford, 1985).

Mixing

Calculations in Appendix B show that the channel flow regime was very turbulent (*Reynold's Number* = 720,000). Therefore, vertical mixing was assumed to be complete. This assumption is verified by the vertical grab sample data shown in Appendix A.

Lateral mixing was complete at each sampling station because the areas under the dye concentration curves for each streamtube were nearly identical. The areas are listed in Appendix A.

Longitudinal Dispersion Coefficient

The longitudinal dispersion coefficient (E_x) for the 5.3-mile test reach was determined by using Equation 9 (*plotted slope method*) and empirical equations from literature (Equations 1 and 2) were used for comparison. The high-level test results used data from all three streamtubes. The low-level comparison test results considered only the center streamtube data. A summary of results is shown in Table 2.

Table 2. Summary of Test Results

Type of Test[a]	E_x (Eq. 9) Experimental	E_x (Eq. 1) Fischer	E_x (Eq. 2) McQuivey/Keefer	Mean Dye Mass Recovery Balance
High-Level	360 ft^2/sec	390 ft^2/sec	515 ft^2/sec	96.2%
Low-Level	203 ft^2/sec	393 ft^2/sec	515 ft^2/sec	89.1%

[a] Dye studies can be conducted at different levels of completeness depending on objectives and budget. The "high-level test" used data from all three streamtubes, whereas the "low-level test" simulated a more economical experiment that only used data from the center streamtube.

Fischer's equation produced an estimate 8 percent larger than the experimental result. The relatively close estimate is probably because the Fischer equation is highly dependent on velocity (and top width), which used reliable velocity (and top width) data acquired during the channel surveying phase of this thesis project. Because the Fischer equation directly used reliable velocity, and is nonlinear, the equation emulated essential features of the one-dimensional advection-dispersion equation for the Nottely Dam tailwater.

The relatively close estimate could also be due to similarities between the Nottely River and Fischer's laboratory flume. Recall that Equation 1 is based on ideal dispersion tests conducted in a flume. Some characteristics of an ideal dispersion test reach are straight reach, no dead zones, no eddies, prismatic cross section, constant depth, uniform slope, and uniform roughness. Similar features found in the Nottely River are minimal dead zones, few eddies, prismatic cross section (steep side slopes), nearly constant depth, uniform slope, and uniform roughness.

It can also be concluded from Table 2 that Equation 2 (by McQuivey and Keefer), when compared with the experimental results, provided a much larger estimate of the longitudinal dispersion coefficient (E_x) for the Nottely Dam tailwater. A weakness is that Equation 2 has no direct input for velocity, and velocity is known to have a major influence on dispersion. Another peril is that Equation 2 is linear, but dispersion is understood to a nonlinear function of velocity (or discharge).

Although the McQuivey/Keefer estimate differed from experimental results by 63 percent, their method may have merit because Equation 2 was developed using natural channels, and the Nottely Dam tailwater is a natural channel. The following analysis investigates if Equation 2 can be modified by incorporating the dispersion test results for the Nottely Dam tailwater.

McQuivey/Keefer Analysis

McQuivey and Keefer (1974) used two plots to develop Equation 2. Their two plots are

$$\frac{2E_x}{\left(\bar{u}_{tt}\right)^3} \quad vs. \quad \frac{2K}{\left(\bar{c}_k\right)^3} \quad \text{and} \quad \bar{u}_{tt} \ vs. \ \bar{c}_k \ ,$$

where $\bar{u}_{tt}$ = mean dye travel time velocity (ft/sec)

c_k = advective velocity (ft/sec)

K = flow dispersion coefficient (ft^2/sec) (Harley, 1967).

The advantage of using K and c_k is that eight hydraulic characteristics are incorporated into just two terms.

$$c_k = \left(\frac{1}{W}\right)\frac{dQ}{dY} \tag{11}$$

where $\frac{dQ}{dY}$ = slope of the rating curve for discharge vs. stage

W = channel top width (ft)

$$K = \frac{Q}{(2)(S)(W)}\left(1 - \frac{F^2}{4}\right) \tag{12}$$

where F = Froude number = $\frac{\bar{u}}{\sqrt{(g)(\bar{D})}}$

$\bar{D}$ = mean hydraulic depth (ft) = $\frac{A}{W}$

$\bar{u}$ = mean channel velocity (ft/sec)

g = gravitational acceleration (ft/sec^2)

S = channel slope (ft/ft)

In developing their equation, McQuivey and Keefer reviewed c_k and K data from over 35 dye studies on 18 natural streams. Table 3 summarizes parameters from those studies, and Figures 23-24 show the hydraulic characteristics of the Nottely Dam tailwater, relative to the studies used to develop Equation 2. The John Day River (OR) and Wind River (WY) are labeled on the figures because they have channel bed slopes similar to the Nottely Dam tailwater. Miscellaneous calculations for the Nottely River are shown in Appendix B.

Table 3. Measurements of Longitudinal Dispersion in Open Channels (McQuivey and Keefer, 1974)

River Name	Slope (ft/ft)	Q (cfs)	Top Width (W)	Travel Time Velocity (u_{tt})	Cross-Sectional Mean Velocity at Two Stations	Advective Velocity (c_k)	Flow Coefficient (K)	Dispersion Coefficient (E_x)
Monocacy (MD)	0.00060	85	115 ft	0.35 ft/sec	0.70 ft/sec	1.18 ft/sec	615 ft^2/sec	50 ft^2/sec
	0.00060	184	120 ft	0.70 ft/sec	1.05 ft/sec	1.87 ft/sec	1,275 ft^2/sec	150 ft^2/sec
	0.00060	650	156 ft	1.26 ft/sec	1.45 ft/sec	2.60 ft/sec	3,470 ft^2/sec	400 ft^2/sec
Antietam (MD)	0.00100	70	52 ft	0.64 ft/sec	1.06 ft/sec	1.55 ft/sec	675 ft^2/sec	100 ft^2/sec
	0.00100	154	65 ft	0.90 ft/sec	1.40 ft/sec	2.05 ft/sec	1,185 ft^2/sec	175 ft^2/sec
	0.00100	315	80 ft	1.39 ft/sec	1.70 ft/sec	2.65 ft/sec	1,970 ft^2/sec	275 ft^2/sec
Missouri (IA)	0.00020	13,400	600 ft	2.97 ft/sec	3.06 ft/sec	5.93 ft/sec	55,835 ft^2/sec	5,000 ft^2/sec
	0.00020	32,200	660 ft	4.07 ft/sec	4.18 ft/sec	8.00 ft/sec	121,970 ft^2/sec	9,000 ft^2/sec
	0.00020	33,000	645 ft	4.86 ft/sec	5.02 ft/sec	8.85 ft/sec	127,905 ft^2/sec	9,600 ft^2/sec
Clinch (TN)	0.00060	325	155 ft	0.68 ft/sec	0.76 ft/sec	1.63 ft/sec	1,745 ft^2/sec	150 ft^2/sec
	0.00060	1,800	175 ft	1.44 ft/sec	1.50 ft/sec	4.00 ft/sec	8,570 ft^2/sec	500 ft^2/sec
	0.00060	3,000	195 ft	2.13 ft/sec	2.20 ft/sec	5.75 ft/sec	12,820 ft^2/sec	600 ft^2/sec
Anacoco (LA)	0.00050	85	65 ft	0.68 ft/sec	0.96 ft/sec	1.46 ft/sec	1,305 ft^2/sec	150 ft^2/sec
	0.00050	290	85 ft	1.10 ft/sec	1.11 ft/sec	2.00 ft/sec	3,410 ft^2/sec	350 ft^2/sec
	0.00050	475	120 ft	1.32 ft/sec	1.31 ft/sec	2.35 ft/sec	3,960 ft^2/sec	425 ft^2/sec
Nooksack (WA)	0.0098	1,150	210 ft	2.23 ft/sec	2.20 ft/sec	3.50 ft/sec	2,795 ft^2/sec	375 ft^2/sec
	0.0098	10,700	282 ft	4.28 ft/sec	3.94 ft/sec	7.80 ft/sec	19,360 ft^2/sec	1,650 ft^2/sec
Wind (WY)	0.00130	2,045	220 ft	2.92 ft/sec	2.90 ft/sec	5.00 ft/sec	3,375 ft^2/sec	450 ft^2/sec
	0.00130	8,150	225 ft	5.11 ft/sec	5.10 ft/sec	8.60 ft/sec	13,930 ft^2/sec	1,750 ft^2/sec
Elkhorn (NE)	0.00073	150	107 ft	1.10 ft/sec	1.42 ft/sec	2.35 ft/sec	960 ft^2/sec	100 ft^2/sec
	0.00053	350	167 ft	1.36 ft/sec	1.52 ft/sec	2.77 ft/sec	1,975 ft^2/sec	225 ft^2/sec

Table 3. Measurements of Longitudinal Dispersion in Open Channels (continued)

River Name	Slope (ft/ft)	Q (cfs)	Top Width (W)	Travel Time Velocity (u_{tt})	Cross-Sectional Mean Velocity at Two Stations	Advective Velocity (c_k)	Flow Coefficient (K)	Dispersion Coefficient (E_x)
John Day (OR)	0.00355	500	82 ft	3.35 ft/sec	3.30 ft/sec	4.82 ft/sec	860 ft^2/sec	150 ft^2/sec
	0.00135	2,440	112 ft	2.70 ft/sec	2.70 ft/sec	6.05 ft/sec	8,070 ft^2/sec	700 ft^2/sec
Comite (LA)	0.00078	35	41 ft	0.75 ft/sec	1.02 ft/sec	1.64 ft/sec	550 ft^2/sec	75 ft^2/sec
	0.00078	85	52 ft	1.15 ft/sec	1.21 ft/sec	2.05 ft/sec	1,050 ft^2/sec	150 ft^2/sec
Amite (LA)	0.00061	305	120 ft	0.78 ft/sec	0.96 ft/sec	1.65 ft/sec	2,080 ft^2/sec	250 ft^2/sec
	0.00061	500	139 ft	1.19 ft/sec	1.37 ft/sec	2.60 ft/sec	2,950 ft^2/sec	325 ft^2/sec
Sabine (LA)	0.00015	4,200	340 ft	1.86 ft/sec	1.85 ft/sec	3.25 ft/sec	41,175 ft^2/sec	3,400 ft^2/sec
	0.00015	13,750	418 ft	2.14 ft/sec	2.11 ft/sec	4.25 ft/sec	109,650 ft^2/sec	7,200 ft^2/sec
Yadkin (NC)	0.00044	2,500	230 ft	1.43 ft/sec	1.42 ft/sec	3.07 ft/sec	12,350 ft^2/sec	1,200 ft^2/sec
	0.00044	7,500	235 ft	2.50 ft/sec	2.53 ft/sec	4.80 ft/sec	36,265 ft^2/sec	2,800 ft^2/sec
Muddy (NC)	0.00083	140	44 ft	0.98 ft/sec	1.20 ft/sec	2.20 ft/sec	1,915 ft^2/sec	150 ft^2/sec
	0.00083	375	64 ft	1.23 ft/sec	1.49 ft/sec	2.84 ft/sec	3,530 ft^2/sec	350 ft^2/sec
Sabine (TX)	0.00018	260	115 ft	0.58 ft/sec	0.70 ft/sec	1.57 ft/sec	6,280 ft^2/sec	425 ft^2/sec
White (IN)	0.00036	450	220 ft	0.98 ft/sec	1.14 ft/sec	2.05 ft/sec	2,840 ft^2/sec	325 ft^2/sec
Chattahoochee (GA)	0.00052	1,025	215 ft	1.13 ft/sec	1.29 ft/sec	2.75 ft/sec	4,585 ft^2/sec	350 ft^2/sec
Susquehanna (PA)	0.00032	3,740	665 ft	1.07 ft/sec	1.27 ft/sec	2.67 ft/sec	8,790 ft^2/sec	1,000 ft^2/sec
Nottely (GA)	0.00138	1,150	94 ft	2.77 ft/sec	2.24 ft/sec	5.04 ft/sec	4,400 ft^2/sec	360 ft^2/sec

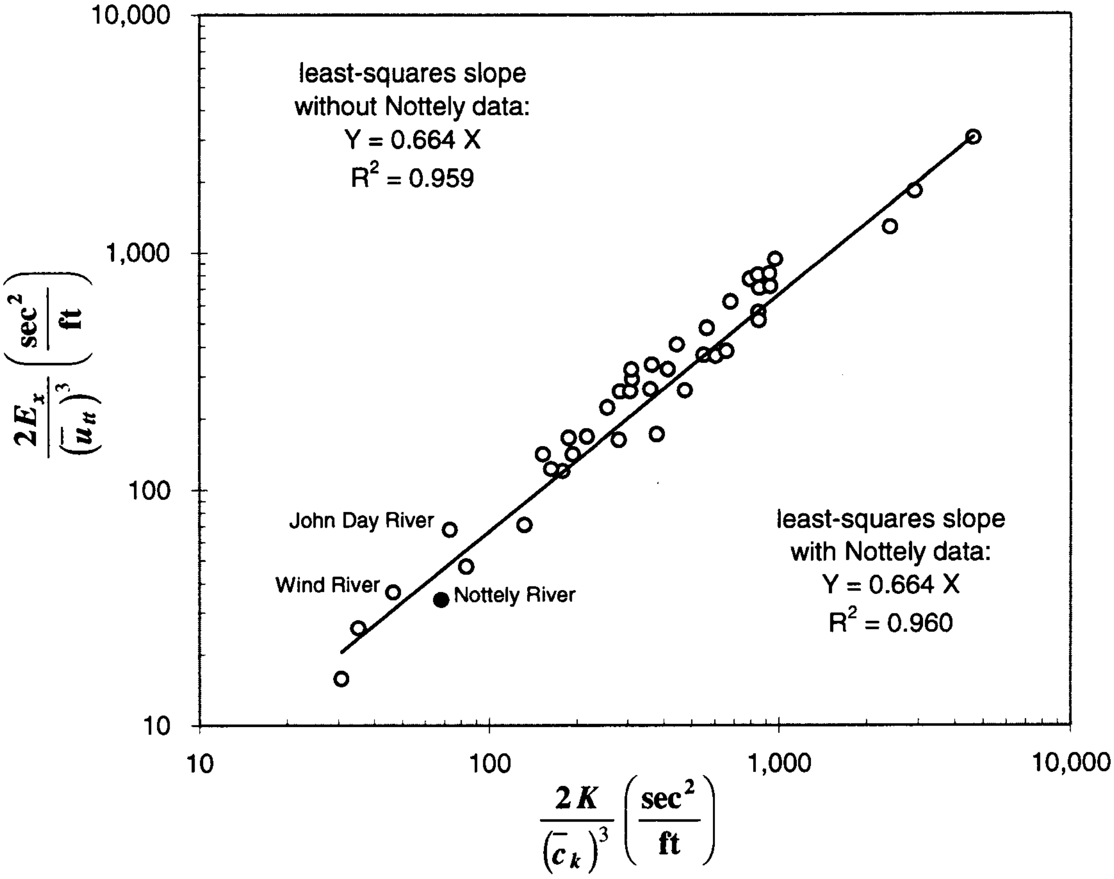


Figure 23. Hydraulic Characteristics of Rivers Used to Develop Equation 2

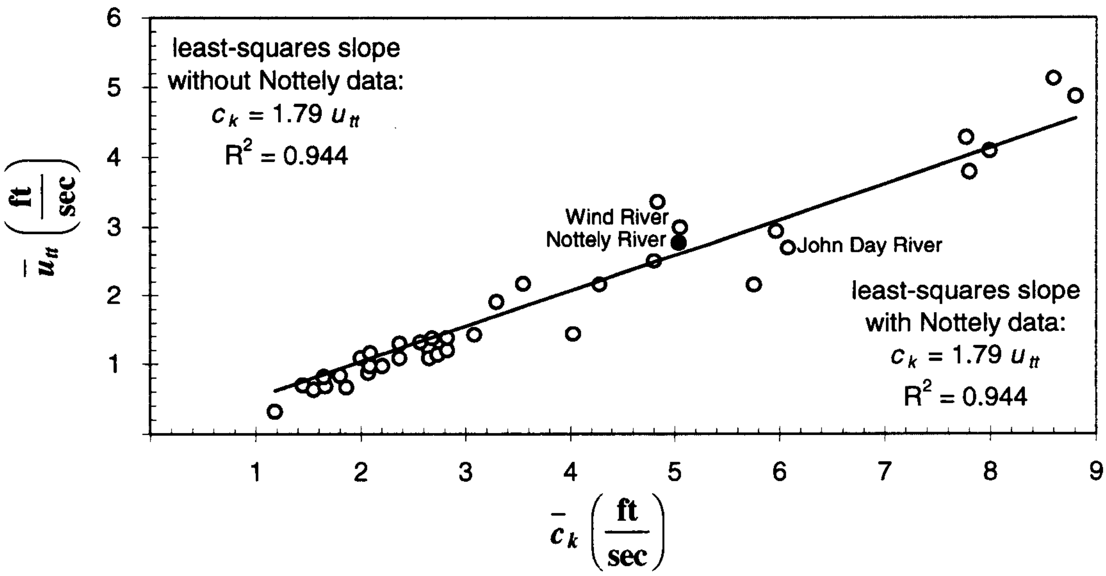


Figure 24. Relation Between Mean Travel Time $(\bar{u}_{tt})$ and Advective Velocity $(\bar{c}_k)$

From Figure 23, least-squares regression indicated a slope of 0.66. Thus, for the range of conditions studied

$$\frac{2E_x}{\left(\bar{u}_{tt}\right)^3} = 0.66\frac{2K}{\left(\bar{c}_k\right)^3} \text{, and then simplifying,} \tag{13}$$

$$E_x = 0.66\frac{\left(\bar{u}_{tt}\right)^3}{\left(\bar{c}_k\right)^3}K. \tag{14}$$

In order to simplify the procedure, McQuivey and Keefer used a relation between the mean travel time velocity $\left(\bar{u}_{tt}\right)$, which is difficult to determine without a time-of-travel study, and the advective velocity $\left(\bar{c}_k\right)$. From Figure 24, the least-squares regression plot of this relation is

$$\bar{c}_k = 1.79\bar{u}_{tt}. \tag{15}$$

Substituting Equation 15 into Equation 14 gives an approximate longitudinal dispersion coefficient

$$E_x \approx 0.115\,K \text{, or} \tag{16}$$

$$E_x\left(\text{ft}^2/\text{sec}\right) \approx 0.058\frac{Q(\text{cfs})}{S \times \overline{W}(\text{ft})}. \tag{17}$$

Because Equation 17 is the same as Equation 2, including the Nottely Dam tailwater data into the development of Equation 2 does not change McQuivey and Keefer's equation.

As does the McQuivey/Keefer paper, Figure 25 indicates that the ratio of advective and mean travel time velocities is a function of the Froude number. Although they did not use such a plot in the final development of Equation 2, they realized the relation does exist. Likewise, Figure 25 was not used to develop Equation 17, but is shown for information only.

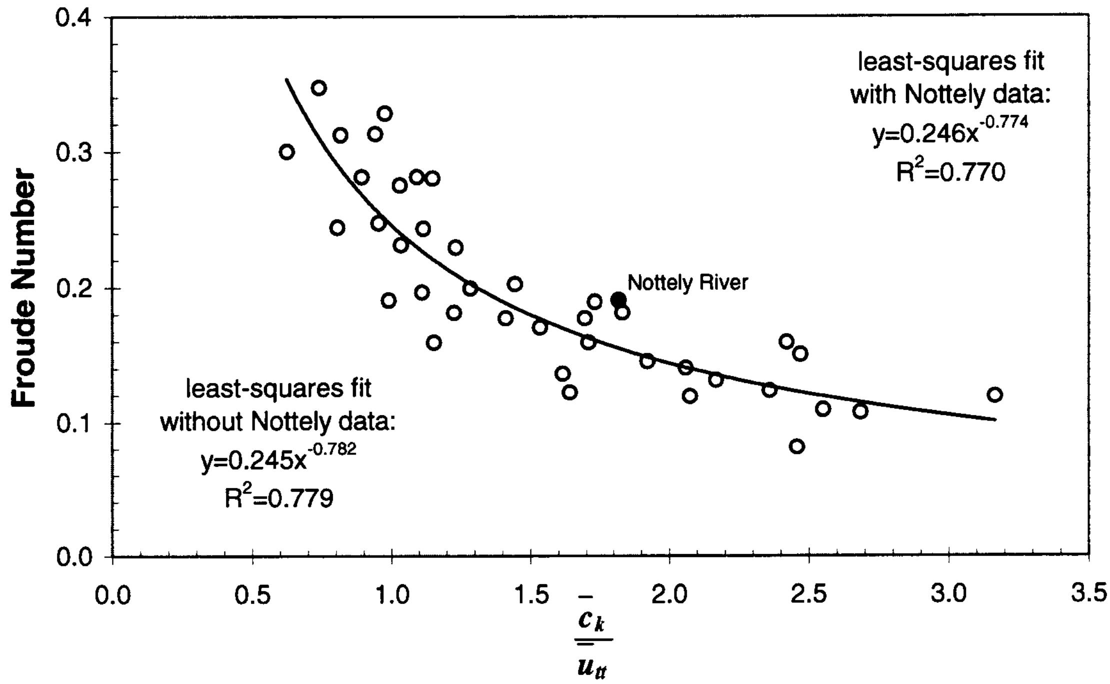


Figure 25. Froude Number Versus Ratio of Advective and Mean Travel Time Velocities

Effect of Discharge on Longitudinal Dispersion

Even though it was shown by Equation 17 that including the Nottely Dam tailwater dye dispersion test data into the McQuivey and Keefer study (1974) did not improve their equation, it is still hypothesized that some benefit can be achieved by combining the Nottely Dam tailwater data with the McQuivey/Keefer study. One such possibility is to explore the relationship between E_x and Q, as plotted in Figure 26. Figure 26 shows an example of how data from the McQuivey/Keefer study can be used to predict the Nottely River longitudinal dispersion coefficient for a variety of discharges other than 1,150 cfs. The example shows that if Q is decreased by 50 percent, then E_x would decrease by 39 percent.

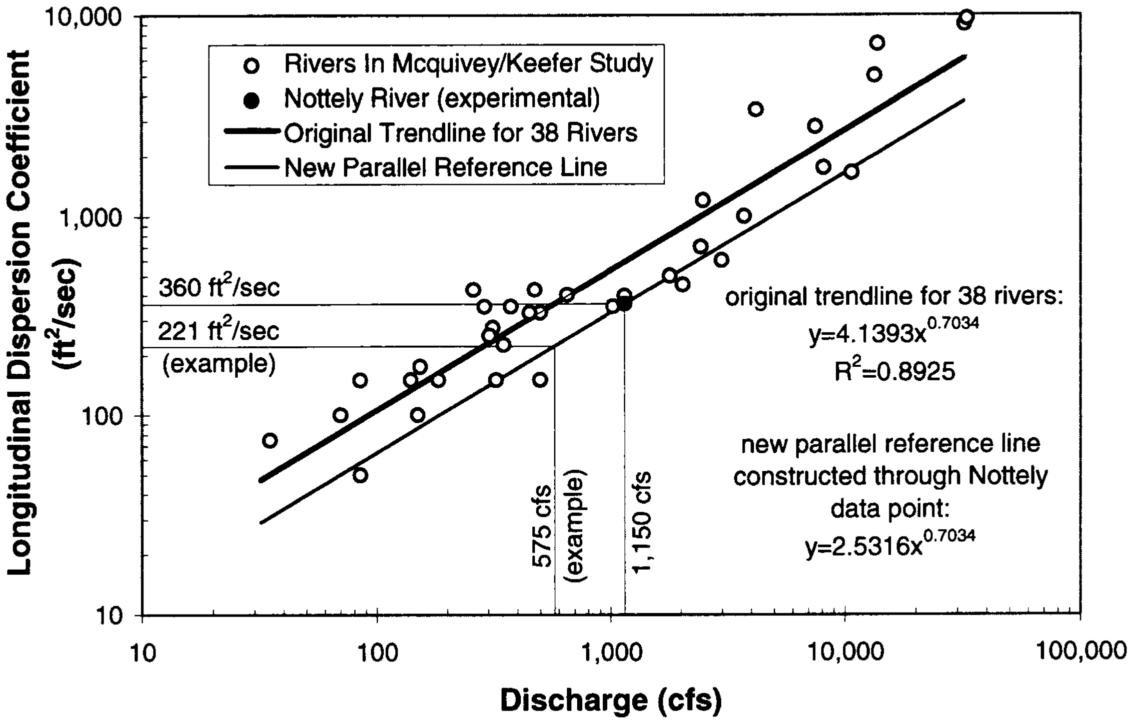


Figure 26. Effect of Discharge on Longitudinal Dispersion in Open Channels

8. CONCLUSIONS

One reason the water tracing experiment performed on the Nottely River can be deemed a successful test was the relatively good percentage of dye mass recovery (96.2%). Additional indicators of a successful test are the traditional Gaussian shapes of the concentration vs. time plots. From the test results, the following conclusions are drawn.

Longitudinal Dispersion Coefficient

E_x for the Nottely Dam tailwater was determined by experiment to be 360 ft^2/sec. If E_x were based only on empirical equations in literature, the best estimate would be 390 ft^2/sec, obtained by using Equation 1 (Fischer and List, 1979). This would understate E_x by only 8.3 percent. Equation 2 (McQuivey and Keefer, 1974) overstated E_x by 43 percent. Because the Fischer equation directly used reliable velocity data, and is nonlinear, the equation emulated essential features of the one-dimensional advection-dispersion for the Nottely Dam tailwater. It was observed that the McQuivey/Keefer equation is linear, and has no input for velocity. Therefore, it can be concluded from this thesis work that the empirical equation published in Fischer and List (1979), when compared with the experimental results, provided a good estimate of the longitudinal dispersion coefficient (E_x) for the Nottely Dam tailwater.

High-Level vs. Low-Level Tests

The high-level test divided the river into three theoretical streamtubes, whereas the low-level test considered only the center streamtube. A comparison of results showed that E_x varied by 43 percent, depending on the level of testing. The significant difference between the high-level and low-level test results suggest that performing only a low-level test is not worth the slight cost savings (relative to a high-level study).

Based on the Nottely River experiment and observations during low-level tests on the White River in the Ozark Mountains, multiple streamtubes should be used. Fortunately, the Ozark tests used excessive dye, so photographs could be used to interpret plume behavior. Therefore, one method of improving results of a low-level dye test is to inject excessive dye so that a dramatic red plume is visible for the entire test reach. This enables observers at the sampling station to visualize the plume. Detailed notes and pictures can then be used to at least qualitatively judge, or interpret, the low-level test results (USGS, 1968).

Lessons Learned

Many lessons were learned while planning, executing, and analyzing the Nottely River dye dispersion experiment. The first important decision in planing a dye tracer study is to determine if the experiment is really needed. There should be a definite purpose for conducting the test, and that purpose is usually to support a water quality model. Otherwise, empirical equations from literature could be used. If an empirical equation is utilized, it is suggested that previous dye studies used in the regression analysis of the equation should be screened to match similar slope, discharge, and hydraulic characteristics of the desired test reach.

The first activity in planning a dye dispersion test is to study topo maps, county maps, and tourist information. Look for public access points, roads, and bridges. Phoning resorts, outfitters, or realtors prior to the first site visit can establish useful contacts. These residents may be helpful by providing a boat, river access, dock, or electricity to power the sampling pumps.

Usually, the test reach is bounded by the modeling needs, but the difficult part is selecting the exact injection and sampling sites. The injection site should be upstream as far as possible to maximize the length of the test reach, but just downstream of the turbine discharge boil because recirculation (or eddy behavior) occurs near the powerhouse as the turbine discharge violently dissipates any remaining energy (head). The primary criteria for selecting the sampling site is accessibility (by car or boat), while at the same time, maximizing the reach length tested.

Dye injection was greatly simplified using the suspended tipping bucket apparatus invented for this thesis project. The suspended buckets can instantaneously inject dye at specified locations, with minimum manpower and maximum safety. Plus, the apparatus can be safely tripped at night (because hydro operations dictate the research schedule, never vice versa).

The decision of whether to use fluorometers in the field often can be immediately determined by the number of fluorometers available. A dye tracer experiment with multiple stream tubes would require at least three (or maybe six) machines. However, the recommended sample collection method is to take bottle samples, then determine the dye concentration with one fluorometer in a laboratory setting. In fact, a field fluorometer is not required to determine when to take the bottle samples. The leading edge of the dye plume is usually visible (for added warning, wood chips or some other floating marker can be dumped in the river a few minutes prior to dye injection). Initial hand calculations used to plan the dye test and visual observations during the test can be used to determine how long to keep taking bottle samples. If in doubt, the procedure should be to keep taking samples. It is very easy work to continue collecting hourly samples to assure that the plume tail is adequately captured.

Cost Control

Controlling costs was mandatory for this research because the project was funded primarily by the author. An estimate of expenses for the dye tracing experiment is tabulated in Appendix C. Several key guidelines were used to control costs as follows:

1. Use minimum staffing - For example, an instrument mechanic is not needed on the trip if no field fluorometer is used.

2. Use inexpensive labor - Dye tracer studies are dramatic and exciting. Volunteer help by relatives and peers is easy to obtain. Required safety observers should not be expensive engineers.

3. Take the modeler along - If the modeler's site visit is planned in conjunction with the dye test, then the modeler can help with the dye study.

4. Use Hoover's suspended tipping buckets for one-person dye injection.

5. Motor boats, trailers, and boat operators are expensive - Use a small, lightweight boat that can be carried by one person and transported by car.

6. Perform equipment set-up during low flow conditions the day before the test.

7. Camp on the river - Save motel expenses by camping at a sampling site. Equipment will be safer overnight, too.

8. Professional aerial photographers are not needed - Phone the nearest airport and offer to pay plane rental. Pilots love to fly and will do it for free (if you pay for the plane). They can shoot pictures through the window while flying.

9. Reduce travel costs - Travel on your own time, as if on vacation. Take family members along. After the test, take a holiday for fishing or canoeing.

10. Trade your talents - Maybe a trout biologist is needed to witness the test. Instead of direct payment, trade services (eg., provide the biologist some complimentary bioenergetic modeling).

11. Recycle the hardware - Be sure to lock-up the hardware while in storage between projects, or it will disappear.

Final Remarks

In the late 1990s, increased personal computer capability, environmental awareness, and new waste discharge permitting requirements have made it necessary for more water quality modeling projects. Since models require field data, it would seem that field studies would be conducted more frequently. However, the literature search shows that is not true. Large-scale dye tracing experiments are relatively rare now. The reason is because in today's downsized economic climate, the bottom line is always cost, and traditional dye tests were expensive—and even more costly today. It does not matter if you are TVA, USGS, a graduate assistant, or in private practice, no research can be done without money. But hopefully, this thesis can start reversing that trend, because this research showed that a high-level water tracing experiment can indeed be performed on a shoestring budget, yet deliver results of good quality.

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APPENDICES

APPENDIX A: FIELD DATA

APPENDIX A: FIELD DATA

Hydraulic Data

Table 4 lists hydraulic data obtained on October 27 and 29, 1997, during steady-state turbine discharge of 1170 cfs.

Table 4. Hydraulic Data

River Mile	Distance From Left Bank	Depth (ft)	Velocity (ft/sec)	Area (ft^2)	Discharge (cfs)	Estimated Precision
21.0	0 ft	0.0	-	-	-	-
21.0	11 ft	5.0	-	-	-	-
21.0	30 ft	5.5	-	-	-	-
21.0	44 ft	5.0	-	-	-	-
21.0	59 ft	0.0	-	-	-	-
20.5	0 ft	0.0	-	-	-	-
20.5	10 ft	4.8	-	-	-	-
20.5	70 ft	5.6	-	-	-	-
20.5	115 ft	4.8	-	-	-	-
20.5	124 ft	0.0	-	-	-	-
20.0	0 ft	0.0	-	-	-	-
20.0	1 ft	4.2	-	-	-	-
20.0	45 ft	5.7	-	-	-	-
20.0	104 ft	4.2	-	-	-	-
20.0	105 ft	0.0	-	-	-	-
19.5	0 ft	0.0	0.0	-	-	-
19.5	1 ft	4.0	0.99	60	59	-
19.5	30 ft	6.1	1.68	180	303	-
19.5	60 ft	6.3	2.08	210	438	-
19.5	97 ft	6.0	2.08	144	299	-
19.5	108 ft	4.4	1.68	30	52	-
19.5	111 ft	0.0	0.0	Σ=624	Σ=1152	fair (± 8 percent)
19.0	0 ft	0.0	-	-	-	-
19.0	6 ft	4.5	-	-	-	-
19.0	39 ft	5.2	-	-	-	-
19.0	69 ft	4.5	-	-	-	-
19.0	72 ft	0.0	-	-	-	-
						-

Table 4. Hydraulic Data (continued)

River Mile	Distance From Left Bank	Depth (ft)	Velocity (ft/sec)	Area (ft^2)	Discharge (cfs)	Estimated Precision
18.5	0 ft	0.0	-	-	-	-
18.5	2 ft	5.6	-	-	-	-
18.5	69 ft	4.8	-	-	-	-
18.5	123 ft	5.3	-	-	-	-
18.5	127 ft	0.0	-	-	-	-
18.0	0 ft	0.0	-	-	-	-
18.0	10 ft	5.0	-	-	-	-
18.0	40 ft	5.5	-	-	-	-
18.0	71 ft	5.0	-	-	-	-
18.0	78 ft	0.0	-	-	-	-
17.3	0 ft	0.0	-	-	-	-
17.3	7 ft	4.1	-	-	-	-
17.3	45 ft	5.4	-	-	-	-
17.3	82 ft	4.1	-	-	-	-
17.3	86 ft	0.0	-	-	-	-
16.7	0 ft	0.0	-	-	-	-
16.7	6 ft	3.9	-	-	-	-
16.7	49 ft	5.2	-	-	-	-
16.7	91 ft	3.9	-	-	-	-
16.7	95 ft	0.0	-	-	-	-
16.3	0 ft	0.0	-	-	-	-
16.3	9 ft	4.9	-	-	-	-
16.3	55 ft	5.4	-	-	-	-
16.3	100 ft	3.9	-	-	-	-
16.3	106 ft	0.0	-	-	-	-
15.7	0 ft	0.0	0.0	-	-	-
15.7	2 ft	5.0	1.72	22	40	-
15.7	9 ft	5.5	2.06	30	62	-
15.7	13 ft	5.5	2.51	19	48	-
15.7	16 ft	5.6	2.74	25	69	-
15.7	22 ft	5.7	2.48	34	85	-
15.7	28 ft	6.1	2.93	37	107	-
15.7	34 ft	6.5	3.32	39	130	-
15.7	40 ft	6.5	3.27	39	128	-
15.7	46 ft	6.5	3.6	52	187	-
15.7	56 ft	6.5	2.51	59	146	-
15.7	64 ft	6.5	2.46	58	143	-
15.7	74 ft	6.0	1.87	33	62	-
15.7	75 ft	0.0	0.0	Σ=448	Σ=1207	good (± 5 percent)

Turbine Discharge Records

Table 5 lists the hourly turbine discharges (based on piezometer taps) reported by the powerhouse operator for October 27-29, 1997. The estimated precision of the powerhouse hourly discharge readings is according to Rader (1998) and Fain (1986).

Table 5. Turbine Discharge Records

Day	Date	Time	Discharge	Estimated Precision
Mon	10/27/97	0400	50 cfs	good (± 5 percent)
Mon	10/27/97	0500	50 cfs	good (± 5 percent)
Mon	10/27/97	0600	1170 cfs	good (± 5 percent)
Mon	10/27/97	0700	1170 cfs	good (± 5 percent)
Mon	10/27/97	0800	1170 cfs	good (± 5 percent)
Mon	10/27/97	0900	1170 cfs	good (± 5 percent)
Mon	10/27/97	1000	1170 cfs	good (± 5 percent)
Mon	10/27/97	1100	1170 cfs	good (± 5 percent)
Mon	10/27/97	1200	1170 cfs	good (± 5 percent)
Mon	10/27/97	1300	1170 cfs	good (± 5 percent)
Mon	10/27/97	1400	50 cfs	good (± 5 percent)
Tue	10/28/97	0400	50 cfs	good (± 5 percent)
Tue	10/28/97	0500	50 cfs	good (± 5 percent)
Tue	10/28/97	0600	1150 cfs	good (± 5 percent)
Tue	10/28/97	0700	1150 cfs	good (± 5 percent)
Tue	10/28/97	0800	1150 cfs	good (± 5 percent)
Tue	10/28/97	0900	1150 cfs	good (± 5 percent)
Tue	10/28/97	1000	1150 cfs	good (± 5 percent)
Tue	10/28/97	1100	1150 cfs	good (± 5 percent)
Tue	10/28/97	1200	1150 cfs	good (± 5 percent)
Tue	10/28/97	1300	1150 cfs	good (± 5 percent)
Tue	10/28/97	1400	1150 cfs	good (± 5 percent)
Wed	10/29/97	0400	50 cfs	good (± 5 percent)
Wed	10/29/97	0500	50 cfs	good (± 5 percent)
Wed	10/29/97	0600	1170 cfs	good (± 5 percent)
Wed	10/29/97	0700	1170 cfs	good (± 5 percent)
Wed	10/29/97	0800	1170 cfs	good (± 5 percent)
Wed	10/29/97	0900	1170 cfs	good (± 5 percent)
Wed	10/29/97	1000	1170 cfs	good (± 5 percent)
Wed	10/29/97	1100	1170 cfs	good (± 5 percent)
Wed	10/29/97	1200	1170 cfs	good (± 5 percent)
Wed	10/29/97	1300	1170 cfs	good (± 5 percent)
Wed	10/29/97	1400	50 cfs	good (± 5 percent)

Dye Data

Table 6 lists the dye concentration data that resulted from a 5-liter dye injection on October 28, 1997 (0825 EST), at NRM 21.0.

Table 6. Dye Sampling Data

River Mile	Time (EST)	Distance From Left Bank	Channel Depth	Sample Depth	Concentration (ppb)
19.5	0855	30 ft	6.1 ft	3.7 ft	0.0
19.5	0902	30 ft	6.1 ft	3.7 ft	3.0
19.5	0905	30 ft	6.1 ft	3.7 ft	11.8
19.5	0908	30 ft	6.1 ft	3.7 ft	23.4
19.5	0911	30 ft	6.1 ft	3.7 ft	22.1
19.5	0915	30 ft	6.1 ft	3.7 ft	18.6
19.5	0925	30 ft	6.1 ft	3.7 ft	6.2
19.5	0935	30 ft	6.1 ft	3.7 ft	2.4
19.5	0945	30 ft	6.1 ft	3.7 ft	1.3
19.5	0955	30 ft	6.1 ft	3.7 ft	1.0
19.5	1005	30 ft	6.1 ft	3.7 ft	0.8
19.5	1015	30 ft	6.1 ft	3.7 ft	0.7
19.5	1035	30 ft	6.1 ft	3.7 ft	0.7
19.5	1055	30 ft	6.1 ft	3.7 ft	0.6
19.5	1115	30 ft	6.1 ft	3.7 ft	0.6
19.5	1145	30 ft	6.1 ft	3.7 ft	0.6
19.5	1215	30 ft	6.1 ft	3.7 ft	0.5
19.5	1300	30 ft	6.1 ft	3.7 ft	0.5
19.5	1325	30 ft	6.1 ft	3.7 ft	0.4
19.5	1400	30 ft	6.1 ft	3.7 ft	0.4
19.5	0855	61 ft	6.3 ft	3.8 ft	0.0
19.5	0902	61 ft	6.3 ft	3.8 ft	5.0
19.5	0905	61 ft	6.3 ft	3.8 ft	18.5
19.5	0908	61 ft	6.3 ft	3.8 ft	23.8
19.5	0911	61 ft	6.3 ft	3.8 ft	21.8
19.5	0915	61 ft	6.3 ft	3.8 ft	16.5
19.5	0925	61 ft	6.3 ft	3.8 ft	5.7
19.5	0935	61 ft	6.3 ft	3.8 ft	2.1
19.5	0945	61 ft	6.3 ft	3.8 ft	1.2
19.5	0955	61 ft	6.3 ft	3.8 ft	0.8
19.5	1005	61 ft	6.3 ft	3.8 ft	0.7
19.5	1015	61 ft	6.3 ft	3.8 ft	0.6
19.5	1035	61 ft	6.3 ft	3.8 ft	0.5
19.5	1055	61 ft	6.3 ft	3.8 ft	0.4
19.5	1115	61 ft	6.3 ft	3.8 ft	0.4
19.5	1145	61 ft	6.3 ft	3.8 ft	0.4
19.5	1215	61 ft	6.3 ft	3.8 ft	0.4

Table 6. Dye Sampling Data (continued)

River Mile	Time (EST)	Distance From Left Bank	Channel Depth	Sample Depth	Concentration (ppb)
19.5	1300	61 ft	6.3 ft	3.8 ft	0.4
19.5	1325	61 ft	6.3 ft	3.8 ft	0.4
19.5	1400	61 ft	6.3 ft	3.8 ft	0.4
19.5	0855	90 ft	6.0 ft	3.8 ft	0.0
19.5	0902	90 ft	6.0 ft	3.8 ft	3.0
19.5	0905	90 ft	6.0 ft	3.8 ft	11.2
19.5	0908	90 ft	6.0 ft	3.8 ft	19.4
19.5	0911	90 ft	6.0 ft	3.8 ft	23.6
19.5	0915	90 ft	6.0 ft	3.8 ft	18.2
19.5	0925	90 ft	6.0 ft	4.5 ft	7.9
19.5	0935	90 ft	6.0 ft	3.8 ft	2.8
19.5	0945	90 ft	6.0 ft	3.8 ft	1.5
19.5	0955	90 ft	6.0 ft	3.8 ft	1.0
19.5	1005	90 ft	6.0 ft	3.8 ft	0.9
19.5	1015	90 ft	6.0 ft	3.8 ft	0.8
19.5	1035	90 ft	6.0 ft	3.8 ft	0.6
19.5	1055	90 ft	6.0 ft	3.8 ft	0.6
19.5	1115	90 ft	6.0 ft	3.8 ft	0.6
19.5	1145	90 ft	6.0 ft	3.8 ft	0.4
19.5	1215	90 ft	6.0 ft	3.8 ft	0.4
19.5	1300	90 ft	6.0 ft	3.8 ft	0.4
19.5	1325	90 ft	6.0 ft	3.8 ft	0.4
19.5	1400	90 ft	6.0 ft	3.8 ft	0.4
15.7	1005	20 ft	5.8 ft	3.5 ft	0.0
15.7	1020	20 ft	5.8 ft	3.5 ft	0.5
15.7	1035	20 ft	5.8 ft	3.5 ft	0.8
15.7	1045	20 ft	5.8 ft	3.5 ft	4.2
15.7	1050	20 ft	5.8 ft	3.5 ft	5.1
15.7	1056	20 ft	5.8 ft	3.5 ft	8.0
15.7	1101	20 ft	5.8 ft	3.5 ft	9.7
15.7	1105	20 ft	5.8 ft	3.5 ft	10.0
15.7	1110	20 ft	5.8 ft	3.5 ft	10.2
15.7	1116	20 ft	5.8 ft	3.5 ft	9.0
15.7	1123	20 ft	5.8 ft	3.5 ft	7.8
15.7	1130	20 ft	5.8 ft	3.5 ft	5.0
15.7	1140	20 ft	5.8 ft	3.5 ft	3.1
15.7	1150	20 ft	5.8 ft	3.5 ft	1.8
15.7	1200	20 ft	5.8 ft	3.5 ft	1.2
15.7	1215	20 ft	5.8 ft	3.5 ft	0.8
15.7	1232	20 ft	5.8 ft	3.5 ft	0.5
15.7	1300	20 ft	5.8 ft	3.5 ft	0.4
15.7	1400	20 ft	5.8 ft	3.5 ft	0.3
15.7	1500	20 ft	5.8 ft	3.5 ft	0.3

Table 6. Dye Sampling Data (continued)

River Mile	Time (EST)	Distance From Left Bank	Channel Depth	Sample Depth	Concentration (ppb)
15.7	1005	40 ft	6.5 ft	3.9 ft	0.0
15.7	1020	40 ft	6.5 ft	3.9 ft	0.9
15.7	1035	40 ft	6.5 ft	3.9 ft	1.4
15.7	1045	40 ft	6.5 ft	3.9 ft	3.0
15.7	1050	40 ft	6.5 ft	3.9 ft	5.9
15.7	1056	40 ft	6.5 ft	3.9 ft	8.3
15.7	1101	40 ft	6.5 ft	3.9 ft	10.3
15.7	1105	40 ft	6.5 ft	3.9 ft	10.1
15.7	1110	40 ft	6.5 ft	3.9 ft	10.0
15.7	1116	40 ft	6.5 ft	3.9 ft	8.6
15.7	1123	40 ft	6.5 ft	3.9 ft	6.7
15.7	1130	40 ft	6.5 ft	3.9 ft	4.7
15.7	1140	40 ft	6.5 ft	3.9 ft	2.6
15.7	1150	40 ft	6.5 ft	3.9 ft	1.8
15.7	1200	40 ft	6.5 ft	3.9 ft	1.4
15.7	1215	40 ft	6.5 ft	3.9 ft	0.8
15.7	1232	40 ft	6.5 ft	3.9 ft	0.8
15.7	1300	40 ft	6.5 ft	3.9 ft	0.6
15.7	1400	40 ft	6.5 ft	3.9 ft	0.4
15.7	1500	40 ft	6.5 ft	3.9 ft	0.2
15.7	1005	62 ft	6.5 ft	3.9 ft	0.0
15.7	1020	62 ft	6.5 ft	3.9 ft	0.7
15.7	1035	62 ft	6.5 ft	3.9 ft	1.2
15.7	1045	62 ft	6.5 ft	3.9 ft	3.6
15.7	1050	62 ft	6.5 ft	3.9 ft	5.9
15.7	1056	62 ft	6.5 ft	3.9 ft	8.1
15.7	1101	62 ft	6.5 ft	3.9 ft	9.3
15.7	1105	62 ft	6.5 ft	3.9 ft	9.8
15.7	1110	62 ft	6.5 ft	3.9 ft	10.4
15.7	1116	62 ft	6.5 ft	3.9 ft	9.6
15.7	1123	62 ft	6.5 ft	3.9 ft	7.3
15.7	1130	62 ft	6.5 ft	3.9 ft	5.8
15.7	1140	62 ft	6.5 ft	3.9 ft	3.1
15.7	1150	62 ft	6.5 ft	3.9 ft	2.1
15.7	1200	62 ft	6.5 ft	3.9 ft	1.4
15.7	1215	62 ft	6.5 ft	3.9 ft	0.8
15.7	1232	62 ft	6.5 ft	3.9 ft	0.5
15.7	1300	62 ft	6.5 ft	3.9 ft	0.3
15.7	1400	62 ft	6.5 ft	3.9 ft	0.3
15.7	1500	62 ft	6.5 ft	3.9 ft	0.3

The dye concentration field data is plotted in Figures 27-32.

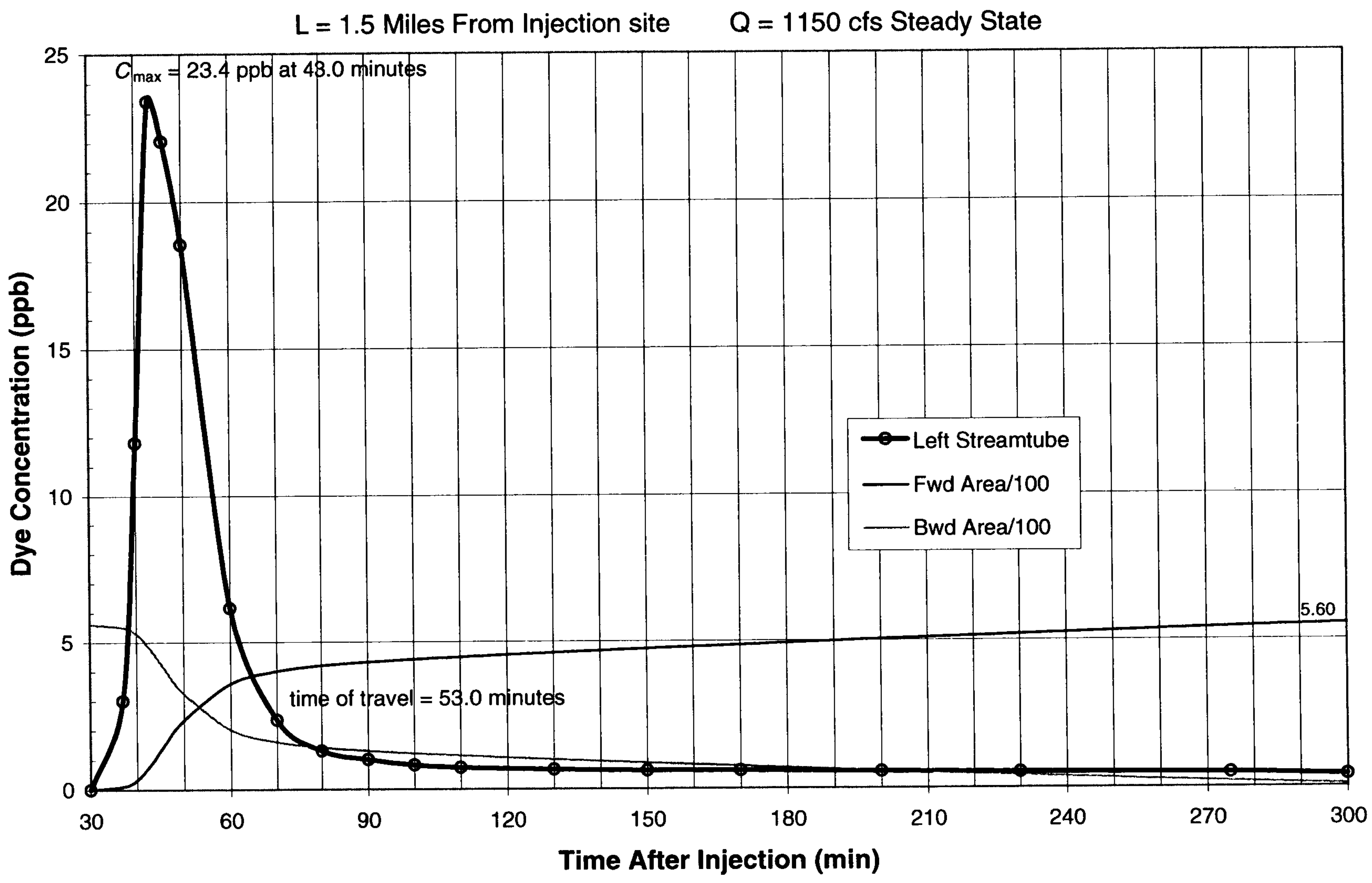

Figure 27. Dye Concentration at NRM 19.5 for Left Streamtube

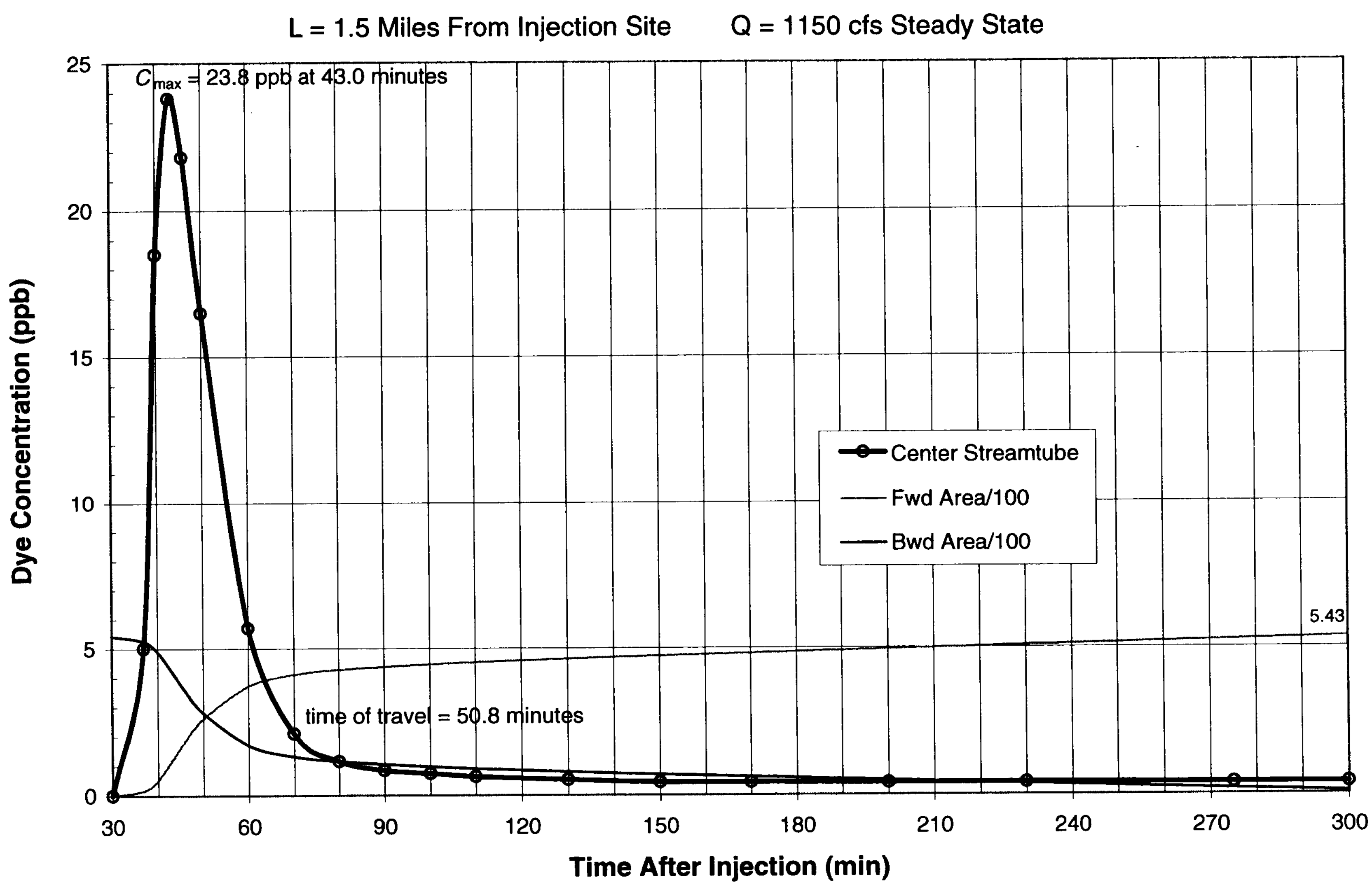

Figure 28. Dye Concentration at NRM 19.5 for Center Streamtube

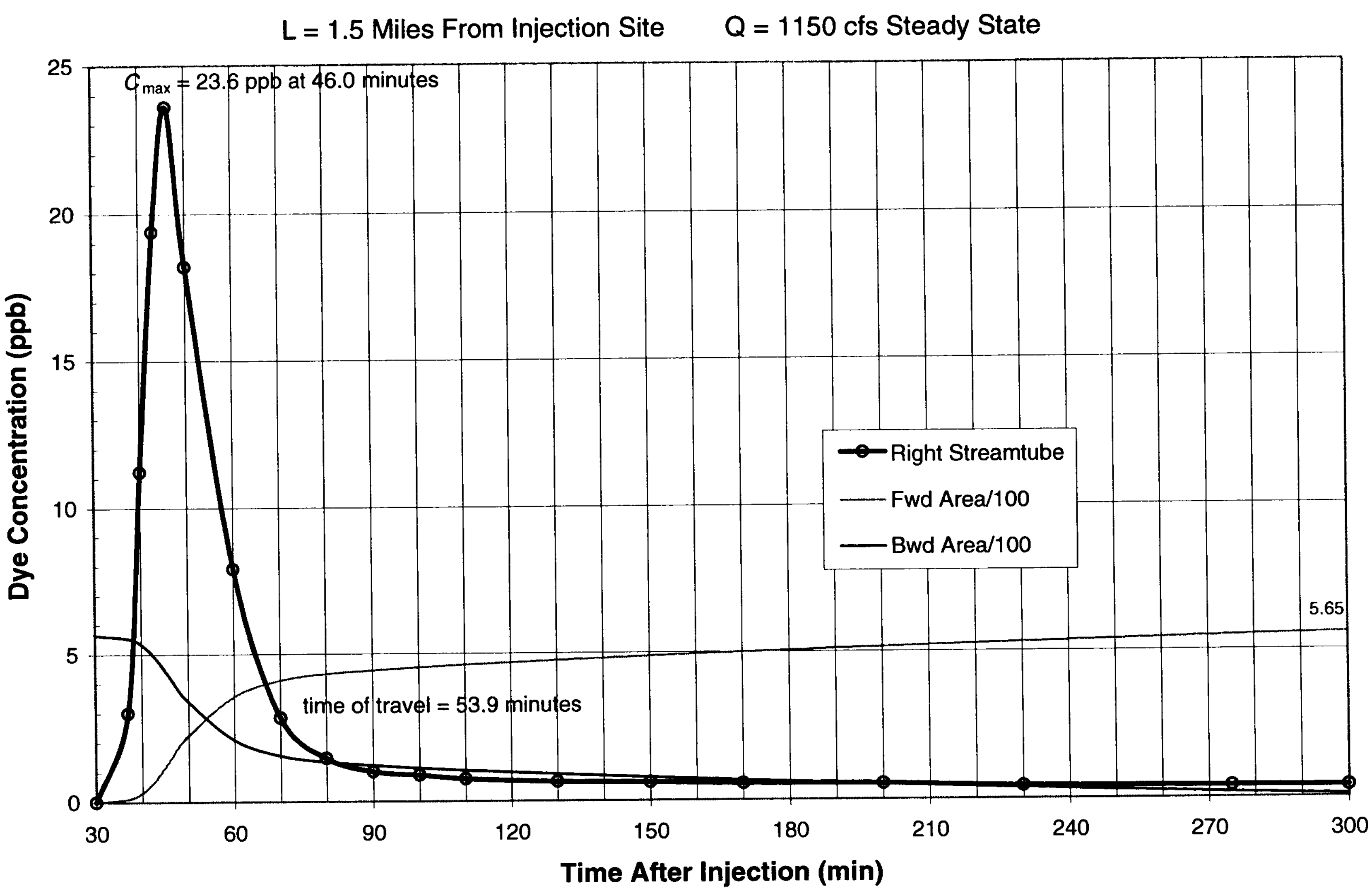

Figure 29. Dye Concentration at NRM 19.5 for Right Streamtube

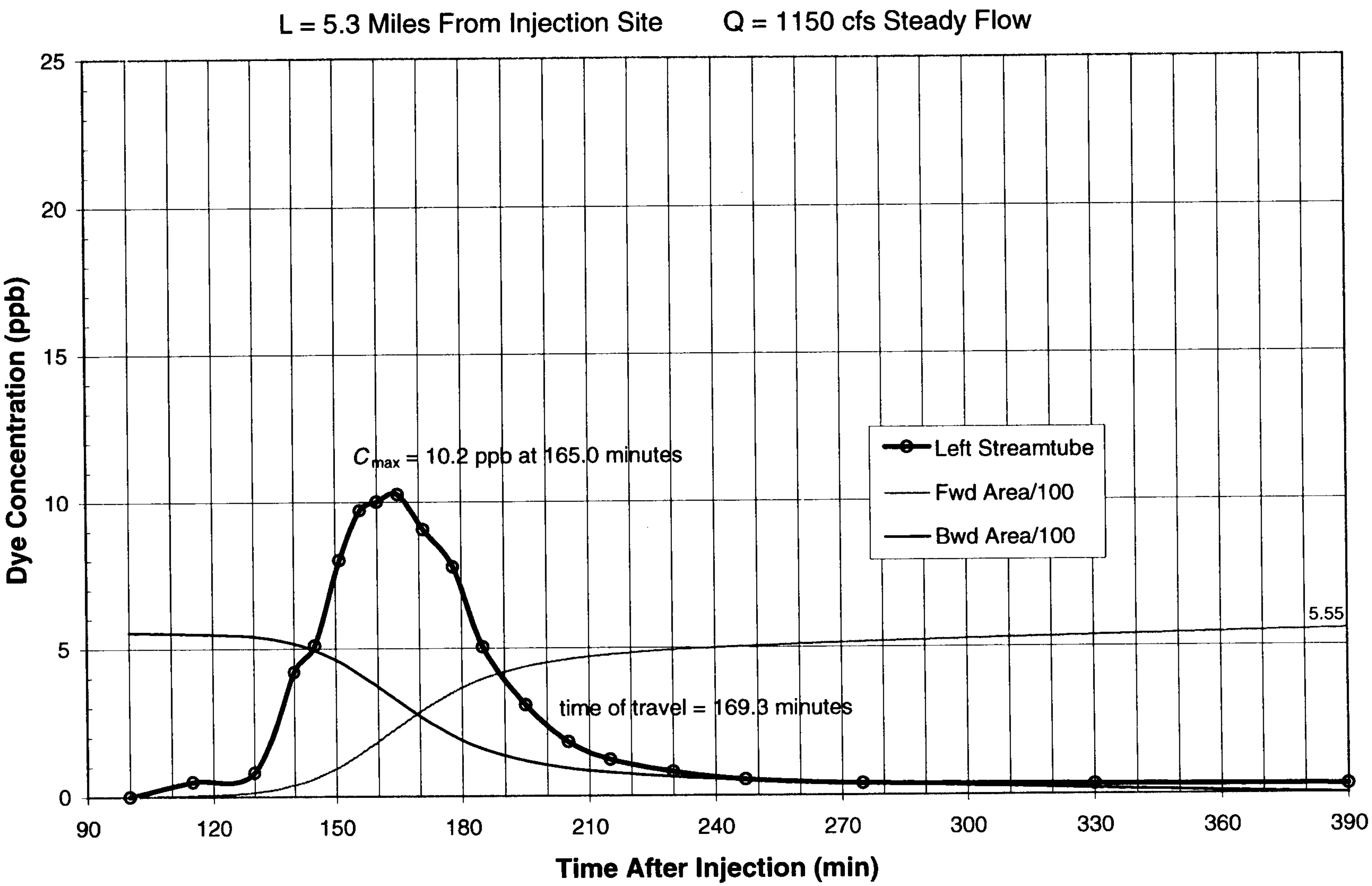

Figure 30. Dye Concentration at NRM 15.7 for Left Streamtube

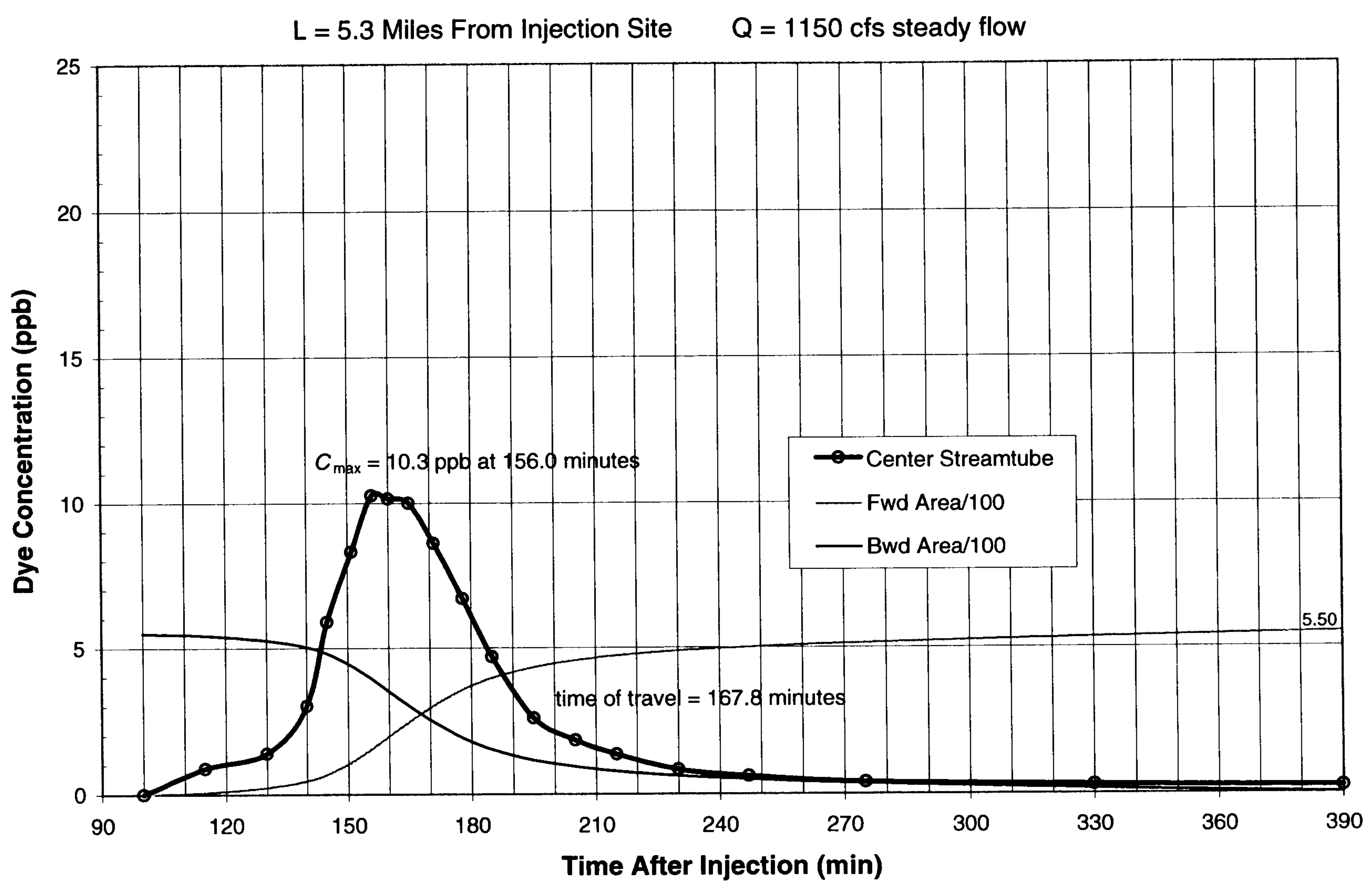

Figure 31. Dye Concentration at NRM 15.7 for Center Streamtube

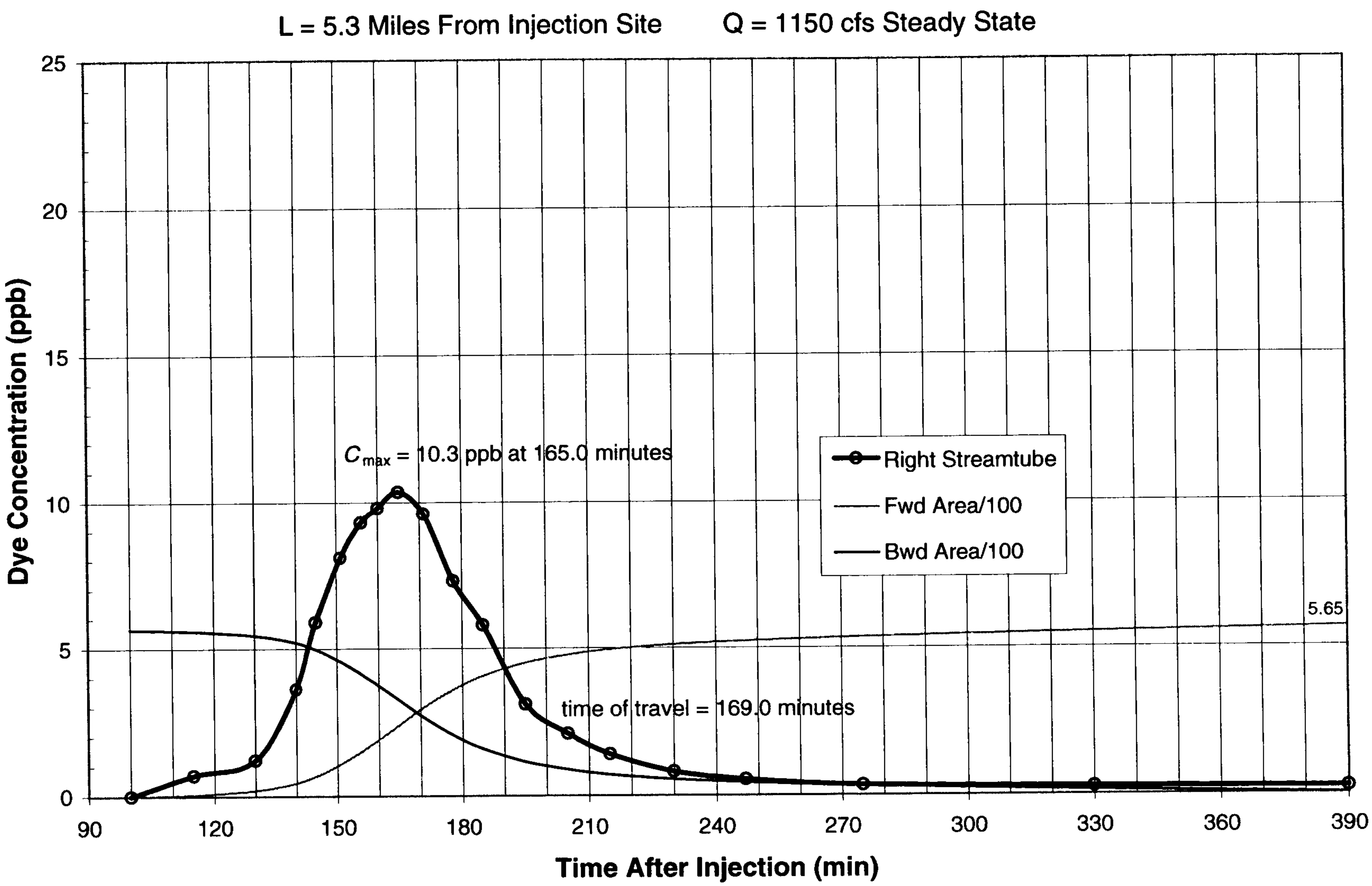

Figure 32. Dye Concentration at NRM 15.7 for Right Streamtube

Grab Sample Data

Grab samples were taken from Smith Bridge and Cook Bridge to check for vertical mixing of the dye in the water column. Figure 33 shows the sampling apparatus and Table 7 lists data that indicate adequate vertical mixing.

Figure 33. Grab Sample Apparatus for Vertical Mixing Check

Table 7. Vertical Mixing Data

River Mile	Time (EST)	Distance From Left Bank	Channel Depth	Sample Depth	Concentration (ppb)
19.3	0915	25 ft	6.0 ft	5.0 ft	19.7
19.3	0915	25 ft	6.0 ft	3.5 ft	19.8
19.3	0915	25 ft	6.0 ft	1.5 ft	19.3
15.6	1135	60 ft	5.5 ft	4.4 ft	4.5
15.6	1135	60 ft	5.5 ft	3.3 ft	4.2
15.6	1135	60 ft	5.5 ft	1.1 ft	4.3

APPENDIX B: CALCULATIONS

APPENDIX B: CALCULATIONS

Calculations

Miscellaneous computations for the Nottely Dam tailwater are documented in this Appendix. The calculations can be used to support the results previously listed (e.g., Tables 1-3), or used as a starting point for future research.

Channel Bed Slope

$$S = \frac{40 \text{ ft}}{(5.5 \text{ mi})(5{,}280 \text{ ft / mi})} = 0.0013774 \text{ ft / ft}$$

Mean Top Width

$$\overline{W} = \frac{(59+124+105+111+72+127+78+86+95+106+75)}{11 \text{ sections}} = 94.4 \text{ ft}$$

Discharge Volume During 290-Minute Test

$$Q_{vol} = (1{,}150 \text{ cfs}) \times (290 \text{ min}) \times (60 \text{ sec/min}) \times 0.02832 \frac{\text{m}^3}{\text{ft}^3} = 566{,}683 \text{ m}^3$$

Dye Weight Injected

$$M_{in} = (20\%)(5 \text{ Liters})(1{,}000 \text{ gm/L})\left(1.13\,\gamma_w\right) = 1{,}130 \text{ gm} = 2.50 \text{ lb}$$

Mean Dye Concentrations at Upstream Sampling Station (NRM 19.5)

$$\overline{C}_{left} = \frac{(5.60 \text{ ppb min}) \times 100}{290 \text{ min}} = 1.93 \text{ ppb} = 1.93 \text{ mg / m}^3$$

$$\overline{C}_{center} = \frac{(5.43\,\text{ppb min}) \times 100}{290\text{ min}} = 1.87\text{ ppb} = 1.87\text{ mg / m}^3$$

$$\overline{C}_{right} = \frac{(5.65\,\text{ppb min}) \times 100}{290\text{ min}} = 1.95\text{ ppb} = 1.95\text{ mg / m}^3$$

where 5.60, 5.43, and 5.65 ppb min are from Figures 27-29.

Dye Mass Recovery at Upstream Sampling Station (NRM 19.5)

$$\frac{M_{out}}{M_{in}} = \frac{(1.93 \times 0.330 + 1.87 \times 0.320 + 1.95 \times 0.350) \times 566{,}683\text{ m}^3}{1{,}130\text{ gm}} = 96.2\%$$

where 0.330, 0.320, and 0.350 are from Figure 17.

Peak Concentration at Upstream Sampling Station (NRM 19.5)

$$23.4\text{ ppb} \times 0.330 + 23.8\text{ ppb} \times 0.320 + 23.6\text{ ppb} \times 0.350 = 23.6\text{ ppb}$$

where 23.4, 23.8, and 23.6 ppb are from Figures 27-29.

Time-to-Peak Concentration at Upstream Sampling Station (NRM 19.5)

$$43.0\text{ min} \times 0.330 + 43.0\text{ min} \times 0.320 + 46.0\text{ min} \times 0.350 = 44.1\text{ min}$$

where 43.0, and 46.0 minutes are from Figures 27-29.

Travel Time to Upstream Sampling Station (NRM 19.5)

$$53.0\text{ min} \times 0.330 + 50.8\text{ min} \times 0.320 + 53.9\text{ min} \times 0.350 = 52.6\text{ min}$$

where 53.0, 50.8, and 53.9 minutes are from Figures 27-29.

Mean Dye Concentrations at Downstream Sampling Station (NRM 15.7)

$$\overline{C}_{left} = \frac{(5.55\,\text{ppb min}) \times 100}{290\ \text{min}} = 1.92\ \text{ppb} = 1.92\ \text{mg}/\text{m}^3$$

$$\overline{C}_{center} = \frac{(5.50\,\text{ppb min}) \times 100}{290\ \text{min}} = 1.89\ \text{ppb} = 1.89\ \text{mg}/\text{m}^3$$

$$\overline{C}_{right} = \frac{(5.65\,\text{ppb min}) \times 100}{290\ \text{min}} = 1.95\ \text{ppb} = 1.95\ \text{mg}/\text{m}^3$$

where 5.55, 5.50, and 5.65 ppb min are from Figures 30-32.

Dye Mass Recovery at Downstream Sampling Station (NRM 15.7)

$$\frac{M_{out}}{M_{in}} = \frac{(1.92 \times 0.340 + 1.89 \times 0.333 + 1.95 \times 0.327) \times 566{,}683\ \text{m}^3}{1{,}130\ \text{gm}} = 96.2\%$$

where 0.340, 0.333, and 0.327 are from Figure 18.

Peak Concentration at Downstream Sampling Station (NRM 15.7)

$$10.2\ \text{ppb} \times 0.340\ +\ 10.3\ \text{ppb} \times 0.333\ +\ 10.3\ \text{ppb} \times 0.327 = 10.3\ \text{ppb}$$

where 10.2 and 10.3 ppb are from Figures 30-32.

Time-to-Peak Concentration at Downstream Sampling Station (NRM 15.7)

$$165.0\ \text{min} \times 0.340\ +\ 156.0\ \text{min} \times 0.333\ +\ 165.0\ \text{min} \times 0.327 = 162.0\ \text{min}$$

where 165.0 and 156.0 minutes are from Figures 30-32.

Travel Time to Downstream Sampling Station (NRM 15.7)

$$169.3\ \text{min} \times 0.340\ +\ 167.8\ \text{min} \times 0.333\ +\ 169.0\ \text{min} \times 0.327 = 168.7\ \text{min}$$

where 169.3, 167.8, and 169.0 minutes are from Figures 30-32.

Thomann's Plotted Slope (high-level study)

$$S_p = \frac{(23.6\text{ ppb} - 10.3\text{ ppb})}{(44\text{ min})^{-0.5} - (162\text{ min})^{-0.5}} = \frac{13.3\text{ ppb}}{0.0721\text{ min}^{-0.5}} = 184.5\frac{\text{ppb}}{\text{min}^{-0.5}}$$

Time-of-Travel Velocity

$$u_{tt} = \frac{(5.3\text{ mi} \times 5{,}280\text{ ft / mi})}{(168.7\text{ min} \times 60\text{ sec / min})} = 2.765\text{ ft / sec}$$

Area

$$A = \frac{Q}{u} = \frac{1{,}150\text{ cfs}}{2.765\text{ ft / sec}} = 415.9\text{ ft}^2$$

Mean Hydraulic Depth

$$\overline{D} = \frac{A}{W} = \frac{416\,\text{ft}^2}{94\,\text{ft}} = 4.43\text{ ft}$$

Wetted Perimeter Approximation

$$P = W + d = 94\text{ ft} + 4.5\text{ ft} \approx 100\text{ ft}$$

Fischer's Equation (Equation 1)

$$E_x = \frac{(0.011)(2.77\text{ ft / sec})^2(94\text{ ft})^2}{4.43\text{ ft} \times \sqrt{(32.2\text{ ft / sec}^2)\left(\frac{416\text{ ft}^2}{100\text{ ft}}\right)\left(0.00137741\frac{\text{ft}}{\text{ft}}\right)}} = 390\frac{\text{ft}^2}{\text{sec}}$$

McQuivey/Keefer Equation (Equation 2)

$$E_x = 0.058 \times \frac{1{,}150 \text{ cfs}}{\left(0.00137741 \frac{\text{ft}}{\text{ft}}\right)(94 \text{ ft})} = 515.2 \frac{\text{ft}^2}{\text{sec}}$$

Mean Dye Concentration for Low-Level Study at Upstream Sampling Station

$$\overline{C} = \frac{(5.43 \text{ ppb min}) \times 100}{290 \text{ min}} = 1.872 \text{ ppb} = 1.872 \text{ mg / m}^3$$

where 5.43 ppb min is from Figure 28.

Dye Mass Recovery for Low-Level Study at Upstream Sampling Station

$$M_{out} = \frac{1.872 \text{ mg / m}^3 \times 566{,}683 \text{ m}^3}{1{,}130 \text{ gm}} = \frac{939 \text{ gm}}{1{,}130 \text{ gm}} = 83.1\%$$

Peak Concentration Adjustment for Low-Level Study at Upstream Sampling Station

$$23.8 \text{ ppb} \times \frac{100\%}{83.1\%} = 28.6 \text{ ppb}$$

where 23.8 ppb is from Figure 28.

Mean Dye Concentration for Low-Level Study at Downstream Sampling Station

$$\overline{C} = \frac{(5.50 \text{ ppb min}) \times 100}{290 \text{ min}} = 1.897 \text{ ppb} = 1.897 \text{ mg / m}^3$$

where 5.50 ppb min is from Figure 31.

Dye Mass Recovery for Low-Level Study at Downstream Sampling Station

$$M_{out} = \frac{1.897 \text{ mg / m}^3 \times 566{,}683 \text{ m}^3}{1{,}130 \text{ gm}} = \frac{1{,}075 \text{ gm}}{1{,}130 \text{ gm}} = 95.1\%$$

Peak Concentration Adjustment for Low-Level Study at Downstream Station

$$10.3 \text{ ppb} \times \frac{100\%}{95.1\%} = 10.8 \text{ ppb}$$

where 10.3 ppb is from Figure 31.

Thomann's Plotted Slope (low-level study)

$$S_p = \frac{(28.6 \text{ ppb} - 10.8 \text{ ppb})}{(43 \text{ min})^{-0.5} - (156 \text{ min})^{-0.5}} = \frac{17.8 \text{ ppb}}{0.07249 \text{ min}^{-0.5}} = 245.5 \frac{\text{ppb}}{\text{min}^{-0.5}}$$

where 43 and 156 min are from Figures 28 and 31,

and where $245.5 \frac{\text{ppb}}{\text{min}^{-0.5}} \times \sqrt{60 \frac{\text{sec}}{\text{min}}} = 1{,}902 \frac{\text{ppb}}{\text{sec}^{-0.5}} = 1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}$.

Longitudinal Dispersion Coefficient Using Equation 9 (low-level study)

$$S_p = \frac{M}{2A\sqrt{\pi}\sqrt{E_x}} = \frac{(2.5 \text{lb}) \times \frac{\text{one billion parts}}{\text{one billion parts}}}{2 \times 416 \text{ ft}^2 \times \sqrt{\pi} \times \sqrt{E_x \frac{\text{ft}^2}{\text{sec}}} \times 62.4 \frac{\text{lb}}{\text{ft}^3}} = 1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{(2.5 \text{ lb}) \times 10^9 \text{ ppb}}{2 \times 416 \text{ ft}^2 \times \sqrt{\pi} \times \sqrt{E_x \text{ ft}^2 / \text{sec}} \times 62.4 \frac{\text{lb}}{\text{ft}^3}} = 1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{40{,}000{,}000 \text{ ft}^3 \bullet \text{ppb}}{2 \times 416 \text{ ft}^2 \times \sqrt{\pi} \times \sqrt{E_x \text{ ft}^2 / \text{sec}}} = 1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{40{,}000{,}000 \text{ ft} \bullet \text{ppb}}{2 \times 416 \times \sqrt{\pi} \times \sqrt{E_x \text{ ft}^2 / \text{sec}}} = 1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}$$

$$S_p = \frac{27{,}200 \text{ ft} \bullet \text{ppb}}{\sqrt{E_x \text{ ft}^2 / \text{sec}}} = 1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}\,.$$

$$E_x = \left(\frac{27{,}200 \text{ ppb} \bullet \text{ft}}{1{,}902 \text{ ppb} \bullet \sqrt{\text{sec}}} \right)^2 = 203 \frac{\text{ft}^2}{\text{sec}}$$

Mean Dye Mass Recovery for Low-Level Study

$$\frac{83.1\% + 95.1\%}{2} = 89.1\%$$

Mean Velocity at Upstream Sampling Station (NRM 19.5)

$$\bar{u} = \frac{Q}{A_u} = \frac{1{,}150 \text{ ft}^3 / \text{sec}}{624 \text{ ft}^2} = 1.85 \text{ ft} / \text{sec}$$

Mean Velocity at Downstream Sampling Station (NRM 15.7)

$$\bar{u} = \frac{Q}{A_d} = \frac{1{,}150 \text{ ft}^3 / \text{sec}}{448 \text{ ft}^2} = 2.57 \text{ ft} / \text{sec}$$

Cross-Sectional Mean Velocity at Two Stations

$$\bar{u} = \frac{1.85 \text{ ft} / \text{sec} + 2.57 \text{ ft} / \text{sec}}{2 \text{ stations}} = 2.21 \text{ ft} / \text{sec}$$

Slope of Rating Curve for Gaging Station at NRM 20.5 (USGS, 1969)

$$\frac{\Delta Q}{\Delta Y} = \frac{1{,}300 \text{cfs} - 1{,}050 \text{cfs}}{4.20 \text{ft} - 3.80 \text{ft}} = 625 \frac{\text{cfs}}{\text{ft}}$$

Advective Velocity at Nottely River Gaging Station (Equation 11)

$$c_k = \frac{1}{W}\frac{\Delta Q}{\Delta Y} = \frac{1}{124 \text{ ft}}\left(625\frac{\text{cfs}}{\text{ft}}\right) = 5.04\frac{\text{ft}}{\text{sec}}$$

where *W* is from Table 4.

Froude Number

$$\mathbf{F} = \frac{u}{\sqrt{g\,D}} = \frac{2.21 \text{ ft / sec}}{\sqrt{\left(32.2\frac{\text{ft}}{\text{sec}^2}\right)(4.43 \text{ ft})}} = 0.19$$

Flow Dispersion Coefficient (Equation 12)

$$K = \frac{1{,}150 \text{ cfs}}{2(0.00137741 \text{ ft / ft})(94 \text{ ft})}\left(1 - \frac{0.19^2}{4}\right) = 4{,}440(0.991) = 4{,}400\frac{\text{ft}^2}{\text{sec}}$$

Turbine Discharge Check for October 27, 1997

$$\textit{Measured } Q = \frac{1{,}152 \text{ cfs} + 1{,}207 \text{ cfs}}{2 \text{ stations}} = 1{,}179 \text{ cfs}$$

where turbine discharge records reported Q = 1,170 cfs.

Sampling Cut-Off Ratio for Downstream Sampling Station (NRM 15.7)

$$\frac{C_{min}}{C_{max}} = \frac{0.25 \text{ ppb}}{10.3 \text{ ppb}} = 0.024$$

Turbulent Flow Regime Check for Vertical Mixing

$$\textit{Reynold's Number} = \frac{u \times \frac{A}{P}}{\nu} = \frac{2.8\frac{\text{ft}}{\text{sec}} \times \frac{415.9 \text{ ft}^2}{100 \text{ ft}}}{1.62 \times 10^{-5} \text{ ft}^2/\text{sec}} = 720{,}000 \quad \therefore \text{ very turbulent}$$

APPENDIX C: COST ESTIMATE

APPENDIX C: COST ESTIMATE

Cost Estimate

This appendix is a cost estimate of the Nottely Dam tailwater dye dispersion test. It was prepared at the end of the job so that actual times and costs could be included to reflect an accurate estimate. This estimate can be used as a basis to bid future dye tracing experiments.

- Initial Scoping

evaluate need for performing the dye dispersion test, order maps, study maps, search literature for existing models of reach, retrieve water records from TVA and USGS, phone local contacts	
	12 hrs (technician)
	12 hrs (engineer)
maps, references, documents, phone expenses	$50

- Site Visit

trip preparation, round-trip travel, inspection, surveying, coordination with state officials	
	16 hrs (technician)
	16 hrs (engineer)
car rental, gasoline, phone calls	$60
survey supplies and equipment	$200[b]

- Test Set-Up

trip preparation, travel to site, hydraulic measurements, surveying, set up sampling stations, install tipping bucket apparatus, perform discharge calculations	
	21 hrs (technician)
	14 hrs (engineer)
motel and food for two people, phone calls	$130
van rental and gasoline	$70
generator rental	$25
rope, hardware, pumps, hoses, fittings, etc.	$500[b]
boat, life jacket, paddle, rain gear, waders, gloves, etc.	$500[b]

- Testing

final inspection, dye injection, sampling, travel home

	12 hrs (technician)
	12 hrs (engineer)
food for two people and phone calls	$30
van rental and gasoline	$70
generator rental	$25
aerial photographer	$200
Rhodamine WT dye	$200

- Post-Testing

unpack, store gear, prepare calibration samples, laboratory analysis

	15 hrs (technician)
	8 hrs (engineer)
fluorometer rental	$50
laboratory supplies	$100

- Data Analysis and Reporting

spreadsheet entry, computation, plotting, review, letter report

	24 hrs (technician)
	24 hrs (engineer)
office supplies and printing	$100
film developing	$50

Totals

86 hrs (engineer) x $40/hr = $3,440
100 hrs (technicican) x $20/hr = $2,000
cash expenses = $2,360[b]

Total = $7,800[c]

[b] Nearly half of the total cash expenses estimate was for capital equipment. For conservatism, it was assumed that all capital equipment would be purchased for each new project. However, with secure storage, this hardware can be used again for future projects. A reasonable assumption is to replace (or supplement) 50 percent of the capital hardware for each project. Therefore, the total estimate could be reduced by $600, which is 50 percent of $200 + $500 + $500.

[c] Additional cost savings can be achieved by using cost control tips presented in the conclusion of this thesis, such as, camping at the sampling site, or eliminating travel time by using vacation time.

VITA

John Henry Hoover was born in North Manchester, Indiana. Raised on a farm, he spent countless hours in the farm shop designing, building, and repairing various mechanical attractions (go carts, dune buggies, off-road vehicles, hot-rods, trailers, etc.). Prior to graduation from North Manchester High School in 1973, he had already earned trade school certifications in welding and auto body repair from Upper Wabash Vocational School. Although Mr. Hoover entered college in 1973 as a mechanical engineer, summer employment with the Wabash County Surveyor exposed him to the enjoyment of working outside and the many fascinating aspects of civil engineering. He graduated from Valparaiso University (IN) in May 1977 with a B.S in Civil Engineering. After spending two years in the Chicago area designing and testing power plant relief valves, he moved to Knoxville to join the Tennessee Valley Authority. He obtained Professional Engineering registration in 1981, and a M.S. in Civil Engineering (structures) from the University of Tennessee in 1986. He is a member of the American Society of Civil Engineers (ASCE) and is presently working at TVA's Engineering Laboratory in Norris, TN. While stationed in Norris, he has co-authored over a dozen publications on water quality modeling of numerous hydropower tailwaters for TVA, USCOE, Nantahala Power & Light, Southwest Power Administration, Arkansas Game & Fish Commission, Waterpower '97, and the Eighth Tennessee Water Resources Symposium.