# Stream Velocity and Dispersion Characteristics Determined by Dye-Tracer Studies on Selected Stream Reaches in the Willamette River Basin, Oregon

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 95–4078

Prepared in cooperation with
OREGON DEPARTMENT OF ENVIRONMENTAL QUALITY

**Cover photograph.** Cottonwood seeds float on the Willamette River looking upstream between Harrisburg and Eugene (at river mile 169), June 24, 1993. *(Photograph by Dennis A. Wentz, U.S. Geological Survey.)*

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By Karl K. Lee

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Portland, Oregon
1995

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U.S. GEOLOGICAL SURVEY
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## CONVERSION FACTORS

[SI = International System of units, a modernized metric system of measurement]

| Multiply | By | To obtain |
|---|---|---|
| *A. Factors for converting SI metric units to inch/pound units* | | |
| | Length | |
| centimeter (cm) | 0.3937 | inch (in) |
| millimeter (mm) | 0.03937 | inch |
| meter (m) | 3.281 | foot (ft) |
| | Area | |
| hectare | 2.471 | acre |
| square meter ($m^2$) | 10.76 | square foot ($ft^2$) |
| | Volume | |
| milliliter (mL) | 0.001057 | quart (qt) |
| liter (L) | 1.057 | quart |
| liter | 0.264l3 | gallon (gal) |
| Volume per unit time (includes flow) | | |
| cubic foot per second ($ft^3$/s) | 0.02832 | cubic meters per second ($m^3$/s) |
| acre | 4,047 | cubic meter ($m^3$) |
| | Concentration, in water | |
| milligrams per liter (mg/L) | 1 | parts per million (ppm) |
| micrograms per liter (µg/L) | 1 | parts per trillion (ppt) |
| *B. Factors for converting inch/pound units to SI metric units* | | |
| | Length | |
| inch | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Volume | |
| cubic foot ($ft^3$) | 0.02832 | cubic meter ($m^3$) |
| acre-foot (acre-ft) | 1,233 | cubic meter ($m^3$) |
| | Mass | |
| gram (g) | 0.03527 | ounce (oz avoirdupois) |
| kilogram (kg) | 2.205 | pound (lb avoirdupois) |

# Stream Velocity and Dispersion Characteristics Determined by Dye-tracer Studies on Selected Stream Reaches in the Willamette River Basin, Oregon

*By* Karl K. Lee

## Abstract

Dye-tracer analyses were done in the Willamette River and nine tributaries of the Willamette River, from April 1992 to July 1993 during low to medium stream discharge conditions, to determine velocity and dispersion. These dye-tracer analyses provided information on time of arrival, peak concentration, and the occurrence and longevity of a constituent dissolved in streamflow at various discharges. The time of travel of the peak and leading and trailing edge of the dye cloud were determined for each stream segment and were related to discharge at an index location in each stream. On the basis of the dye-tracer measurements, an equation was developed to estimate the velocity of the peak of a solute cloud for unmeasured streams. The results of the dye-tracer study on the Willamette River from river mile 161.2 to river mile 138.3 were compared with a previous study of the same river reach. The results of the comparison indicate that, since 1968, the discharge velocity relation has not changed in the streamflow range observed in this study. In order to identify dye-dispersion characteristics of a conservative solute in each stream segment, a relation was developed between the elapsed time from injection to the unit-peak concentration of dye measured at each sampling location. A general equation was developed to estimate the peak concentration of dye at a given elapsed time. Channel characteristics and streamflow magnitude are known to effect dye dispersion; however, comparison of streams with apparently similar characteristics resulted in different unit-peak concentration values at various times after dye injection.

## INTRODUCTION

Stream velocity and dispersion characteristics are important physical properties that affect river-water quality. Stream velocity controls mixing and residence time in pools and riffles and the time required for a soluble material to travel a given distance. Dispersion, the scattering of particles in water, controls the concentration of a constituent as it is transported downstream. Stream velocity and dispersion characteristics can be determined by time-of-travel studies that use dye-tracer techniques. Velocity and dispersion data can be used to make predictions regarding time of arrival, peak concentration, and the occurrence duration of a constituent dissolved or suspended in the flow for various discharges at any given point in a stream reach that is being studied.

Stream-velocity and dispersion-characteristics data from this study will aid Federal, State and local officials, planners, and managers in making decisions concerning water-quality management in the Willamette River Basin. Water resources in the basin are used for many purposes, including drinking water, wildlife habitat, irrigation, recreation, municipal and industrial use, and commerce. Managing water resources for such a variety of uses makes an understanding of physical factors in the Willamette River and its tributaries, such as stream velocity and dispersion characteristics, essential.

## Background

The dye-tracer study discussed in this report is part of a larger hydrologic and water-quality study of the Willamette River Basin being done in cooperation with Oregon Department of Environmental Quality (ODEQ). The purpose of the larger study is to gain a better understanding of the hydrology, chemistry, and aquatic biology of the Willamette River Basin and to develop predictive models that will subsequently be used to aid the ODEQ and other agencies in making decisions about the water quality in the Willamette River and its tributaries. Data collected during this study also will be used for calibrating hydrodynamic and water-quality models.

## Purpose and Scope

The purpose of this report is to document stream-velocity and dispersion- characteristics data collected at several locations in the Willamette River Basin (fig. 1). The velocity and dispersion data will be used in streamflow and water-quality analyses essential to stream management in the basin. The dye-tracer studies were made in 11 stream reaches during low- and medium-streamflow periods from April 1992 to July 1993. This report also includes results of dye-tracer studies of the Tualatin River that were done by the Unified Sewerage Agency from 1984 to 1988.

## Study Area

The Willamette River drains the western Cascade Range and the eastern Coast Range of west-central and northwestern Oregon. The Willamette River flows northward and enters the Columbia River at Portland.

The streams measured had a variety of conditions that were expected to control stream velocity and dispersion in the Willamette River Basin. For the stream reaches studied, drainage areas ranged from 3.4 to 3,420 square miles, length of streams ranged from 6.9 to 43.3 miles, and average channel slope ranged from 0.10 to 22 feet per mile (ft/mi).

Rural streams in the basins studied flow predominantly in channels that were formed naturally. Most streambeds consist of sand, gravel, and bedrock. The Clackamas, Molalla, and upper Calapooia Rivers are relatively steep-gradient streams with alternating pools and riffles. The lower Calapooia, Tualatin, South Yamhill, Yamhill, and Pudding Rivers are meandering streams incised in silt.

Three primarily urban streams—Mill, Johnson, and Amazon Creeks—have channels altered by man. The channel of Mill Creek is natural in the upper part of the reach measured. In the lower part of Mill Creek, which flows through urban areas of Salem, the channel has been straightened and is partly lined with concrete. In the study reach of Johnson Creek, the channel has short sections of gravel streambed; however, most of the channel has been cleared, straightened, and lined with masonry. The Amazon Creek study reach is an artificially straightened and cleared trapezoidal channel with a gravel bed, except for a 1.1 mile reach that is a box channel lined with concrete.

Flow is unregulated in all of the stream reaches studied, except for those in the Calapooia River and Mill Creek. In the Calapooia River during the June 1992 time-of-travel measurement, one-third of the flow was diverted at Brownsville Dam for 3 miles and returned to the river at Brownsville. Another diversion occurs at Sodom Ditch, bypassing approximately 9 miles of the Calapooia River near Halsey. Extensive daily regulation in the Calapooia River can occur downstream of Thompson Dam, resulting in unsteady flow conditions. In Mill Creek, most of the summer flow is a result of a diversion from the North Santiam River at Stayton. The diversion is carried to Mill Creek by Salem Ditch. The study reach was located immediately below the diversion. Regulation also occurs at control structures at the head of Shelton Ditch diversion and at the Mill Ditch diversion, both of which are located in Salem. Significant changes in streamflow into the Salem Ditch diversion or distribution through the diversions in the urban areas of Salem did not occur in any of the reaches during the time-of-travel measurements.

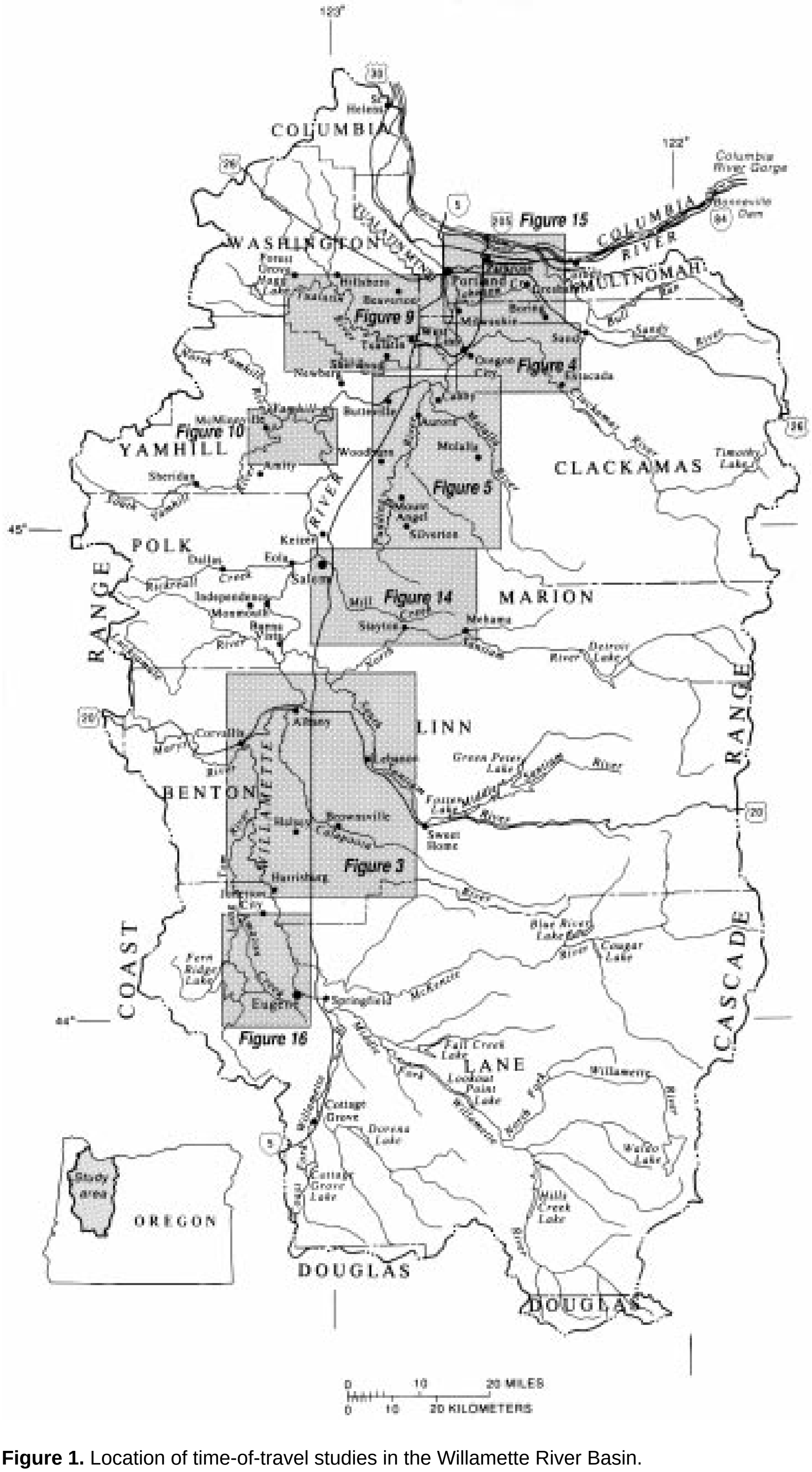

**Figure 1.** Location of time-of-travel studies in the Willamette River Basin.

## Acknowledgments

The U.S. Geological Survey (USGS) would like to acknowledge the assistance of John Jackson and Janice Miller of the Unified Sewerage Agency for the time-of-travel data collected on the Tualatin River. The USGS also extends thanks to Shirley Kengla and Edward Sale of Oregon Department of Environmental Quality, who notified water-facility personnel and the general public of the studies.

# METHOD OF INVESTIGATION

The dye tracer used for this study was rhodamine WT, a nontoxic, fluorescent red chemical dye (Wilson and others, 1986). A measured amount of dye was injected into a stream reach at selected downstream locations. The dye concentration was measured over a time period sufficient to define the passage of the dye cloud. Time-of-travel and dispersion characteristics in the reach were calculated on the basis of the measurements described by Kilpatrick and Wilson (1989). In order to better understand time of travel and dispersion as it relates to stream velocity and discharge, dye tracers were injected over a range of stream discharges.

## Stream Reach Selection

Streams selected for the study were chosen because they were either tributaries with significant inflow to the Willamette River or urban streams with a high potential for contamination. The combined streamflows of the Clackamas, Molalla, Calapooia, Tualatin, Yamhill, and Pudding Rivers contribute about 30 percent of the average streamflow of the Willamette River at Portland (Moffatt and others, 1990). Johnson, Mill, and Amazon Creeks are smaller than the other streams in this study and drain urban areas of Portland, Salem, and Eugene, respectively. The Pudding and Tualatin Rivers drain predominantly agricultural basins. Time-of-travel characteristics of the Tualatin River were previously measured by the Unified Sewerage Agency, and those data are included in this report. Time of travel was measured for the Willamette River between Harrisburg and Peoria for comparison with data in a study by Harris (1968).

Each stream reach was divided into several subreaches to minimize travel time and any possible effects of high dye concentrations on water users. The subreaches generally were contiguous. The most downstream sampling location for a given subreach became the site of dye injection for the next subreach, thereby creating one continuous downstream reach. Shorter subreaches were studied during low velocity and when time or personnel limitations did not allow for extended sampling periods.

## Field Methods

Dye was injected in one to three subreaches of each stream reach; the farthest downstream subreach was injected first, followed by upstream subreaches in succession. At the upstream end of each subreach, a predetermined quantity of a 20-percent solution of rhodamine WT dye was injected by rapidly pouring the dye into the stream either at midchannel or at multiple points across the stream. The dye was distributed from a boat, a bridge, or by wading. The volume of dye used for each segment was determined by methods described by Hubbard and others (1982). The volume is a function of stream discharge, mean stream velocity, the distance to the farthest downstream sampling location, and the minimum dye concentration desired.

Water samples were collected and analyzed for dye concentrations using standard methods (Kilpatrick and Wilson, 1989) at selected downstream locations in each subreach. Samples were collected by dipping a bottle in moving water or by using an automatic sampler. Samples were collected from midstream for the streams that could be waded. Samples were collected from moving water near the streambank at streams that could not be waded. Automatic samplers were used to sample many locations, minimizing personnel requirements and logistical problems.

The dye concentration was determined in the field by measuring the fluorescence of the water samples with a fluorometer. The amount of fluorescence measured is directly proportional to the concentration of the dye in the water sample.

At each sampling location, a series of samples were collected to sufficiently define the passage of the dye cloud. Typical time-concentration curves, depicting the passage of a dye cloud at selected sites, are shown in figure 2. A sample was collected to determine background fluorescence of the water in the stream, prior to the arrival of the dye cloud, and that value was subsequently subtracted from the sample fluorescence.

To characterize discharge, measurements were made at several locations within each reach. Measurement techniques conformed to standards established by Rantz and others (1982). Discharge was not measured at all sampling locations; however, tributary inflow was measured or estimated, allowing cumulative streamflow estimates for each sampling location.

To simplify computation of dye-travel time and dispersion at selected locations downstream, the dye must be mixed vertically and laterally in the streamflow. The distance necessary to insure mixing from the first downstream sampling section was determined by methods described by Kilpatrick and Wilson (1989). The length of channel required for mixing depends on stream velocity, width, depth, slope, and the number and location of injection points. This information was collected from preliminary field surveys, historical data, and topographic maps.

## Quality Control

Quality control was assured during the study by checking fluorometer calibration in the

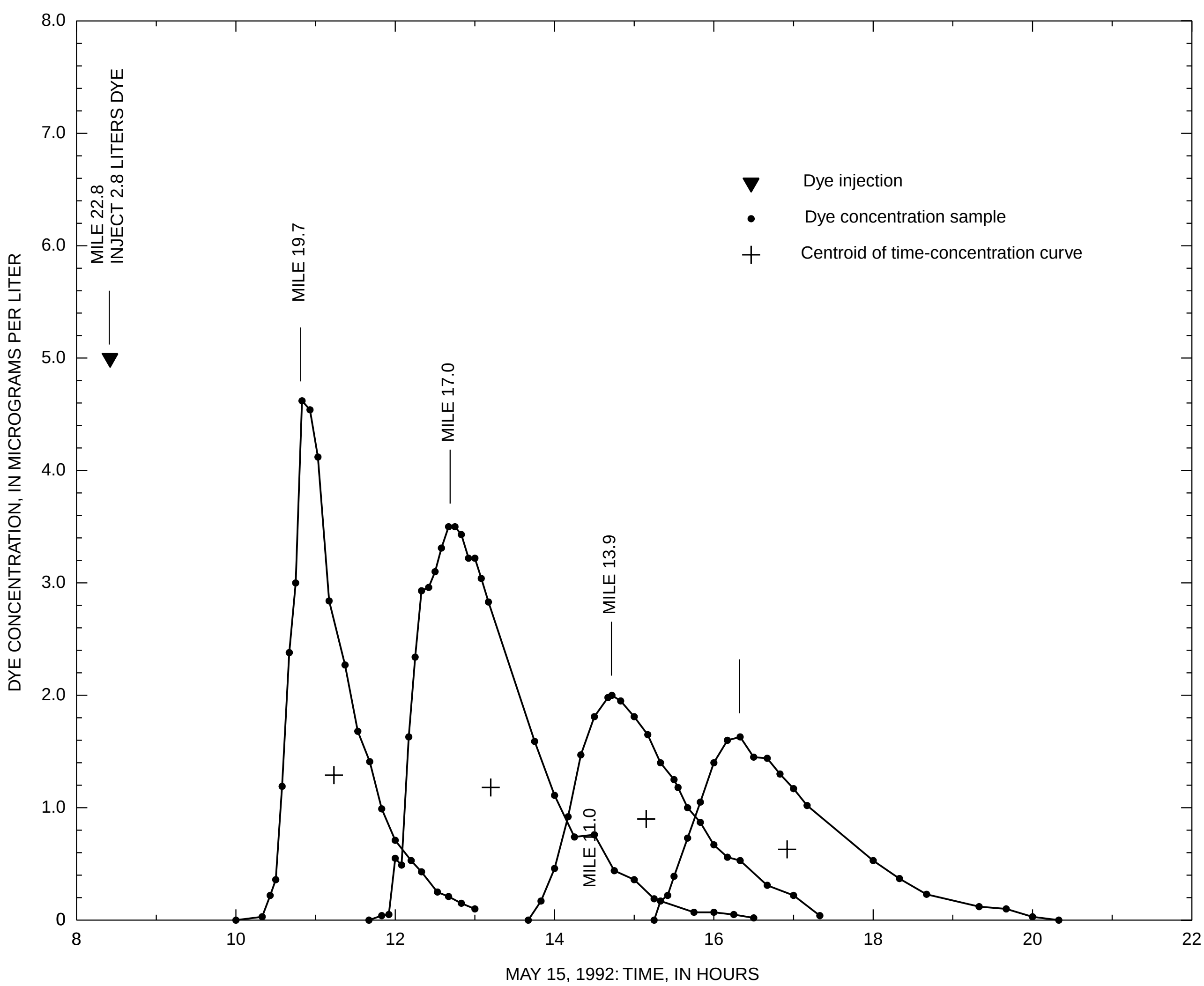


**Figure 2.** Typical time-concentration curves of dispersed dye in the Clackamas River.

laboratory before and after field measurements. The calibration also was checked in the field with standards of known dye concentrations. Dye-calibration curves were developed in the laboratory by preparing dilutions of the dye used in the field and by measuring the fluorescence of the dye dilutions with the field fluorometers (Wilson and others, 1986). In the field, samples were measured with the fluorometer, and dye standards within the anticipated range of sample fluorescence were checked. The fluorescence of a distilled water sample also was measured as a control. The dye standards were checked several times each day. Because fluorescence is strongly affected by temperature, samples were placed in a water bath for several minutes prior to measurement to ensure stabilization of temperature. Readings of fluorescence were made with the fluorometer within several seconds after inserting the water-sample vial. A prompt reading prevents warming of the sample by the fluorometer light source and helps eliminate errors due to temperature fluctuations. Fluorometer readings were made using the most sensitive scale applicable to the fluorescence of the sample.

Measures were taken to assure the accuracy of samples obtained with the automatic sampler. To prevent contamination of subsequent samples, the plastic syringes (reused by the automatic sampler) were rinsed several times between use. After cleaning, a subset of the syringes was checked for contamination by analyzing the rinse water for fluorescence. The concentration of dye in samples obtained using automatic samplers was compared with the concentration of dye in samples taken manually.

## Data Analysis

After data collection in each stream reach, adjustments and computations were made to determine the velocity and dispersion of the dye cloud. To obtain the correct dye concentrations for each sample, correction factors were applied to the fluorometer readings for sample temperature by using a correction curve (Wilson and others, 1986) and for fluorometer calibration by using the dye standards. Background fluorometer readings were subtracted from each sample reading. The sample times and associated corrected dye concentrations were used to define points of a time-concentration curve for each sampling location (fig. 2). Elapsed time was determined from the time of dye injection to the leading edge, the peak, the centroid, and the trailing edge of the dye cloud. A straight-line relation exists between discharge and dye-cloud velocity when the variables are plotted logarithmically (Kilpatrick and Wilson, 1989). Dispersion is determined from the attenuation of the peak concentration of the dye cloud. Peak dye-concentration results were used to develop dispersion equations for each stream.

The stream velocity in a given reach was indexed to discharge at a fixed location. For example, the Clackamas River velocity was indexed to the stream-gaging station near Estacada, operated by the USGS. For a few stream segments, such as the diversion from Mill Creek into Shelton Ditch, velocity in the ditch was indexed to the discharge at the mouth of the ditch. Continuous discharge data were not collected at Shelton Ditch.

Plots of discharge and dye-cloud velocity were prepared. For plotting purposes, each reach was divided into two to four subreaches. The discharge used was the average at the index location. The velocity was determined by dividing the distance traveled by the elapsed time since injection of dye.

For dispersion calculations, it is advantageous to eliminate the effects of dye loss so that the results can represent a conservative substance. Dye losses are variable and depend on the type of tracer and the stream characteristics (Tai and Rathbun, 1988; Scott and others, 1969). By removing the effects of dye loss (Hubbard and others, 1982), variables that affect only dispersion in a stream can be analyzed, and the dispersive characteristics of various streams can be compared.

The relation between peak concentration and the time elapsed after injection was identified for each stream reach. After the adjustment for dye loss, the peak concentration was converted to a unit-peak concentration. To make that conversion, the peak concentration of dye at each measuring section was multiplied by the stream discharge and divided by the weight of tracer injected. The unit-peak concentration is that concentration resulting from the injection of 1 pound of dye into a discharge of 1 cubic foot per second. This concentration is plotted against elapsed time on a logarithmic scale. The slope of the line indicates the dispersion efficiency or the ability of the stream to disperse a solute. The intercept of the line is the unit-peak concentration after 1 hour. Trends in dispersion efficiency can be identified by comparing stream reaches and comparing results with previous studies.

## STREAM VELOCITY RESULTS

In this section of the report, discussion will be according to stream type. For each stream type, general characteristics described will be slope, streamflow regime (pool and riffle makeup), streambed, and channel. Data for the Willamette River main stem were obtained from one reach of the Willamette River from Harrisburg (river mile [RM] 160.2) to Peoria (RM 138.3). The dye-tracer test for this report was done in a section of the Willamette River that is braided, and the main flow of the stream frequently changes channels. The Cascade Range tributaries generally have steep gradients, short pools, and long, turbulent riffles. The Coast Range and Willamette Valley tributaries are slow moving, with long, deep pools and few riffles. The urban tributaries have smaller drainage areas than the other measured streams in this study, and have channel reaches significantly altered by manmade embankments and structures.

Velocity data for 37 subreaches were used in multiple-linear-regression analyses to provide an equation for estimating velocity in unmeasured streams. The equation probably could be refined with the addition of other independent variables and organized according to geographic and geologic provinces. However, for this study, only the logarithms of discharge and channel slope were used as independent variables in the regression. The equation developed for velocity of the peak is:

$$v = 1.4 Q^{0.4} S^{0.4} \qquad (1)$$

where:

$v$ = velocity of the peak in miles per hour,

$Q$ = stream discharge in cubic feet per second,

$S$ = channel slope in foot per foot.

The standard error of estimate is 0.15 log units, corresponding to an error of -29 to +41 percent. The high standard error is attributed to variation in the channel shape and roughness. These channel variables are not easily estimated, and therefore, were not included in this analysis.

### Willamette River Main Stem

The Willamette River (fig. 3) is highly regulated and flows through an area with a variety of land uses. The river flows northward in a wide valley, bounded on the east by the Cascade Range and on the west by the Coast Range. Upstream from RM 187, the adjacent land is primarily forested. Downstream of RM 187, the adjacent lands are primarily agricultural and have riparian vegetation, small forested areas, and urban communities. Significant regulation occurs from dams on the Coast Fork and Middle Fork Willamette River and other major tributaries.

Since the Harris (1968) study, natural channel changes in the Willamette River include meandering, eroding of the streambanks, and channel widening. The reach from Harrisburg to Peoria was selected for the current study because more change occurred in this stream reach of the Willamette River than in any other reach previously studied.

For this report, one time-of-travel measurement was made on the Willamette River from Harrisburg (RM 161.2) to Peoria (RM 138.3). The index station for that reach is station 14166000 (the Willamette River at Harrisburg, RM 161.0), where streamflow records have been collected by the USGS since 1944. That study reach was divided into two subreaches, and dye was injected at three points across each subreach.

For the subreach between Harrisburg (RM 161.2) and Irish Bend (RM 150.9), Harris (1968) measured the same dye-peak velocity as the velocity measured in this study—1.8 mi/hr (miles per hour) [table 1]. For the subreach between Irish Bend and Peoria (RM 141.2), Harris also measured the same peak velocity that was measured in this study—1.9 mi/hr. The similarity between results of this study and the study by Harris indicates that although channel changes have occurred in the

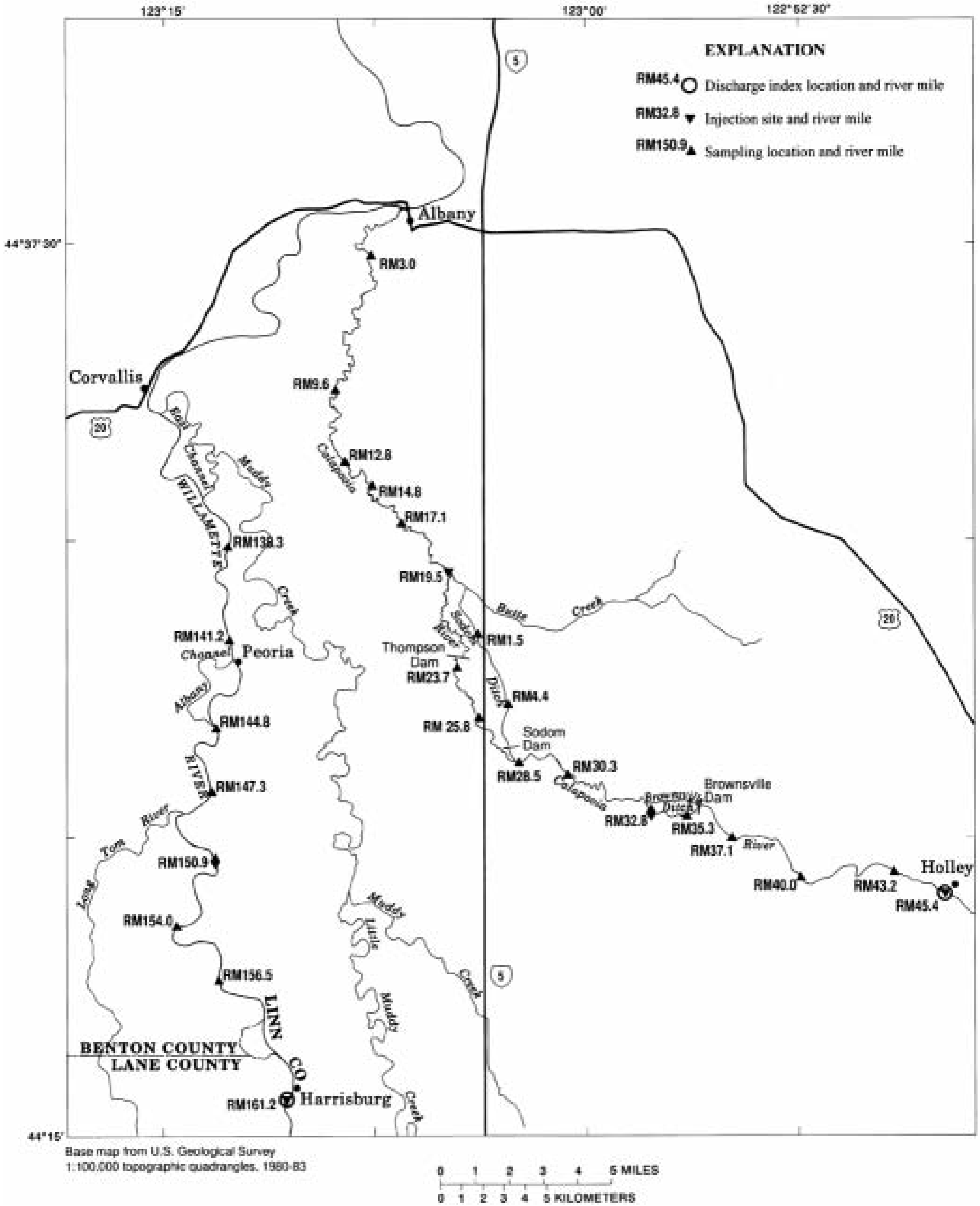


**Figure 3**. Study reaches, injection sites, and sampling locations on the Willamette River and Calapooia River.

**Table 1.** Time-of-travel and dispersion data for reaches studied in the Willamette River

[Index location is gaging station 14166000, Willamette River at Harrisburg, at river mile 161.0]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth times (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter hours) |
| Injection of 7.000 liters of 20-percent dye solution at 0940 hours on June 10, 1992, at river mile 161.2<br>Discharge at index location: 3,610 cubic feet per second; corresponding flow-duration frequency: 95 percent | | | | | | | | | | | | |
| 156.5 | 3,450 | 1.94 | 2.42 | 2.25 | 2.09 | 2.45 | 1.92 | 3.31 | 1.42 | 6.82 | 6,710 | 4.53 |
| 154.0 | 3,560 | 3.21 | 1.97 | 3.71 | 1.71 | 4.08 | 1.53 | 5.44 | 1.17 | 3.85 | 3,960 | 4.33 |
| 150.9 | 3,600 | 4.92 | 1.81 | 5.83 | 1.46 | 6.27 | 1.42 | 8.33 | 1.07 | 2.64 | 2,580 | 4.57 |
| 141.2 | 3,390 | 9.71 | 2.03 | 11.00 | 1.88 | 11.90 | 1.72 | 14.66 | 1.53 | 1.33 | 1,550 | 3.80 |
| Injection of 5.000 liters of 20-percent dye solution at 1250 hours on June 9, 1992, at river mile 150.9<br>Discharge at index location: 3,610 cubic feet per second; corresponding flow-duration frequency: 95 percent | | | | | | | | | | | | |
| 147.3 | 3,530 | 1.46 | 2.47 | 1.83 | 1.97 | 2.26 | 1.59 | 3.34 | 1.08 | 3.74 | 4,760 | 3.50 |
| 144.8 | 3,480 | 2.54 | 2.31 | 2.90 | 2.34 | 3.41 | 2.17 | 4.75 | 1.77 | 3.37 | 4,290 | 3.50 |
| 138.3 | 3,390 | 5.63 | 2.10 | 6.59 | 1.76 | 7.09 | 1.76 | 9.46 | 1.38 | 1.45 | 2,240 | 2.88 |

study reach during the past 24 years, the net effect on stream velocity has been minimal.

## Cascade Range Tributaries

The Clackamas (fig. 4), Molalla (fig. 5), and Calapooia (fig. 3) Rivers are steep-gradient streams with a well-developed pool-and-riffle streamflow regime. The average channel slope is approximately 12 ft/mi; for each stream, channel slope decreases toward the mouth. The streambeds consist of cobble- to sand- size material and have areas of exposed bedrock. The rivers flow through forested and agricultural areas. Near its mouth, the Calapooia River has a more deeply incised, meandering, stable channel and a lower gradient than reaches near the mouths of the Clackamas and Molalla Rivers. Streamflow regulation from dams or diversions can affect the velocity in the Clackamas and Calapooia Rivers.

### Clackamas River

The Clackamas River reach studied extends from RM 22.8 near Estacada to the mouth. The index location station is 14210000 (Clackamas River at Estacada, RM 23.1) and has a record of discharge collected by the USGS since 1908.

Two time-of-travel measurements were made in May and July 1992 (table 2). The dye was injected in the center of the stream for the subreaches that began at RM 22.8 and at RM 8.0, and in two points of the stream cross section for the subreach beginning at RM 13.3. For the first time-of-travel measurement, the reach was divided into two subreaches. Two subreaches were used for the second time-of-travel measurement, but due to missing data at one of the sampling locations, a third injection was made. Background samples were taken prior to injection of dye on July 24 to ensure that no dye residue was in the stream from the injection of dye the previous day.

The relation of the velocity of the peak and leading and trailing edge of the dye cloud to discharge at the index location is shown in figure 6. Variations in velocity occurred in each subreach. These variations were most likely due to locally changing channel slope and pool-riffle configuration.

### Molalla River

The Molalla River reach studied extends from RM 18.6 near Molalla to RM 1.7, just above the confluence with the Pudding River. The index location station is 14200000 (Molalla River near

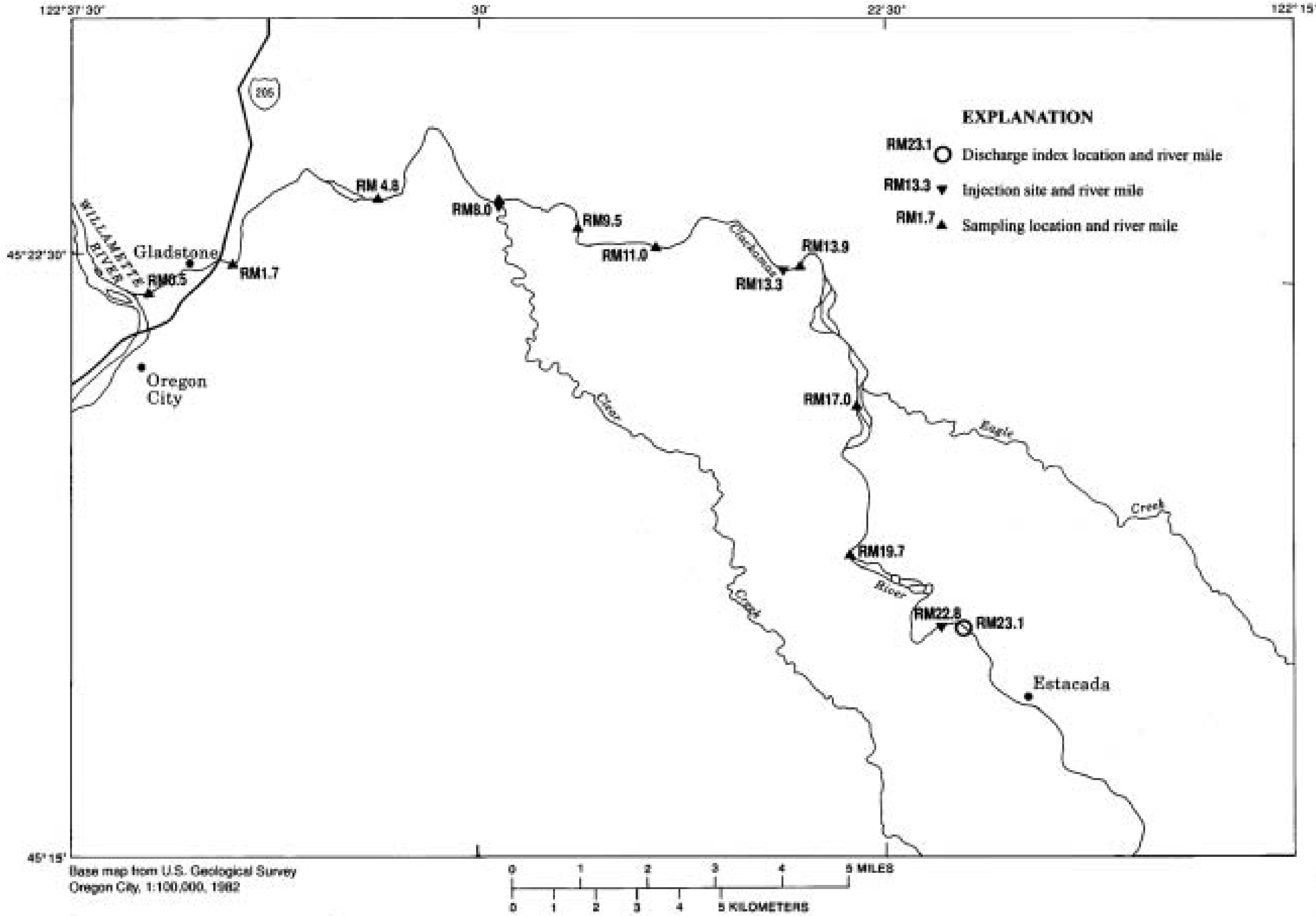


**Figure 4.** Study reaches, injection sites, and sampling locations on the Clackamas River.

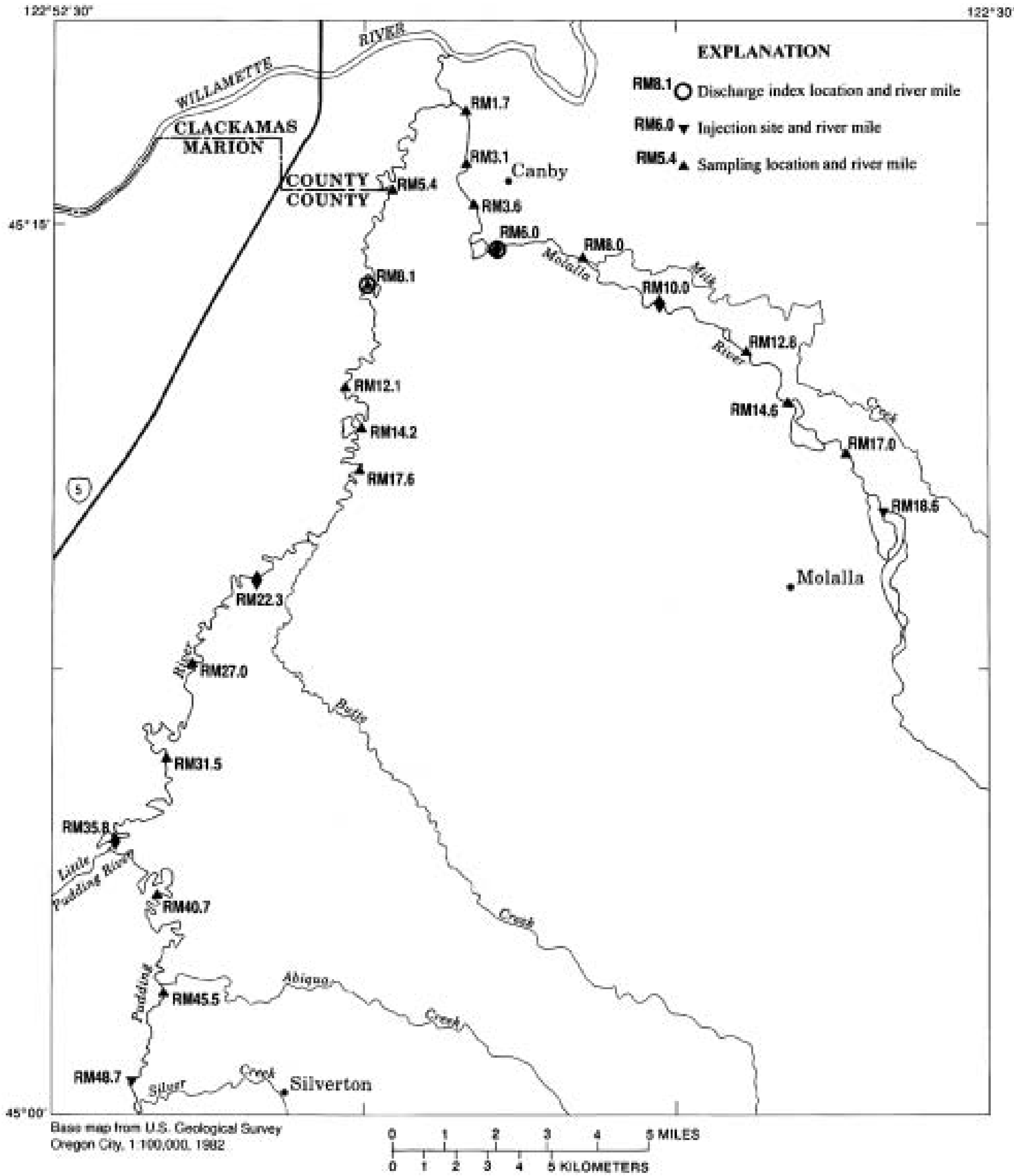


**Figure 5.** Study reaches, injection sites, and sampling locations on the Molalla and Pudding Rivers

**Table 2.** Time-of-travel and dispersion data for reaches studied in the Clackamas River

[Index location is station 14210000 Clackamas River at Estacada, at river mile 23.1]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 2.800 liters of 20-percent dye solution at 0825 hours on May 15, 1992, at river mile 22.8<br>Discharge at index location: 1,350 cubic feet per second; corresponding flow-duration frequency: 68 percent | | | | | | | | | | | | |
| 19.7 | 1,350 | 2.09 | 1.48 | 2.41 | 1.29 | 2.81 | 1.10 | 3.86 | 0.80 | 4.62 | 5,310 | 3.88 |
| 17.0 | 1,320 | 3.56 | 1.84 | 4.28 | 1.44 | 4.78 | 1.37 | 6.58 | .99 | 3.50 | 2,740 | 5.70 |
| 13.9 | 1,290 | 5.48 | 1.61 | 6.30 | 1.53 | 6.73 | 1.59 | 8.58 | 1.55 | 2.00 | 2,690 | 3.32 |
| 11.0 | 1,290 | 6.91 | 2.03 | 7.91 | 1.80 | 8.50 | 1.64 | 10.67 | 1.39 | 1.63 | 2,260 | 3.21 |
| Injection of 3.000 liters of 20-percent dye solution at 0900 on May 14, 1992, at river mile 13.3<br>Discharge at index location: 1,350 cubic feet per second; corresponding flow-duration frequency: 68 percent | | | | | | | | | | | | |
| 11.0 | 1,310 | .96 | 2.40 | 1.08 | 2.13 | 1.23 | 1.87 | 1.62 | 1.42 | 14.84 | 12,300 | 5.38 |
| 9.5 | 1,310 | 1.72 | 1.97 | 1.92 | 1.79 | 2.18 | 1.58 | 2.78 | 1.29 | 9.80 | 8,620 | 5.06 |
| 8.0 | 1,370 | 2.71 | 1.52 | 3.25 | 1.13 | 3.54 | 1.10 | 4.74 | .77 | 4.09 | 4,050 | 4.49 |
| 4.8 | 1,370 | 4.55 | 1.74 | 5.28 | 1.58 | 6.06 | 1.27 | 8.00 | .98 | 2.89 | 2,550 | 5.04 |
| 1.7 | 1,370 | 6.85 | 1.35 | 7.58 | 1.35 | 8.18 | 1.46 | 10.07 | 1.50 | 2.31 | 2,430 | 4.22 |
| .5 | 1,370 | 7.48 | 1.90 | 8.75 | 1.03 | 9.37 | 1.01 | 11.82 | .69 | 2.17 | 1,880 | 5.14 |
| Injection of 1.500 liters of 20-percent dye solution at 0832 hours on July 23, 1992, at river mile 22.8<br>Discharge at index location: 750 cubic feet per second; corresponding flow-duration frequency: 94 percent | | | | | | | | | | | | |
| 19.7 | 750 | 2.72 | 1.14 | 3.39 | .91 | 3.97 | .78 | 6.02 | .51 | 2.63 | 2,730 | 4.28 |
| 17.0 | 750 | 5.10 | 1.13 | 6.22 | .95 | 6.82 | .95 | 9.24 | .84 | 1.86 | 1,960 | 4.22 |
| 13.9 | 750 | 7.43 | 1.33 | 8.80 | 1.20 | 9.39 | 1.21 | 11.97 | 1.14 | 1.40 | 1,830 | 3.40 |
| Injection of 3.000 liters of 20-percent dye solution at 0847 hours on July 22, 1992, at river mile 13.3<br>Discharge at index location: 650 cubic feet per second; corresponding flow-duration frequency: 98 percent | | | | | | | | | | | | |
| 11.0 | 600 | 1.39 | 1.65 | 1.65 | 1.39 | 1.87 | 1.23 | 2.42 | .95 | 22.87 | 7,960 | 12.79 |
| 9.5 | 600 | 2.56 | 1.28 | 2.92 | 1.18 | 3.28 | 1.06 | 4.44 | .74 | 12.88 | 4,780 | 12.00 |
| 8.0 | 600 | 4.28 | .87 | 4.97 | .73 | 5.60 | .65 | 7.60 | .47 | 6.33 | 2,510 | 11.24 |
| 1.7 | 600 | 10.27 | 1.05 | 11.72 | .93 | 11.99 | .99 | 14.89 | .86 | 2.75 | 1,970 | 6.21 |
| .5 | 600 | 11.33 | 1.13 | 12.72 | 1.20 | 13.47 | .81 | 16.34 | .83 | 2.77 | 1,700 | 7.26 |
| Injection of 0.300 liters of 20-percent dye solution at 1012 hours on July 24, 1992, at river mile 8.0<br>Discharge at index location: 650 cubic feet per second; corresponding flow-duration frequency: 98 percent | | | | | | | | | | | | |
| 4.8 | 650 | 2.34 | 1.37 | 2.72 | 1.18 | 3.19 | 1.00 | 4.40 | .73 | 0.93 | 4,100 | 1.01 |

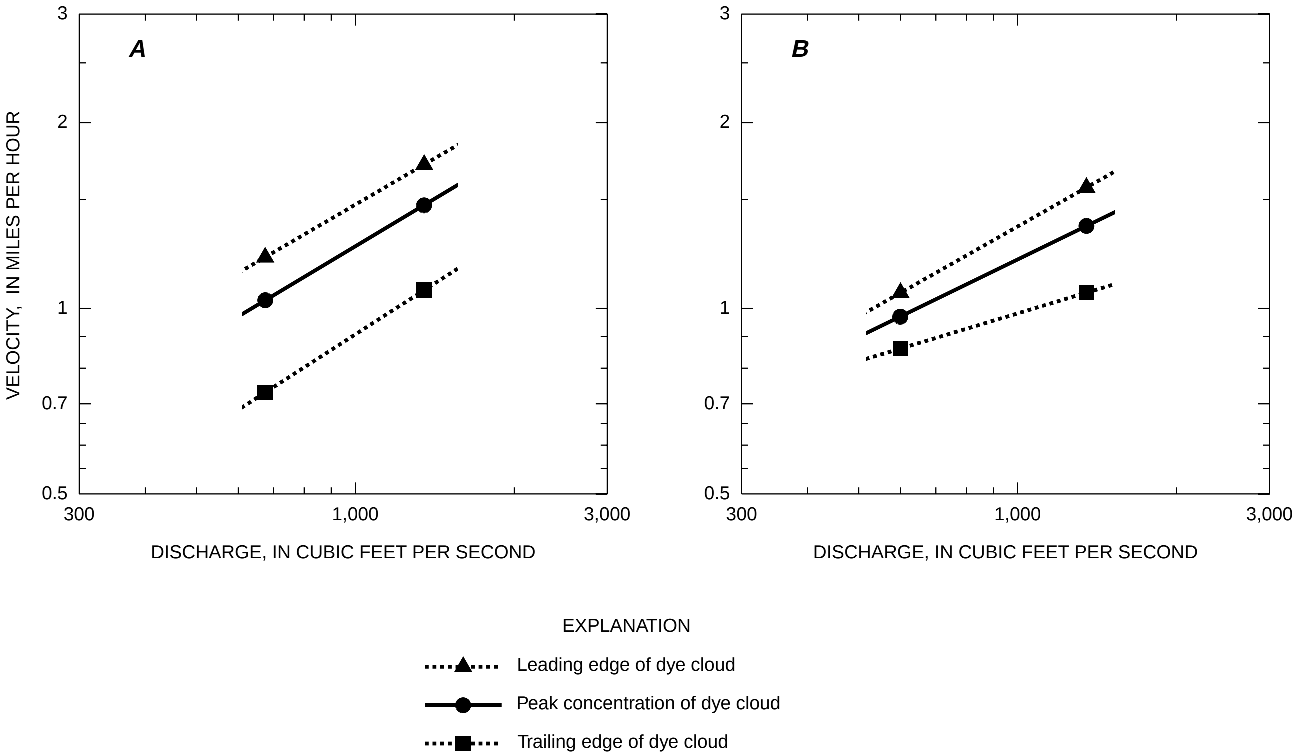


**Figure 6.** Relation of velocity of the Clackamas from (A) river mile 22.8 to river mile 8.0 (B) river mile 8.0 to river mile 0.5 to discharge at the Clackamas River at Estacada (stream-gaging station 14210000).

Canby, RM 6.0) and has a record of discharge that was collected by the USGS during the periods 1928–59 and 1963–78.

Time-of-travel measurements were made during June and July 1992 and April 1993 (table 3). The June 1992 and April 1993 measurements extended from RM 18.6 to RM 1.7. The July 1992 measurement extended from RM 12.8 to RM 1.7. The dye was injected at a single point for each subreach. The relation of the velocity of the peak and leading and trailing edge of the dye cloud to discharge at the index location is shown in figure 7.

## Calapooia River

The Calapooia River reach studied extends from RM 45.4 (at Holley) to RM 3.0. The index location is station 14172000 (Calapooia River at Holley, RM 45.4) and has a record of discharge that was collected by the USGS from 1936 to 1990.

Three control structures affect streamflow in the Calapooia River: (1) Brownsville Dam diverts water through Brownsville Ditch during summer months, (2) Sodom Dam diverts streamflow away from the river during medium to high streamflow, and (3) Thompson Dam diverts water into a slough and stores it for power generation.

The first time-of-travel measurement was made in June 1992 and extended from RM 45.4 to RM 23.7 (table 4). During this period, about one-third of the streamflow was diverted into Brownsville Ditch. Behind Brownsville Dam, ponded water decreased the velocity in the Calapooia River between RM 37.1 and RM 35.3. Streamflow in Sodom Ditch was minimal during this study. Streamflow regulation at Thompson Dam caused unsteady streamflow conditions in the Calapooia River from RM 23.7 to the mouth, precluding study in this subreach. The dye was injected at a single point at midstream for each subreach of the Calapooia River.

The second time-of-travel measurement was made May 1993 (table 4) and extended from RM 45.4 to RM 3.0. The conditions of the diversions for the second measurement were quite different from conditions during the first time-of-

**Table 3.** Time-of-travel and dispersion data for reaches studied in the Molalla River
[Index location is station 14200000, Molalla River near Canby, at river mile 6.0]

| Sampling location under times: Distance from mouth (mile) | Sampling location: Discharge (cubic feet per second) | Travel time and velocity: Leading edge: Time (hours) | Leading edge: Velocity (miles per hour) | Peak: Time (hours) | Peak: Velocity (miles per hour) | Centroid: Time (hours) | Centroid: Velocity (miles per hour) | Trailing edge: Time (hours) | Trailing edge: Velocity (miles per hour) | Dye curve characteristics: Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area curve (micrograms per liter hours) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Injection of 0.700 liters of 20-percent dye solution at 0815 hours on June 4, 1992, at river mile 18.6 | | | | | | | | | | | | |
| Discharge at index location: 128 cubic feet per second; corresponding flow-duration frequency: 81 percent | | | | | | | | | | | | |
| 17.0 | 95.0 | 2.05 | 0.78 | 2.42 | 0.66 | 2.90 | 0.55 | 4.21 | 0.38 | 15.67 | 4,540 | 15.35 |
| 14.6 | 100 | 7.85 | .41 | 9.58 | .34 | 10.21 | .33 | 13.75 | .25 | 3.53 | 1,380 | 11.36 |
| 12.8 | 105 | 11.25 | .53 | 13.25 | .49 | 14.24 | .45 | 18.14 | .41 | 2.65 | 1,150 | 10.29 |
| Injection of 0.800 liters of 20-percent dye solution at 0950 hours on June 3, 1992, at river mile 10.0 | | | | | | | | | | | | |
| Discharge at index location: 128 cubic feet per second; corresponding flow-duration frequency: 81 percent | | | | | | | | | | | | |
| 8.00 | 115 | 2.40 | .83 | 2.83 | .71 | 3.18 | .63 | 4.49 | .45 | 12.68 | 4,480 | 12.58 |
| 6.00 | 128 | 5.40 | .67 | 6.41 | .56 | 7.08 | .51 | 9.26 | .42 | 3.98 | 2,060 | 8.57 |
| 3.60 | 133 | 9.61 | .57 | 11.17 | .50 | 11.99 | .49 | 15.72 | .37 | 2.69 | 1,450 | 8.26 |
| 1.70 | 138 | 13.50 | .49 | 15.67 | .42 | 16.99 | .38 | 22.48 | .28 | 1.57 | 988 | 7.07 |
| Injection of 0.250 liters of 20-percent dye solution at 0555 hours on July 16, 1992, at river mile 12.8 | | | | | | | | | | | | |
| Discharge at index location: 50.3 cubic feet per second; corresponding flow-duration frequency: 96 percent | | | | | | | | | | | | |
| 10.00 | 37.0 | 9.05 | .31 | 13.33 | .21 | 14.57 | .19 | 21.48 | .13 | 1.32 | 718 | 8.20 |
| 8.00 | 39.0 | -- | -- | 18.33 | .40 | -- | -- | 28.22 | .30 | .95 | -- | -- |
| Injection of 0.500 liters of 20-percent dye solution at 0922 hours on July 15, 1992, at river mile 6.0 | | | | | | | | | | | | |
| Discharge at index location: 50.3 cubic feet per second; corresponding flow-duration frequency: 96 percent | | | | | | | | | | | | |
| 3.60 | 51.0 | 6.16 | .39 | 7.63 | .31 | 8.98 | .27 | 13.07 | .18 | 4.70 | 1,370 | 15.28 |
| 3.10 | 51.0 | 7.16 | .50 | 9.30 | .30 | 9.91 | .54 | 14.18 | .45 | 3.93 | 1,320 | 13.25 |
| 1.70 | 54.9 | 13.20 | .23 | 17.13 | .18 | 18.24 | .17 | 24.10 | .14 | 2.03 | 734 | 12.32 |
| Injection of 2.000 liters of 20-percent dye solution at 1130 hours on April 14, 1993, at river mile 18.6 | | | | | | | | | | | | |
| Discharge at index location: 2,300 cubic feet per second; corresponding flow-duration frequency: 13 percent | | | | | | | | | | | | |
| 17.0 | 1,550 | .41 | 3.90 | .53 | 3.02 | .61 | 2.62 | .87 | 1.84 | 13.21 | 19,600 | 3.00 |
| 14.6 | 1,680 | 1.59 | 2.03 | 1.90 | 1.75 | 2.06 | 1.66 | 2.65 | 1.35 | 4.48 | 7,340 | 2.72 |
| 12.8 | 1,700 | 2.23 | 2.81 | 2.67 | 2.34 | 2.78 | 2.50 | 3.52 | 2.07 | 3.97 | 6,510 | 2.71 |
| 10.0 | 1,710 | 3.23 | 2.80 | 3.67 | 2.80 | 3.91 | 2.48 | 4.79 | 2.20 | 2.91 | 4,930 | 2.63 |
| Injection of 2.500 liters of 20-percent dye solution at 1048 hours on April 13, 1993, at river mile 10.0 | | | | | | | | | | | | |
| Discharge at index location: 2,420 cubic feet per second; corresponding flow-duration frequency: 12 percent | | | | | | | | | | | | |
| 8.0 | 1,840 | .57 | 3.51 | .70 | 2.86 | .76 | 2.63 | .99 | 2.02 | 13.71 | 20,300 | 3.01 |
| 6.0 | 2,420 | 1.18 | 3.28 | 1.40 | 2.86 | 1.54 | 2.56 | 2.01 | 1.96 | 5.13 | 9,810 | 2.33 |
| 3.6 | 2,560 | 1.99 | 2.96 | 2.28 | 2.73 | 2.47 | 2.58 | 3.04 | 2.33 | 3.90 | 7,720 | 2.25 |
| 1.7 | 2,600 | 2.78 | 2.41 | 3.18 | 2.11 | 3.39 | 2.07 | 4.27 | 1.54 | 3.10 | 5,890 | 2.34 |

**Table 4.** Time-of-travel and dispersion data for reaches studied in the Calapooia River

[Index location is station 14172000, Calapooia River at Holley, at river mile 45.4]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 0.500 liters of 20-percent dye solution at 0845 hours on June 23, 1992, at river mile 45.4. Discharge at index location: 38.6 cubic feet per second; corresponding flow-duration frequency: 86 percent | | | | | | | | | | | | |
| 43.2 | 38.6 | 3.80 | 0.58 | 4.72 | 0.47 | 5.21 | 0.42 | 7.18 | 0.31 | 13.09 | 2,360 | 24.72 |
| 40.0 | 38.6 | 9.82 | .53 | 11.92 | .44 | 12.61 | .43 | 16.15 | .36 | 5.74 | 1,220 | 20.96 |
| 37.1 | 38.6 | 17.21 | .39 | 20.25 | .35 | 21.28 | .33 | 26.65 | .28 | 3.65 | 858 | 18.95 |
| 35.3 | 24.2 | 31.57 | .13 | 35.25 | .12 | 38.94 | .10 | 50.56 | .08 | 1.59 | 482 | 14.68 |
| 32.8 | 24.2 | 36.25 | .53 | 40.25 | .50 | 44.66 | .44 | 56.75 | .40 | 1.01 | 433 | 10.33 |
| Injection of 0.400 liters of 20-percent dye solution at 1305 hours on June 22, 1992, at river mile 32.8. Discharge at index location: 38.6 cubic feet per second; corresponding flow-duration frequency: 86 percent | | | | | | | | | | | | |
| 30.3 | 40.5 | 5.48 | .46 | 7.09 | .35 | 7.37 | .34 | 10.40 | .24 | 5.75 | 1,710 | 15.00 |
| 28.5 | 41.0 | 9.79 | .42 | 11.92 | .37 | 13.07 | .32 | 15.47 | .36 | 4.37 | 1,440 | 13.56 |
| 25.8 | 42.0 | 16.00 | .43 | 18.59 | .40 | 19.14 | .44 | 23.70 | .33 | 3.24 | 1,120 | 12.83 |
| 23.7 | 43.1 | 21.26 | .40 | 23.99 | .39 | 24.75 | .37 | 30.00 | .33 | 2.79 | 1,070 | 11.57 |
| Injection of 1.500 liters of 20-percent dye solution at 1015 hours on May 26, 1993, at river mile 45.4. Discharge at index location: 377 cubic feet per second; corresponding flow-duration frequency: 38 percent | | | | | | | | | | | | |
| 43.2 | 377 | 1.24 | 1.77 | 1.34 | 1.64 | 1.44 | 1.53 | 1.90 | 1.16 | 21.11 | 10,200 | 9.24 |
| 40.0 | 423 | 2.83 | 2.01 | 3.25 | 1.68 | 3.42 | 1.62 | 4.17 | 1.41 | 11.52 | 5,920 | 8.66 |
| 37.1 | 450 | 4.44 | 1.80 | 5.08 | 1.58 | 5.24 | 1.59 | 6.12 | 1.49 | 7.50 | 4,560 | 7.31 |
| 32.8 | 481 | 7.10 | 1.62 | 8.00 | 1.47 | 9.43 | 1.03 | 9.95 | 1.12 | 3.88 | 3,240 | 5.32 |
| Injection of 2.000 liters of 20-percent dye solution at 0953 hours on May 25, 1993, at river mile 32.8. Discharge at index location: 380 cubic feet per second; corresponding flow-duration frequency: 38 percent | | | | | | | | | | | | |
| 30.3 | 468 | 1.25 | 2.00 | 1.54 | 1.62 | 1.66 | 1.51 | 2.18 | 1.15 | 18.38 | 8,830 | 9.26 |
| 28.5 | 454 | 2.30 | 1.71 | 2.70 | 1.55 | 2.90 | 1.45 | 3.70 | 1.18 | 11.40 | 5,710 | 8.89 |
| 25.8 | 132 | 5.63 | .81 | 6.37 | .74 | 6.46 | .76 | 7.49 | .71 | 8.27 | 4,380 | 8.41 |
| 23.7 | 132 | 9.25 | .58 | 10.12 | .56 | 10.35 | .54 | 11.45 | .53 | 6.89 | 3,620 | 8.46 |
| Calapooia River through Sodom Ditch. River miles indicated are measured from mouth of Ditch at Butte Creek. Injection of 2.000 liters of 20-percent dye solution at 0953 hours on May 25, 1993, in the Calapooia River, 4.3 miles upstream of diversion at Sodom Ditch. Upstream end of Sodom Ditch is 5.9 miles above mouth of ditch, and at Calapooia River at mile 28.5. | | | | | | | | | | | | |
| 4.4 | 329 | 3.54 | 1.21 | 4.12 | 1.06 | 4.27 | 1.09 | 5.28 | .95 | 9.49 | 4,500 | 9.40 |
| 1.5 | 329 | 5.50 | .77 | 6.37 | .67 | 6.62 | .64 | 7.92 | .57 | 6.35 | 3,200 | 8.83 |
| Injection of 2.000 liters of 20-percent dye solution at 0955 hours on May 24, 1993, at river mile 19.5. Discharge at index location: 283 cubic feet per second; corresponding flow-duration frequency: 46 percent | | | | | | | | | | | | |
| 17.1 | 383 | 2.63 | .91 | 3.25 | .74 | 3.44 | .70 | 4.36 | .55 | 13.51 | 4,670 | 12.87 |
| 14.8 | 390 | 5.38 | .84 | 6.33 | .75 | 6.55 | .74 | 7.94 | .64 | 8.86 | 3,140 | 12.58 |
| 12.8 | 390 | 7.87 | .80 | 9.08 | .73 | 9.26 | .74 | 10.89 | .68 | 6.65 | 2,630 | 11.26 |
| 9.6 | 400 | 12.29 | .72 | 13.89 | .67 | 14.01 | .67 | 15.96 | .63 | 5.12 | 2,090 | 10.91 |
| 3.0 | 402 | 20.82 | .77 | 23.08 | .72 | 23.39 | .70 | 26.18 | .65 | 2.97 | 1,520 | 8.71 |

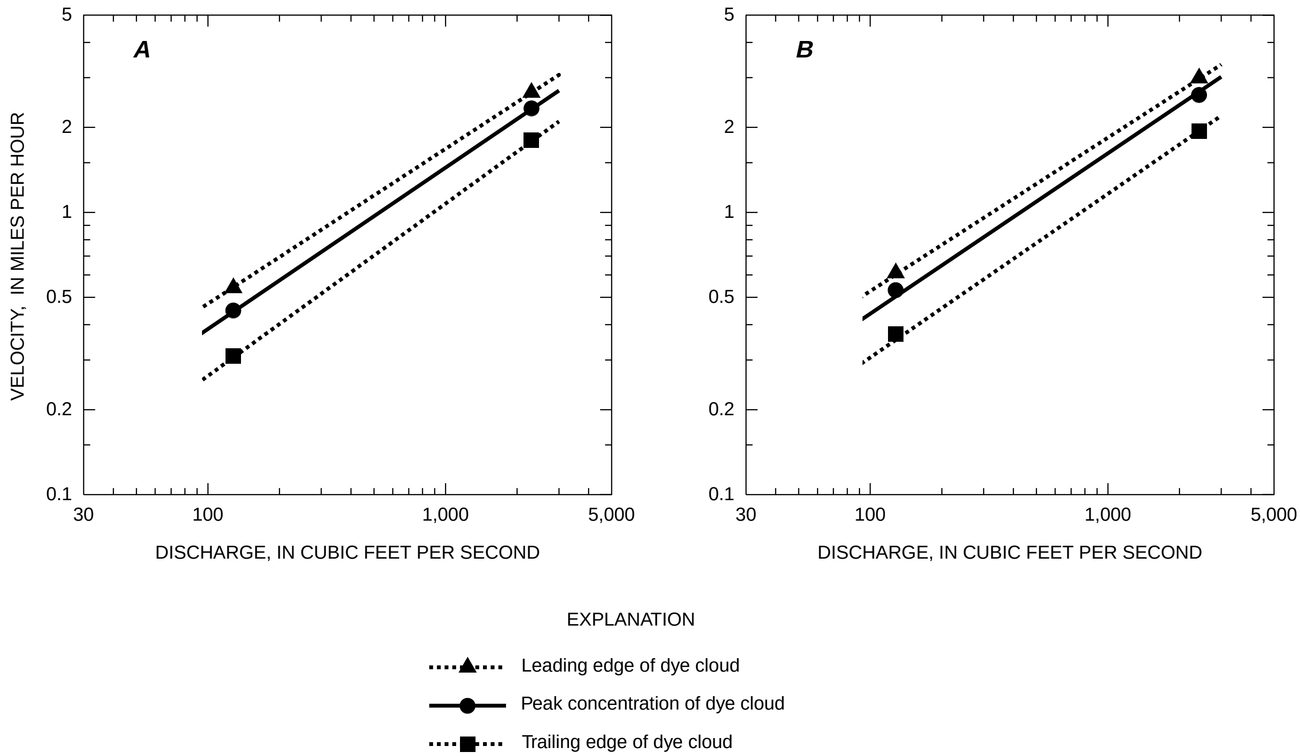


**Figure 7.** Relation of velocity of the Molalla River from (A) river mile 18.6 to river mile 12.8 and (B) river mile 10.0 to river mile 1.7 to discharge at the Molalla River near Canby (stream-gaging station 14200000).

travel measurement. Water was not ponded at Brownsville Dam or diverted into Brownsville Ditch. About three-fourths of the streamflow was diverted into Sodom Ditch. Streamflow regulation at Thompson Dam was minimal.

Graphs of discharge and velocity were developed for three subreaches of the Calapooia River (fig. 8). The upper subreach from RM 45.4 to RM 37.1 and the subreach from RM 32.8 to RM 28.5 are unaffected by regulation. The subreach from RM 37.1 to RM 32.8 is subject to regulation from Brownsville Dam; the steep slope of the graphs of discharge and velocity was caused by ponded water behind the dam.

If streamflow distribution in the diversions changes significantly, future estimates of travel time would not be as well-defined as estimates made for this study. Travel time of a constituent through Sodom Ditch and back into the Calapooia River will be reduced, because of the shorter length, greater slope, and straighter channel of Sodom Ditch, depending on the streamflow distribution at Sodom Dam, when compared with travel time in the natural channel of the Calapooia River. A multiple peak of a constituent could occur downstream of the confluence of Sodom Ditch and the Calapooia River because of the different travel times.

## Coast Range and Willamette Valley Tributaries

The Tualatin River (fig. 9), the South Yamhill and Yamhill Rivers (fig. 10), and the Pudding River (fig. 5) are low-gradient, deeply incised, meandering streams that primarily drain rolling, agricultural lands. Channel slope is generally less than 1.0 ft/mi. Streams in the study reaches are slow moving and have long, deep pools and short riffles. Streambanks are deeply incised and composed of sand and silt laid down during the Pleistocene epoch, when backwater lakes were formed during the Missoula Floods (Allison, 1978). The many meanders of these rivers are permanent, because stream velocities are low and channels are well incised even at high streamflows.

### Tualatin River

The Tualatin River reach studied extends from RM 53.8 to RM 23.3. The index station

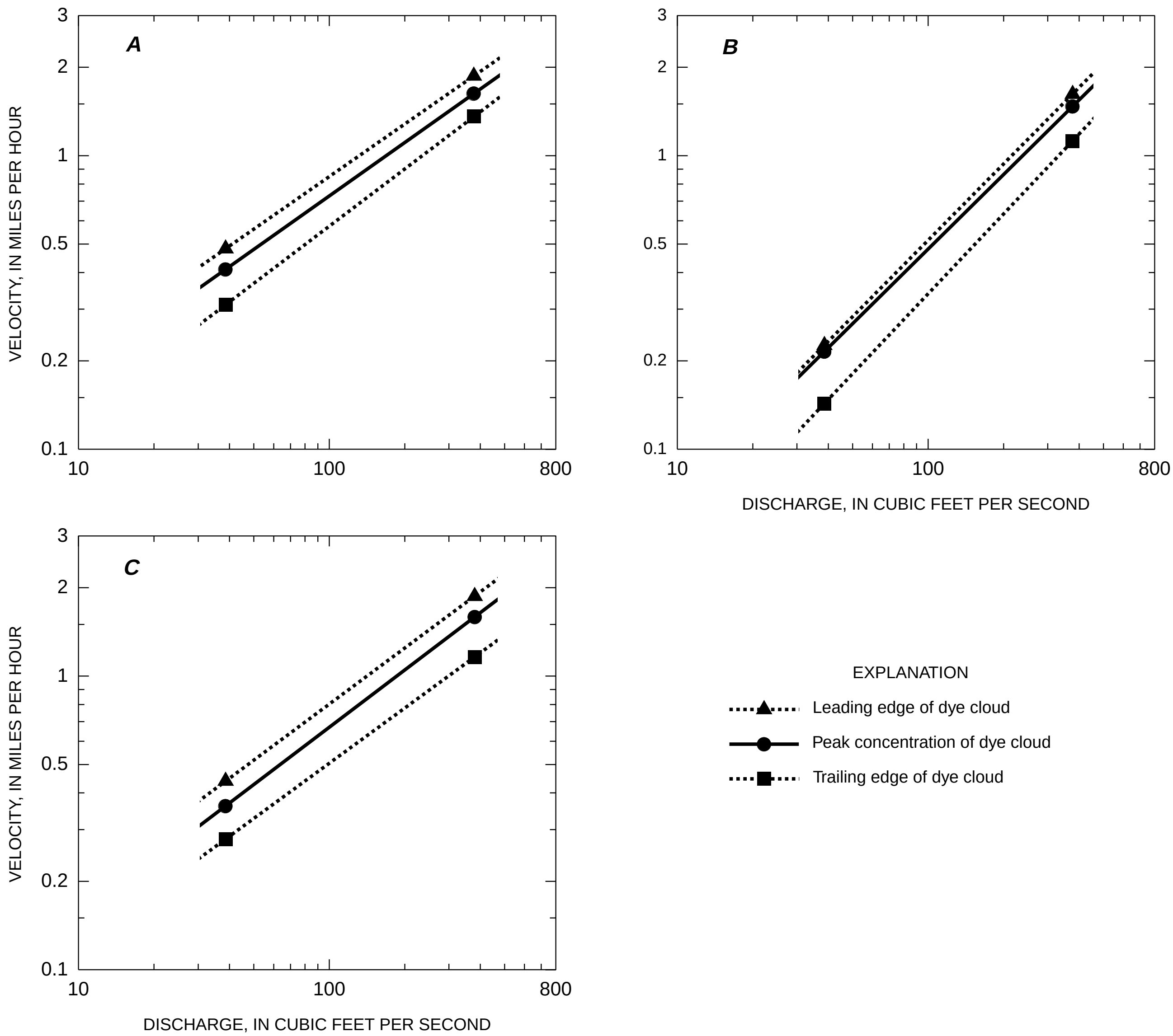


**Figure 8.** Relation of velocity of the Calapooia River from (A) river mile 45.4 to river mile 37.1, (B) river mile 32.8 to river mile 28.5, and (C) river mile 37.1 to river mile 32.8 to discharge at Calapooia River at Holley (stream-gaging station 14172000).

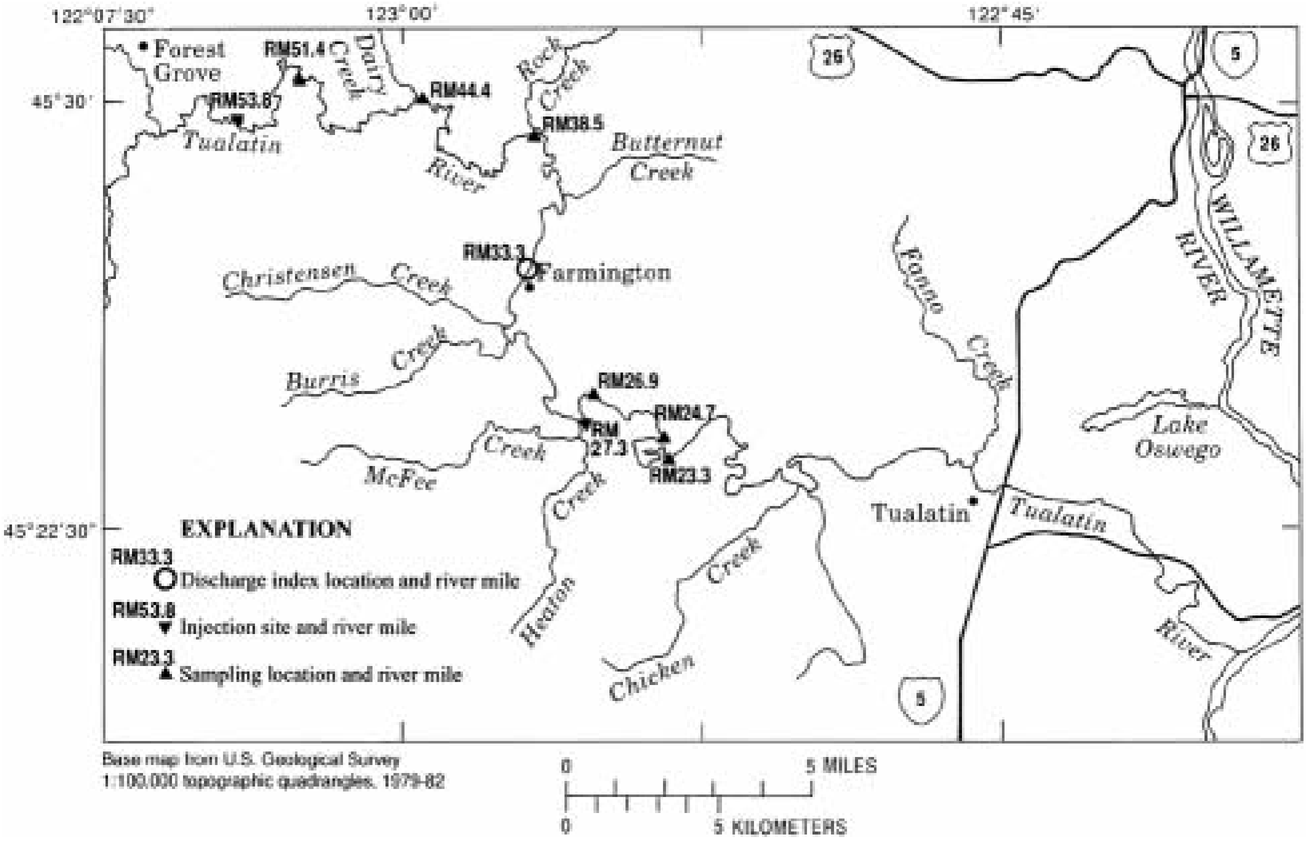


**Figure 9.** Study reach, injection sites, and sampling locations on the Tualatin River.

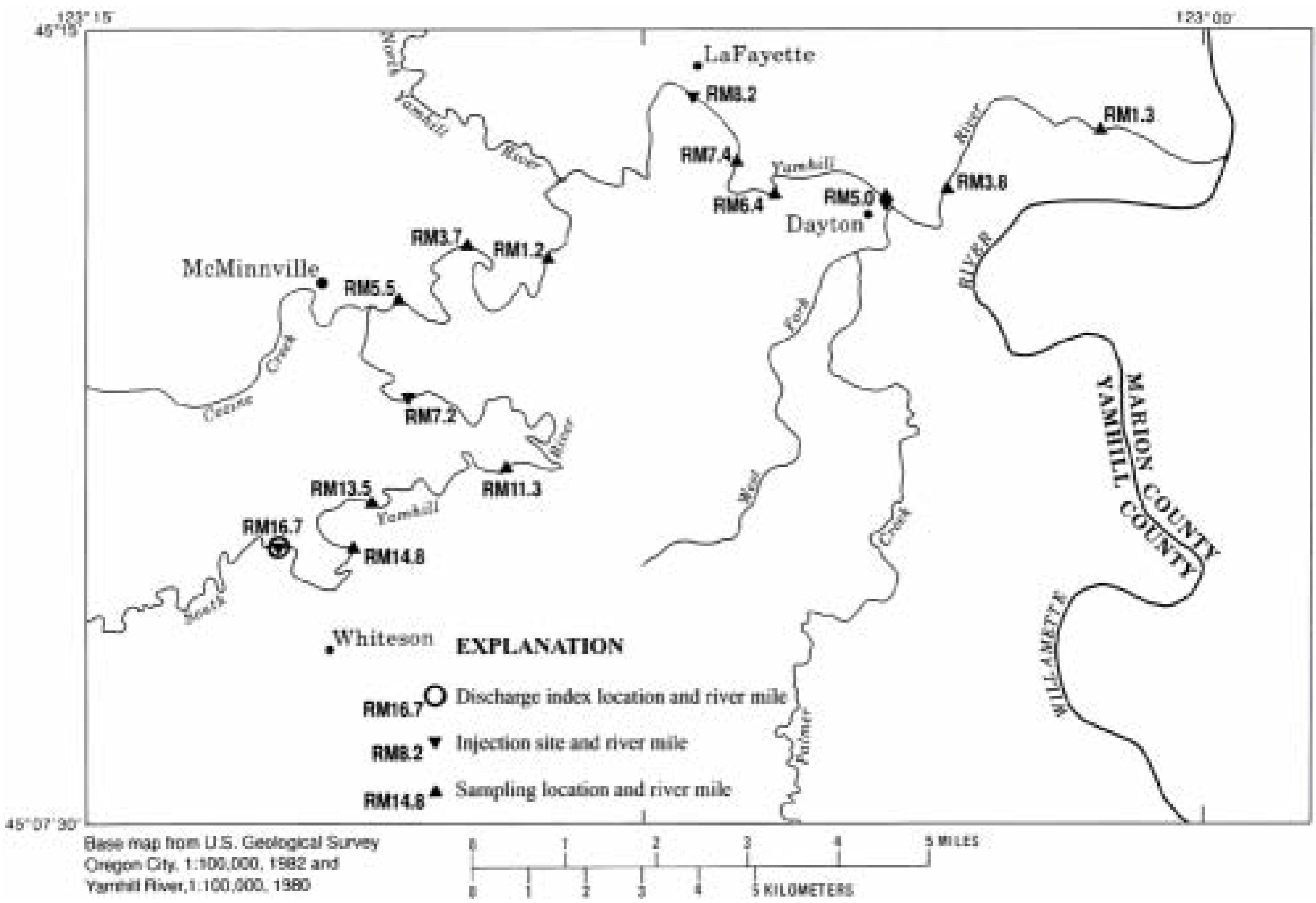


**Figure 10.** Study reaches, injection sites, and sampling locations on Yamhill River and South Yamhill River.

is14206500 (Tualatin River at Farmington, RM 33.3) and has a record of discharge that was collected by the USGS from 1940–58 and 1973–76. Beginning in 1992, the station was operated by the State of Oregon Water Resources Department (OWRD). Discharge is affected by additional flow from the sewage-treatment plant at Rock Creek, immediately downstream of the sampling location at RM 38.5.

One time-of-travel measurement was made in two subreaches of the Tualatin River (table 5). In the subreach from RM 53.8 to RM 26.9, the dye was injected in the middle of the stream, above a riffle, which enhanced mixing. In the subreach from RM 27.3 to RM 23.3, the dye was injected by pouring it from a boat traveling across the stream. With this technique, a line of dye was put in the stream across the channel, causing the dye to mix more rapidly than if it was injected at one or at several points.

Data collected in the current study were compared to time-of-travel and streamflow data collected by the Unified Sewerage Agency in 1987 (Janice Miller, Unified Sewerage Agency., written commun., 1992). In the Unified Sewerage Agency study dye-tracer techniques were used to measure the travel time of the peak to several locations on the Tualatin River. The relation of velocity of the peak to discharge at the index location is presented for four stream segments in figure 11.

### South Yamhill and Yamhill Rivers

The South Yamhill River was studied from RM 16.7 to RM 1.2 (table 6). Limited access and excessive travel times precluded studying the subreach from RM 11.3 to RM 7.2 during the periods of low discharge. For each subreach, the dye was injected at a single, midchannel point. The index location is station 14194000 (South Yamhill River near Whiteson, RM 16.7). A record of discharge was collected at the station by the USGS from 1940 to 1991 and by OWRD beginning in 1992.

The relation of velocity to discharge at the index location, for the subreaches of the South Yamhill River (RM 16.7 to RM 11.3 and RM 5.5 to RM 1.2) is shown in figure 12. The decrease in velocity in the lower subreach is attributable to long, deep pools.

The Yamhill River was studied from RM 8.2 to RM 1.3. The index location is the same as for the South Yamhill River. Travel-time and dispersion data for the Yamhill River are shown in table 7.

**Table 5.** Time-of-travel and dispersion data for reaches studied in the Tualatin River
[Index location is station 14206500, Tualatin River at Farmington, at mile 33.3.]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 1.000 liters of 20-percent dye solution at 0905 hours on September 15, 1992, at mile 53.8<br>Discharge at index location: 130 cubic feet per second; corresponding flow-duration frequency: 72 percent | | | | | | | | | | | | |
| 51.4 | 112 | 3.49 | 0.69 | 4.09 | 0.59 | 4.17 | 0.58 | 4.93 | 0.49 | 24.61 | 5,290 | 20.71 |
| 44.4 | 112 | 17.03 | .52 | 18.92 | .47 | 19.50 | .46 | 22.12 | .41 | 5.44 | 1,660 | 14.58 |
| 38.5 | 112 | 34.14 | .34 | 36.92 | .33 | 38.17 | .32 | 42.79 | .29 | 2.58 | 931 | 12.31 |
| 26.9 | 138 | 82.99 | .24 | 90.92 | .21 | 91.63 | .22 | 100.80 | .20 | 0.98 | 405 | 10.76 |
| Injection of 1.000 liters of 20-percent dye solution at 1000 hours on September 14, 1992, at mile 27.3<br>Discharge at index location: 130 cubic feet per second; corresponding flow-duration frequency: 72 percent | | | | | | | | | | | | |
| 26.9 | 130 | 2.56 | .16 | 3.10 | .13 | 3.70 | .11 | 5.47 | .07 | 15.84 | 4,070 | 17.34 |
| 24.7 | 130 | 16.52 | .16 | 20.00 | .13 | 21.01 | .13 | 26.13 | .11 | 2.93 | 878 | 14.83 |
| 23.3 | 130 | 26.64 | .14 | 30.00 | .14 | 31.97 | .13 | 38.64 | .11 | 2.02 | 713 | 12.61 |

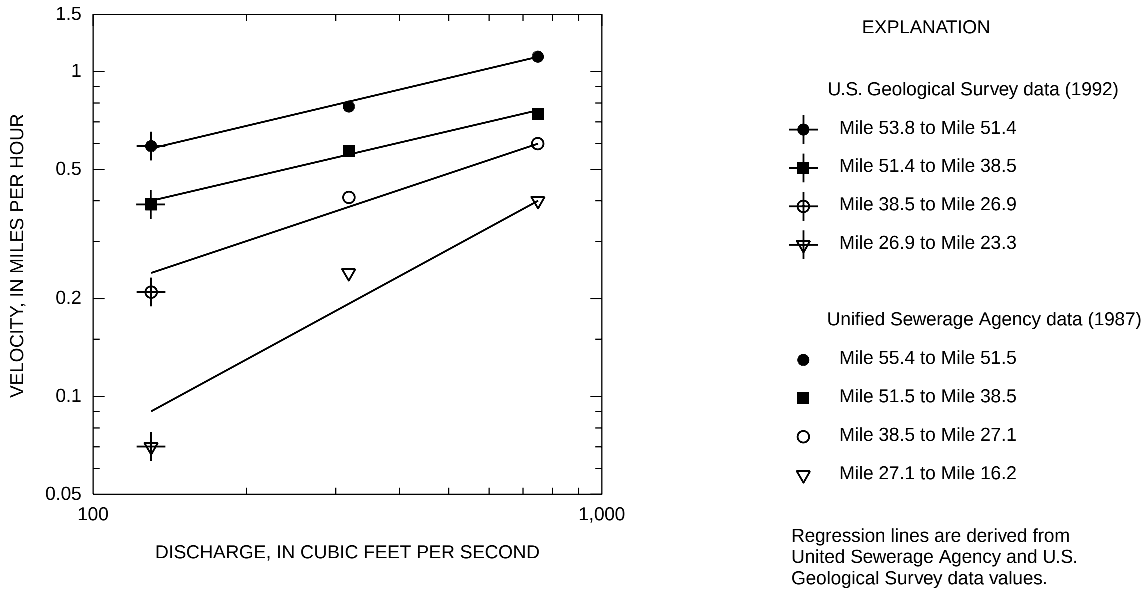


**Figure 11.** Relation of velocity of the Tualatin River from river mile 55.4 to river mile 16.2 to discharge at the Tualatin River at Farmington (stream-gaging station 14206500). (Data for velocity of discharges of 320 and 750 cubic feet per second is from Unified Sewerage Agency [written commun., 1992]).

**Table 6.** Time-of-travel and dispersion data for reaches studied in the South Yamhill River

[Index location is station 14194000, South Yamhill River near Whiteson, at river mile 16.7]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 0.500 liters of 20-percent dye solution at 1140 hours on June 8, 1992, at river mile 16.7<br>Discharge at index location: 116 cubic feet per second; corresponding flow-duration frequency: 75 percent | | | | | | | | | | | | |
| 14.8 | 116 | 3.26 | 0.58 | 4.26 | 0.45 | 4.54 | 0.42 | 6.25 | 0.30 | 5.89 | 2,730 | 9.61 |
| 13.5 | 114 | 6.00 | .47 | 7.33 | .42 | 7.70 | .41 | 9.95 | .35 | 4.22 | 2,110 | 8.90 |
| 11.3 | 113 | 11.45 | .40 | 13.83 | .34 | 15.30 | .29 | 17.79 | .28 | 2.82 | 1,280 | 9.50 |
| Injection of 1.150 liters of 20-percent dye solution at 0815 hours on May 28, 1992, at river mile 7.2<br>Discharge at index location: 194 cubic feet per second; corresponding flow-duration frequency: 68 percent | | | | | | | | | | | | |
| 5.5 | 194 | 3.05 | .56 | 4.02 | .42 | 4.33 | .39 | 6.11 | .28 | 8.10 | 2,760 | 13.06 |
| 3.7 | 194 | 7.39 | .41 | 9.08 | .36 | 9.67 | .34 | 12.55 | .28 | 3.94 | 1,540 | 11.41 |
| 1.2 | 194 | 16.16 | .29 | 19.75 | .23 | 20.64 | .23 | 26.06 | .19 | 2.13 | 753 | 12.60 |
| Injection of 2.900 liters of 20-percent dye solution at 1115 hours on June 29, 1993, at river mile 16.7<br>Discharge at index location: 245 cubic feet per second; corresponding flow-duration frequency: 65 percent | | | | | | | | | | | | |
| 14.8 | 275 | 1.92 | .99 | 2.38 | .80 | 2.58 | .74 | 3.46 | .55 | 27.49 | 5,270 | 23.20 |
| 13.5 | 275 | 3.56 | .79 | 4.30 | .68 | 4.58 | .65 | 5.74 | .57 | 18.82 | 3,430 | 24.39 |
| 11.3 | 270 | 6.40 | .77 | 7.85 | .62 | 7.94 | .65 | 9.67 | .56 | 13.14 | 2,680 | 21.86 |
| 5.5 | 265 | 17.28 | .53 | 19.75 | .49 | 19.76 | .49 | 23.05 | .43 | 6.53 | 1,310 | 22.16 |
| 3.7 | 260 | 21.03 | .48 | 24.03 | .42 | 24.24 | .40 | 28.26 | .35 | 5.56 | 1,150 | 21.51 |
| 1.2 | 260 | 28.43 | .32 | 31.75 | .31 | 32.58 | .29 | 36.75 | .28 | 3.69 | 958 | 17.12 |

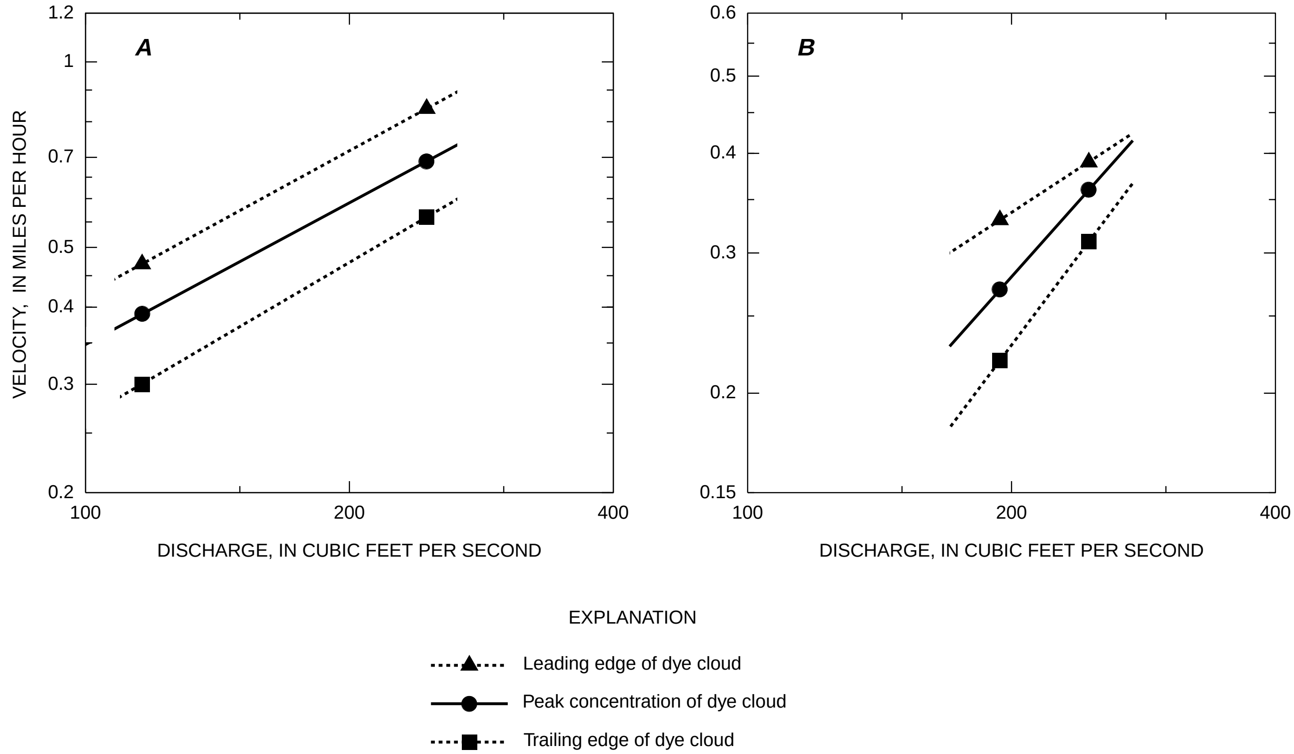


**Figure 12.** Relation of velocity of the South Yamhill River from (A) river 16.7 to river mile 11.3 and (B) river mile 5.5 to river 1.2 to discharge at the South yamhill River near Whiteson (stream-gaging station 14194000).

**Table 7.** Time-of-travel and dispersion data for reaches studies in the Yamhill River

[Index location is station 14194000, South Yamhill River near Whiteson, at river mile 16.7]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 1.900 liters of 20-percent dye solution at 1045 hours on May 27, 1992, at river mile 8.2<br>Discharge at index location: 207 cubic feet per second; corresponding flow-duration frequency: 67 percent | | | | | | | | | | | | |
| 7.4 | 328 | 1.48 | 0.54 | 1.83 | 0.44 | 2.41 | 0.33 | 3.98 | 0.20 | 13.96 | 4,130 | 15.03 |
| 6.4 | 312 | 3.47 | .50 | 4.58 | .36 | 5.42 | .33 | 8.37 | .23 | 5.81 | 1,730 | 14.95 |
| 5.0 | 296 | 8.93 | .26 | 11.25 | .21 | 12.47 | .20 | 16.41 | .17 | 3.75 | 1,140 | 14.64 |
| 3.8 | 280 | 13.25 | .28 | 15.75 | .27 | 17.00 | .26 | 21.97 | .22 | 3.19 | 969 | 14.64 |
| 1.3 | 280 | 26.48 | .19 | 31.25 | .16 | 33.10 | .16 | 41.75 | .13 | 1.49 | 506 | 13.13 |
| Injection of 5.200 liters of 20-percent dye solution at 0943 hours on May 11, 1993, at river mile 8.2<br>Discharge at index location: 1,680 cubic feet per second; corresponding flow-duration frequency: 30 percent | | | | | | | | | | | | |
| 7.4 | 1,800 | .52 | 1.54 | .66 | 1.21 | .80 | 1.00 | 1.19 | .67 | 21.53 | 13,300 | 7.19 |
| 6.4 | 1,800 | 1.41 | 1.12 | 1.86 | .83 | 2.09 | .78 | 3.10 | .52 | 7.05 | 5,060 | 6.19 |
| 5.0 | 1,800 | 3.60 | .64 | 4.50 | .53 | 4.81 | .51 | 6.48 | .41 | 3.84 | 2,750 | 6.22 |
| 3.8 | 1,800 | 5.30 | .71 | 6.28 | .67 | 6.81 | .60 | 8.84 | .51 | 2.90 | 2,260 | 5.73 |
| Injection of 3.000 liters of 20-percent dye solution at 1212 hours on May 12, 1993, at river mile 5.0<br>Discharge at index location: 1,530 cubic feet per second; corresponding flow-duration frequency: 32 percent | | | | | | | | | | | | |
| 3.8 | 1,800 | 1.31 | .92 | 1.63 | .74 | 1.85 | .65 | 2.72 | .44 | 5.95 | 6,720 | 3.94 |
| 1.3 | 1,800 | 5.86 | .55 | 7.13 | .45 | 7.90 | .41 | 10.87 | .31 | 1.36 | 1,690 | 3.58 |

The velocity in the Yamhill River downstream of RM 7.4 is decreased by backwater from the Willamette River. This effect is more pronounced during periods of low discharge. Figure 13 shows the relation of velocity to discharge at the index location.

### Pudding River

The Pudding River reach studied extends from RM 48.7 to RM 5.4. The index location station is 14202000 (Pudding River at Aurora, RM 8.1); record of discharge was collected for this station by the USGS from 1929–64 and during 1993. A single time-of-travel measurement was made in July 1993. The reach was divided into three subreaches and the dye was injected at midchannel in each subreach. The results are tabulated in table 8.

## Urban Streams

Mill Creek (fig. 14), Johnson Creek (fig. 15), and Amazon Creek (fig. 16) are small, steep-gradient streams whose headwaters lie in primarily agricultural or forested basins; because these creeks flow through urban areas, the streamflow conditions are significantly altered by manmade structures. The channel slope of these creeks varies greatly, from approximately 5 ft/mi in the lower Amazon Creek Basin to 29 ft/mi in the lower Johnson Creek Basin. Where the streambeds of the creeks consist of natural gravel-and-cobble material, they have pool-and-riffle flow conditions; where the creeks flow through concrete culverts, they have canal-like flow conditions. In general, these urban creeks have more constricted channels and meander less than the Coast Range, Willamette, or Cascade tributaries because of channel modification and stabilization projects. The distribution of streamflow in Mill Creek and Amazon Creek is regulated by the setting of gates at diversion structures in the lower part of each basin. Streamflow in Mill Creek is affected by an interbasin diversion. Rapid runoff from paved areas of Salem, Portland, and Eugene affects streamflow characteristics of Mill, Johnson, and Amazon Creeks, respectively.

### Mill Creek

Mill Creek serves as a conduit for a major diversion. The diversion, from the North Santiam River at Stayton, channels water through Salem Ditch for 2 miles and enters Mill Creek at RM 17.7. Below RM 3.3, Mill Creek flows through urban areas of Salem and is divided into three channels: Shelton Ditch, Mill Ditch, and the main channel of Mill Creek.

The reach studied on Mill Creek extended from Salem Ditch at Stayton, 2.0 miles above the confluence of Salem Ditch and Mill Creek, to the mouth of Mill Creek. Four index locations are used in the Mill Creek Basin because of diversions in the Salem area. Stream velocity in the two diversions in Salem, as well as the main channel of Mill Creek below RM 3.3, is dependent on the discharge in each of these subreaches. For the subreach from Stayton to RM 3.3, the index location is station 14191500 (Mill Creek at Penitentiary Annex near Salem at RM 6.7), which was operated by the USGS during the period 1940–56. For the subreach from RM 3.3 to the mouth of Mill Creek, the index location is at RM 0.1. For Shelton Ditch and Mill Ditch, the index location is at the mouth of each ditch.

Time-of-travel measurements were made on Mill Creek during May and July 1992 and August 1993 (table 9 and fig. 17). Sampling sites were located on Mill Creek at the point of diversion for Shelton and Mill Ditches and at the mouth of each ditch. In this manner, time of travel was determined for the main channel of Mill Creek and the ditches. Dye was injected midchannel at a single point for each subreach. At RM 17.7, the confluence of Mill Creek and Salem Ditch, flow from the North Santiam River diversion was 99 and 76 percent of the total streamflow for the lower and higher discharges studied, respectively.

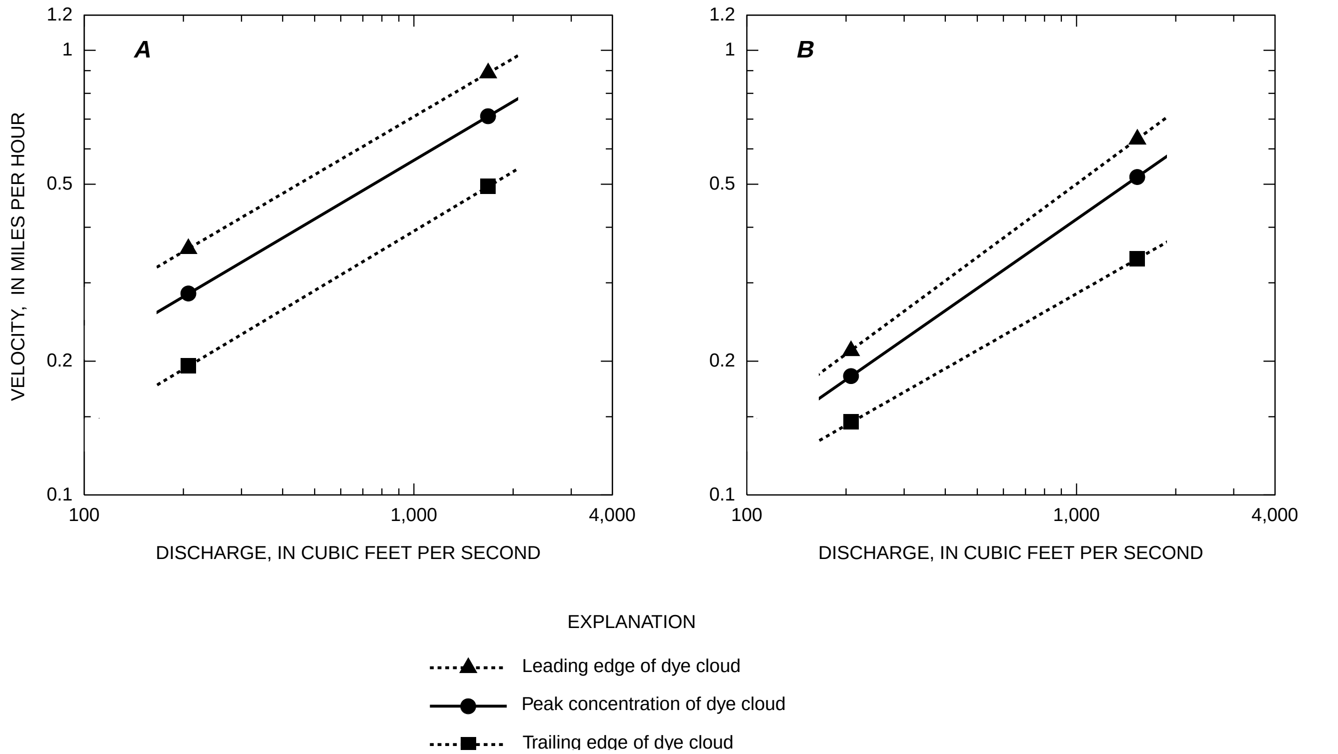


**Figure 13.** Relation of velocity of the Yamhill River from (A) river mile 8.2 to river mile 5.0 and (B) river mile 5.0 to river mile 1.3 to discharge at the South Yamhill River near Whiteson (stream-gaging station 14194000).

**Table 8**. Time-of-travel and dispersion data for reaches studied in the Pudding River

[Index location is station 14202000, Pudding River at Aurora, at river mile 8.1]

| Sampling location | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | | | |
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 1.200 liters of 20-percent dye solution at 1050 hours on July 9, 1993, at river mile 48.7. Discharge at index location: 235 cubic feet per second; corresponding flow-duration frequency: 67 percent | | | | | | | | | | | | |
| 45.5 | 126 | 9.35 | 0.34 | 10.67 | 0.30 | 11.22 | 0.29 | 13.42 | 0.24 | 9.88 | 2,070 | 21.23 |
| 40.7 | 129 | 20.29 | .44 | 22.17 | .42 | 22.94 | .41 | 25.91 | .38 | 6.39 | 1,410 | 20.18 |
| 35.8 | 132 | 31.17 | .45 | 33.17 | .45 | -- | -- | -- | -- | 3.85 | -- | -- |
| 31.5 | 135 | 38.56 | .58 | 41.67 | .51 | 42.52 | -- | 47.93 | -- | 2.93 | 909 | 14.33 |
| Injection of 2.000 liters of 20-percent dye solution at 1000 hours on July 8, 1993, at river mile 35.8. Discharge at index location: 250 cubic feet per second; corresponding flow-duration frequency: 66 percent | | | | | | | | | | | | |
| 31.5 | 135 | 6.82 | .63 | 7.75 | .55 | 7.87 | .54 | 9.16 | .47 | 22.33 | 3,408 | 28.60 |
| 27.0 | 150 | 15.50 | .52 | 17.00 | .49 | 17.25 | .48 | 19.14 | .45 | 11.07 | 2,130 | 23.19 |
| 22.3 | 170 | 24.07 | .55 | 26.00 | .52 | 26.45 | .51 | 28.95 | .48 | 7.99 | 1,640 | 21.67 |
| 17.6 | 215 | 32.41 | .56 | 35.00 | .52 | 35.69 | .51 | 38.94 | .47 | 4.64 | 1,140 | 18.14 |
| Injection of 2.490 liters of 20-percent dye solution at 1118 hours on July 7, 1993, at river mile 22.3. Discharge at index location: 270 cubic feet per second; corresponding flow-duration frequency: 65 percent | | | | | | | | | | | | |
| 17.6 | 240 | 7.08 | .66 | 8.05 | .58 | 8.24 | .57 | 9.51 | .49 | 17.64 | 3,190 | 24.63 |
| 14.2 | 245 | 13.01 | .57 | 14.70 | .51 | 14.87 | .51 | 16.75 | .47 | 9.81 | 2,160 | 20.21 |
| 12.1 | 250 | 16.45 | .61 | 18.70 | .52 | 19.04 | .50 | 21.52 | .44 | 7.90 | 1,720 | 20.44 |
| 8.1 | 260 | 25.80 | .43 | 29.20 | .38 | 28.84 | .41 | 32.47 | .37 | 5.26 | 1,220 | 19.25 |
| 5.4 | 270 | 33.79 | .34 | 37.70 | .32 | 38.19 | .29 | 42.94 | .26 | 3.51 | 859 | 18.18 |

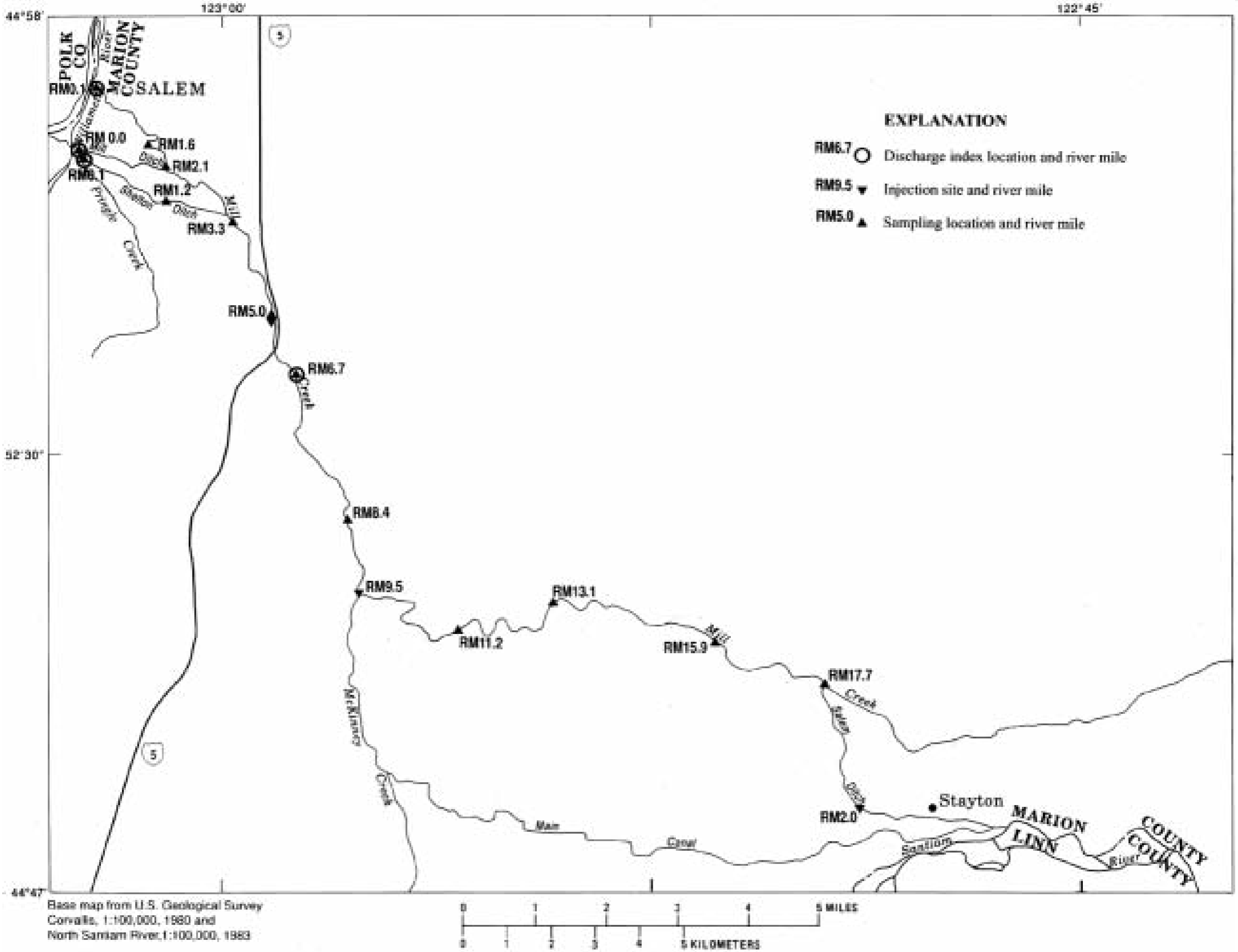


**Figure 14**. Study reaches, injection sites, and sampling locations on Mill Creek, Shelton Ditch, and Mill Ditch.

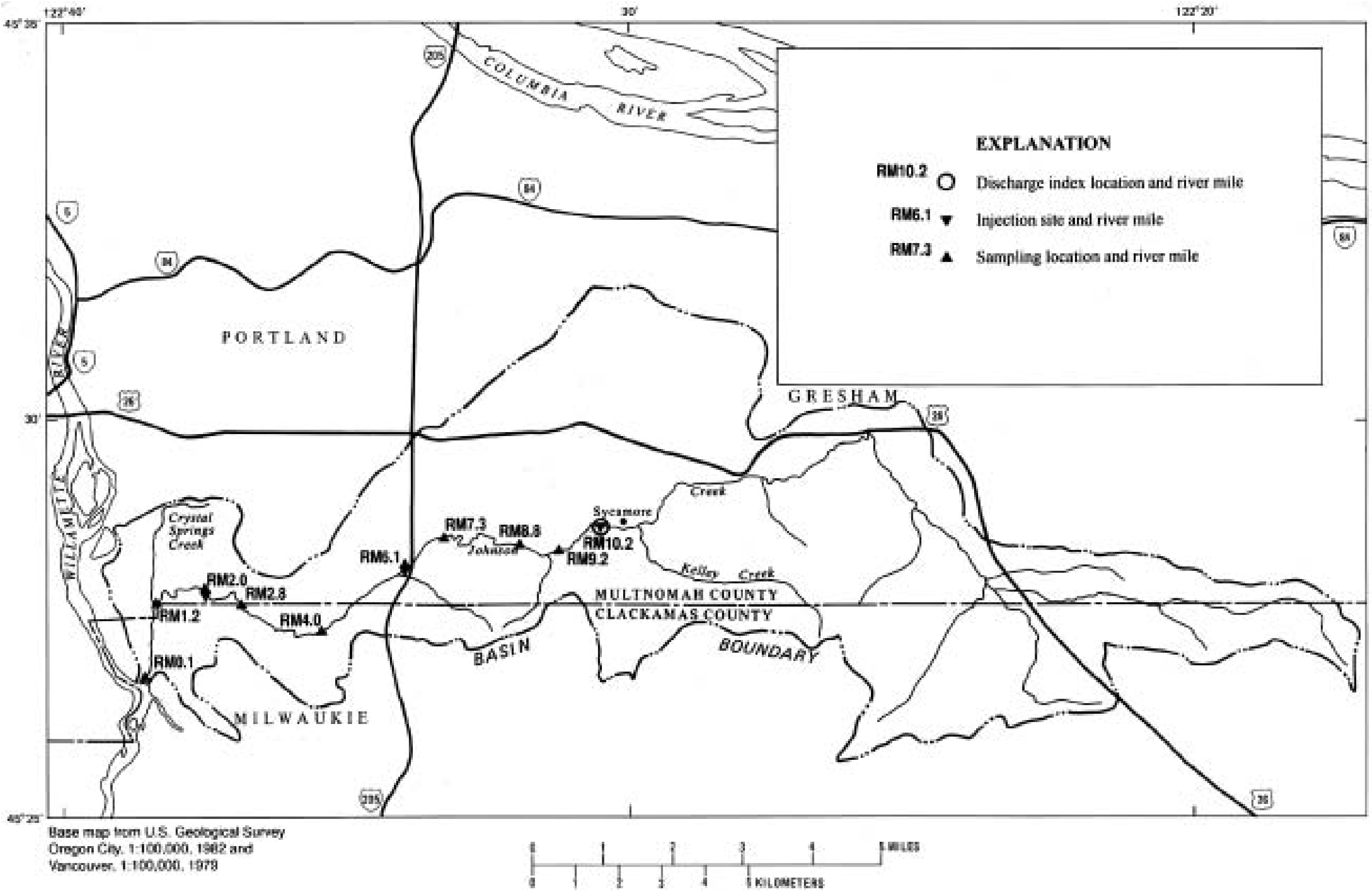


**Figure 15.** Study reaches, infection sites, and sampling locations of Johnson Creek.

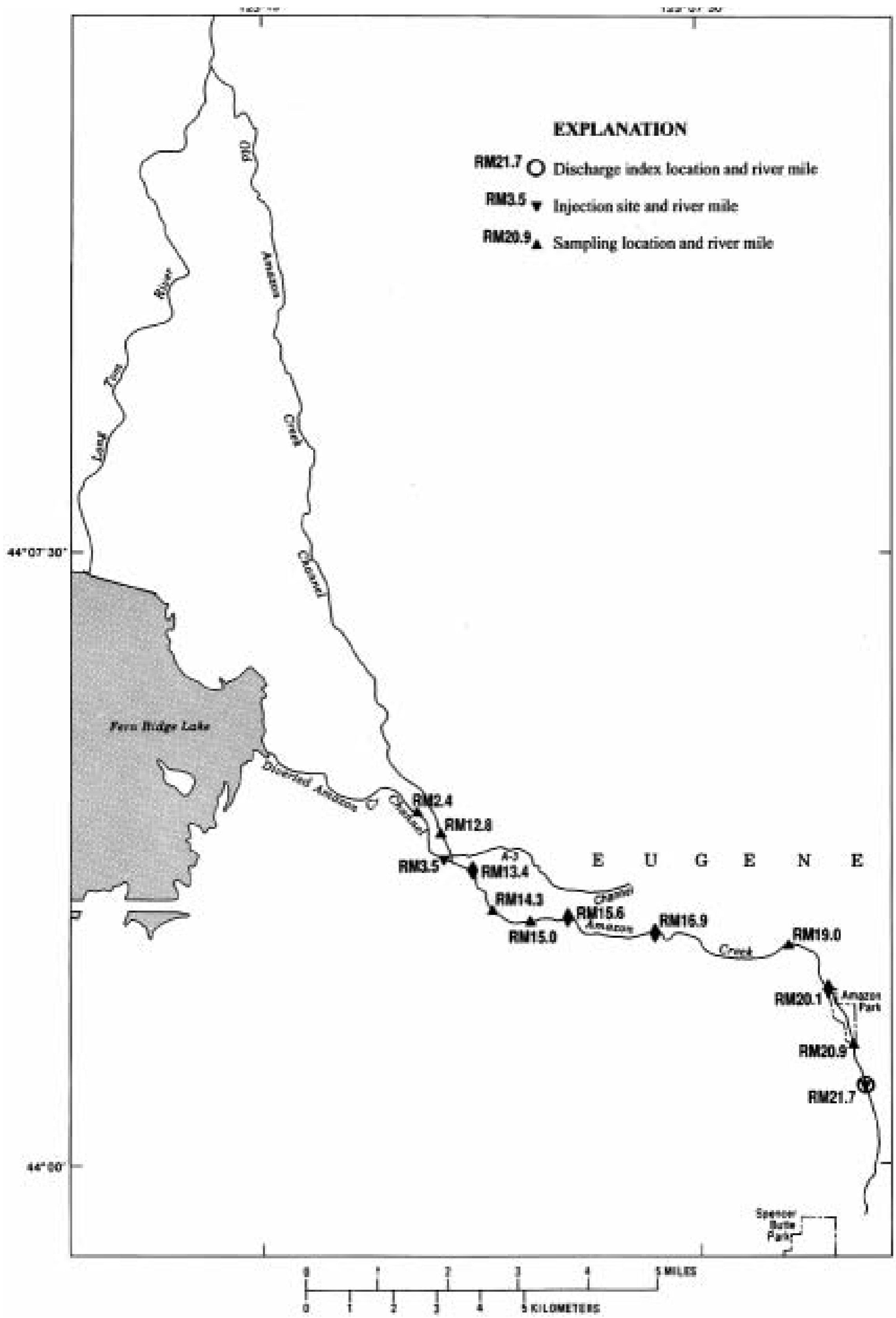


**Figure 16.** Study reaches, injection sites, and sampling locations on Amazon Creek and the Diverted Amazon Creek Canal.

### Johnson Creek

The study reach of Johnson Creek extended from RM 10.2 to the mouth. The index location for this reach is station 14211500, Johnson Creek at Sycamore, at RM 10.2. A continuous record of streamflow has been collected at this site by the USGS since 1940.

Time-of-travel measurements were made in April 1992 and March 1993. For the lower discharge time-of-travel measurement, the stream was divided into three subreaches (table 10): RM 10.2 to 6.1, RM 6.1 to 2.2, and RM 2.2 to 0.1. For the time-of-travel measurement at higher discharge, the stream was divided into two subreaches, RM 10.2 to 6.1, and RM 6.1 to 0.1. In each subreach, the dye was injected midstream at a single point. Velocity of the dye cloud varied considerably between sampling locations, probably because of local changes in slope through the study reach. Velocity increased downstream of RM 2.2 (fig. 18) due to inflow from Crystal Springs Creek, which provided 58 percent of the streamflow at the mouth of Johnson Creek during the lower discharge time-of-travel measurement.

### Amazon Creek

The Amazon Creek reach studied extends from RM 21.7 to RM 12.8. The Diverted Amazon Creek Channel was studied from RM 3.4 to RM 2.4. The RM designation for the Diverted Amazon Creek Channel originates from the channel outlet into Fern Ridge Lake. The index location is station 14169300 (Amazon Creek at Eugene, RM 21.7); a record of discharge was collected by the USGS from 1963–75.

At RM 13.4, the creek is split at a small dam. A portion of the streamflow is piped into the Old Amazon Creek Channel, the natural drainage for Amazon Creek. The remainder of the stream flows into the Diverted Amazon Creek Channel.

Time-of-travel studies on Amazon Creek were done in April and May 1992 and April 1993 (table 11). For the April 1992 study, time of travel in subreaches RM 15.6 to 14.3, RM 13.4 to12.8, and the Diverted Amazon Creek Channel at RM 3.5 to 2.4 was determined. During this time-of travel study the velocity in the Diverted Amazon Creek Channel was affected by fluctuations of backwater from Fern Ridge Lake. For the May 1992 study, time of travel was measured from RM 21.7 to RM 20.1, and RM 20.1 to 16.9. For the April 1993 study, time of travel was measured in reaches RM 21.7 to 19.0, and RM 16.9 to 13.4. The dye was injected midstream at a single point for each subreach. The relation of velocity of the peak and leading and trailing edge of the dye cloud to discharge at the index location for the subreaches from RM 21.7 to 20.1 and RM 15.6 to 14.3 is shown in figure 19.

## DISPERSION CHARACTERISTICS

Dispersion is the scattering of particles in water that controls the concentration of a constituent as it is transported downstream. Dispersion can be depicted as the decrease in unit-peak concentration of a conservative constituent plotted against elapsed time. The dye tracer used was not a conservative constituent; therefore, adjustments had to be made to account for dye that was lost due to natural decay or absorbed by stream sediment. The weight of dye recovered at each cross section was determined, and the dye-recovery ratio was computed to define concentration values of a conservative constituent. Unit concentrations were computed, after concentrations were adjusted by the dye-recovery ratio, using the weight of the injected dye and discharge of the stream. The resulting adjusted unit concentrations define dispersion by the attenuation of the peak concentration as the dye cloud moves downstream or as time elapses.

### Analysis

Adjustments were made to the measured, peak-dye concentration values to determine the conservative unit-peak concentration according to Kilpatrick, 1992:

(1) The weight of the dye recovered at each cross section is determined using the formula,

$$W_r = QA_c \tag{2}$$

where

**Table 9**. Time-of-travel and dispersion data for reaches studied in Mill Creek

[Index location for Mill Creek from river mile 17.7 to 3.3 is station 14191500 Mill Creek at Penitentiary Annex, near Salem, at river mile 6.7.
Index location for Mill Creek from river mile 3.3 to river mile 0.1 is at river mile 0.1.
Index location for Shelton Ditch is at mouth of Ditch. Index location for Mill Ditch is mouth of Ditch]

| Sampling location under | | Travel time and velocity | | | | | | | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Leading edge | | Peak | | Centroid | | Trailing edge | | Peak | Unit-peak | Area |
| Distance from mouth times (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | concentration (micrograms per liter) | concentration (micrograms per liter per pound times cubic foot per second) | curve (micrograms per liter hours) |
| Injection of 0.350 liters of 20-percent dye solution at 0820 hours on May 6, 1992, in Salem ditch, 2.0 miles upstream from confluence with Mill Creek. Discharge at index location: 190 cubic feet per second | | | | | | | | | | | | |
| 17.7 | 49.8 | 1.43 | 1.40 | 1.67 | 1.20 | 1.73 | 1.16 | 2.08 | 0.96 | 37.93 | 11,800 | 14.29 |
| 15.9 | 64.8 | 2.92 | 1.21 | 3.34 | 1.08 | 3.44 | 1.05 | 4.04 | .92 | 15.64 | 7,150 | 9.73 |
| 13.1 | 94.0 | 5.01 | 1.34 | 5.67 | 1.20 | 5.84 | 1.17 | 6.79 | 1.02 | 7.40 | 4,550 | 7.23 |
| 11.2 | 123 | 7.22 | .86 | 8.04 | .80 | 8.18 | .81 | 9.32 | .75 | 2.91 | 3,860 | 3.35 |
| Injection of 0.200 liters of 20-percent dye solution at 1330 hours on May 5, 1992, at river mile 9.5. Discharge at index location: 190 cubic feet per second | | | | | | | | | | | | |
| 8.4 | 184 | .68 | 1.62 | .83 | 1.33 | .98 | 1.12 | 1.39 | .79 | 5.49 | 12,800 | 1.91 |
| 6.7 | 190 | 2.07 | 1.22 | 2.50 | 1.02 | 2.66 | 1.01 | 3.42 | .84 | 2.63 | 6,170 | 1.89 |
| 5.0 | 208 | 3.76 | 1.01 | 4.33 | .93 | 4.65 | .85 | 5.78 | .72 | 1.32 | 3,990 | 1.48 |
| Mill Creek through Shelton Ditch. River miles indicated are measured from mouth of Ditch at Pringle Creek. Injection of 0.300 liters of 20-percent dye solution at 1045 hours on May 4, 1992, in Mill Creek, 1.7 miles upstream of diversion at Shelton Ditch. Upstream end of Shelton Ditch 2.2 miles above mouth of Ditch, and at Mill Creek river mile 3.3. Discharge at index location: 77.6 cubic feet per second | | | | | | | | | | | | |
| 1.2 | 77.6 | 2.43 | .76 | 2.58 | .80 | 2.80 | .76 | 3.33 | .73 | 4.90 | 9,370 | 2.33 |
| .1 | 77.6 | 3.10 | 1.64 | 3.60 | 1.08 | 3.73 | 1.18 | 4.55 | .90 | 4.42 | 5,640 | 3.49 |
| Mill Creek through Mill Ditch. River miles indicated are measured from mouth of Ditch into Pringle Creek. Injection of 0.300 liters of 20-percent dye solution at 1045 hours on May 4, 1992, in Mill Creek, 2.9 miles upstream of diversion at Mill Ditch. Upstream end of Mill Ditch 1.2 miles above mouth of ditch, and at Mill Creek river mile 2.1. Discharge at index location: 47.5 cubic feet per second | | | | | | | | | | | | |
| .0 | 47.5 | 4.24 | 1.04 | 4.88 | .99 | 5.07 | 1.00 | 6.15 | .93 | 3.55 | 4,250 | 3.72 |
| Injection of 0.300 liters of 20-percent dye solution at 0950 hours on July 29, 1992,in Salem ditch, 2.0 miles upstream from confluence with Mill Creek. Discharge at index location: 130 cubic feet per second | | | | | | | | | | | | |
| 17.7 | 65.5 | 1.35 | 1.48 | 1.59 | 1.26 | 1.63 | 1.23 | 2.00 | 1.00 | 27.17 | 11,700 | 10.35 |
| 15.9 | 52.2 | 2.92 | 1.15 | 3.42 | .98 | 3.49 | .97 | 4.17 | .83 | 14.39 | 6,380 | 10.04 |
| 13.1 | 52.2 | 5.37 | 1.14 | 6.09 | 1.05 | 6.26 | 1.01 | 7.46 | .85 | 7.42 | 4,200 | 7.85 |
| 11.2 | 83.2 | 8.21 | .67 | 9.17 | .62 | 9.36 | .61 | 10.67 | .59 | 3.14 | 3,340 | 4.18 |
| Injection of 0.300 liters of 20-percent dye solution at 0915 hours on July 29, 1992, at river mile 9.5. Discharge at index location: 130 cubic feet per second | | | | | | | | | | | | |
| 8.4 | 125 | .85 | 1.29 | 1.08 | 1.02 | 1.22 | .90 | 1.73 | .64 | 10.45 | 9,360 | 4.97 |
| 6.7 | 130 | 2.48 | 1.04 | 3.25 | .78 | 3.36 | .79 | 4.42 | .63 | 5.18 | 4,420 | 5.22 |
| 5.0 | 133 | 4.86 | .71 | 5.68 | .70 | 6.08 | .63 | 7.99 | .48 | 3.03 | 2,810 | 4.79 |
| Injection of 0.350 liters of 20-percent dye solution at 0955 hours on July 28, 1992, at river mile 5.0. Discharge at index location: 39.4 cubic feet per second | | | | | | | | | | | | |
| 3.3 | 140 | 1.25 | 1.36 | 1.50 | 1.13 | 1.61 | 1.06 | 2.16 | .79 | 11.84 | 9,520 | 5.53 |
| 2.1 | 87.6 | 3.24 | .60 | 3.91 | .50 | 4.21 | .46 | 5.54 | .36 | 4.64 | 3,840 | 5.39 |
| 1.6 | 45.0 | 4.16 | .54 | 4.91 | .50 | 5.27 | .47 | 6.72 | .42 | 3.94 | 3,160 | 5.55 |
| .1 | 39.4 | 6.38 | .68 | 7.33 | .62 | 7.75 | .60 | 9.46 | .55 | 3.25 | 2,590 | 5.59 |
| Mill Creek through Shelton Ditch. River miles indicated are measured from mouth of Ditch at Pringle Creek. Injection of 0.350 liters of 20-percent dye solution at 0955 hours on July 28, 1992, in Mill Creek, 1.7 miles upstream of diversion at Shelton Ditch. Upstream end of Shelton Ditch 2.2 miles above mouth of Ditch, and at Mill Creek river mile 3.3. Discharge at index location: 52.4 cubic feet per second | | | | | | | | | | | | |
| 1.2 | 52.4 | 2.47 | .82 | 2.93 | .70 | 3.11 | .67 | 3.99 | .55 | 6.34 | 5,600 | 5.04 |
| .1 | 52.4 | 3.67 | .92 | 4.16 | .89 | 4.45 | .82 | 5.50 | .73 | 5.80 | 4,400 | 5.86 |
| Mill Creek through Mill Ditch. River miles indicated are measured from mouth of Ditch into Pringle Creek. Injection of 0.350 liters of 20-percent dye solution at 0955 hours on July 28, 1992, in Mill Creek, 2.9 miles upstream of diversion at Mill Ditch. Upstream end of Mill Ditch 1.2 mi above mouth of ditch, and at Mill Creek river mile 2.1. Discharge at index location: 35.7 cubic feet per second | | | | | | | | | | | | |
| .0 | 35.7 | 4.88 | .73 | 5.66 | .72 | 5.86 | .73 | 7.31 | .68 | 4.63 | 3,630 | 5.68 |
| Injection of 0.350 liters of 20-percent dye solution at 0705 hours on August 13, 1993, at river mile 5.0. Discharge at index location: 59.4 cubic feet per second | | | | | | | | | | | | |
| 3.3 | 133 | 1.22 | 1.39 | 1.42 | 1.20 | 1.53 | 1.11 | 1.95 | .87 | 11.97 | 11,600 | 4.59 |
| 2.1 | 72.0 | 2.87 | .73 | 3.50 | .58 | 3.67 | .56 | 4.64 | .45 | 5.20 | 4,650 | 4.98 |
| 1.6 | 54.0 | 3.60 | .68 | 4.27 | .65 | 4.50 | .60 | 5.57 | .54 | 4.22 | 3,950 | 4.76 |
| .1 | 59.4 | 5.50 | .79 | 6.34 | .76 | 6.58 | .72 | 7.83 | .66 | 3.43 | 3,380 | 4.52 |

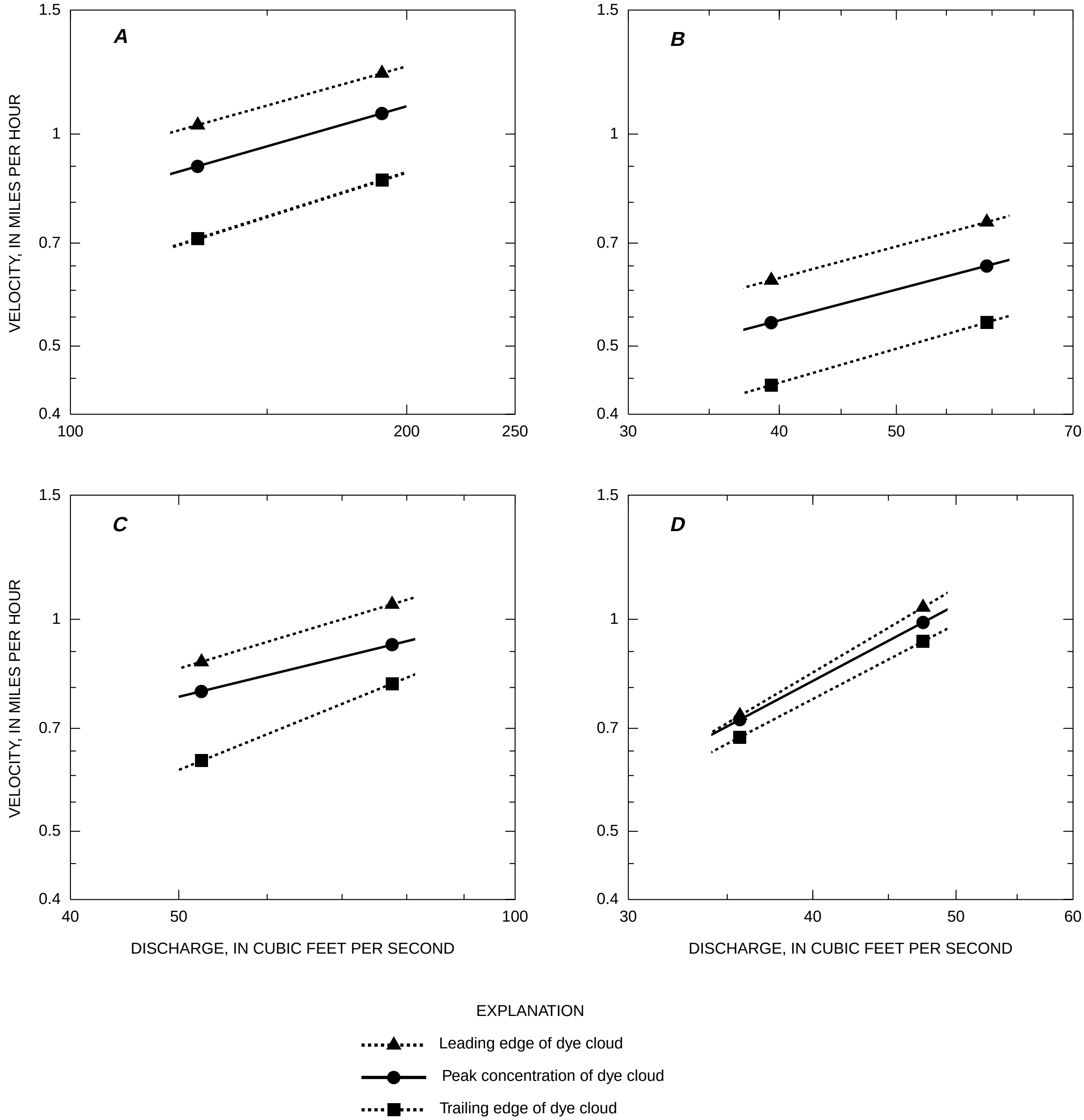


**Figure 17.** Relation of velocity of (A) Mill Creek from Stayton to river mile 3.3 to discharge at Mill Creek at Penitentiary Annex near Salem (14191500) stream-gaging station, (B) Mill Creek from river mile 3.3 to river mile 0.1 to discharge at Mill Creek at river mile 0.1, (C) Shelton Ditch to discharge at the mouth of Shelton Ditch, and (D) Mill Ditch to discharge at the mouth of Mill Ditch.

**Table 10**. Time-of-travel and dispersion data for reaches studied in Johnson Creek

[Index location is station 14211500, Johnson Creek at Sycamore, at river mile 10.2]

| Sampling location | | Travel time and velocity: Leading edge | | Peak | | Centroid | | Trailing edge | | Dye curve characteristics | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance from mouth (mile) | Discharge (cubic feet per second) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Time (hours) | Velocity (miles per hour) | Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
| Injection of 0.100 liters of 20-percent dye solution at 0815 hours on April 28, 1992, at river mile 10.2 Discharge at index location: 14 cubic feet per second; corresponding flow-duration frequency: 50 percent | | | | | | | | | | | | |
| 9.2 | 14.8 | 2.88 | 0.35 | 3.42 | 0.29 | 3.67 | 0.27 | 4.66 | 0.21 | 14.79 | 4,500 | 14.64 |
| 8.8 | 15.7 | 4.55 | .24 | 5.33 | .21 | 5.69 | .20 | 7.00 | .17 | 10.32 | 3,250 | 14.10 |
| 7.3 | 16.5 | 9.73 | .29 | 11.08 | .26 | 11.45 | .26 | 13.49 | .23 | 5.59 | 2,200 | 11.33 |
| 6.1 | 16.5 | 12.54 | .43 | 14.08 | .40 | 14.43 | .40 | 16.79 | .36 | 4.80 | 1,940 | 11.01 |
| Injection of 0.180 liters of 20-percent dye solution at 0935 hours on April 15, 1992, at river mile 6.1 Discharge at index location: 16 cubic feet per second; corresponding flow-duration frequency: 50 percent | | | | | | | | | | | | |
| 4.0 | 18.4 | 2.97 | .71 | 3.50 | .60 | 3.71 | .57 | 4.66 | .45 | 23.96 | 4,840 | 22.03 |
| 2.8 | 22.0 | 4.99 | .59 | 5.67 | .55 | 5.96 | .53 | 7.21 | .47 | 16.11 | 3,750 | 19.09 |
| 2.2 | 22.5 | 6.72 | .35 | 7.67 | .30 | 8.03 | .29 | 9.40 | .27 | 12.57 | 2,980 | 18.76 |
| Injection of 0.100 liters of 20-percent dye solution at 0850 hours on April 15, 1992, at river mile 2.2 Discharge at index location: 16 cubic feet per second; corresponding flow-duration frequency: 50 percent | | | | | | | | | | | | |
| 1.2 | 22.5 | 1.12 | .89 | 1.42 | .70 | 1.58 | .63 | 2.12 | .47 | 15.54 | 7,950 | 8.70 |
| .1 | 39.0 | 2.35 | .89 | 2.75 | .83 | 2.94 | .81 | 3.64 | .72 | 7.27 | 6,070 | 5.34 |
| Injection of 0.25 liters of 20-percent dye solution at 0825 hours on March 25, 1993, at river mile 10.2 Discharge at index location: 105 cubic feet per second; corresponding flow-duration frequency: 15 percent | | | | | | | | | | | | |
| 8.8 | 110 | 1.28 | 1.09 | 1.48 | .95 | 1.53 | .92 | 1.86 | .75 | 13.99 | 14,100 | 4.40 |
| 7.3 | 124 | 2.82 | .97 | 3.16 | .89 | 3.22 | .89 | 3.74 | .80 | 8.15 | 8,270 | 4.38 |
| 6.1 | 124 | 3.68 | 1.40 | 4.12 | 1.25 | 4.21 | 1.22 | 4.87 | 1.06 | 6.23 | 6,560 | 4.22 |
| Injection of 0.50 liters of 20-percent dye solution at 0850 hours on March 24, 1993, at river mile 6.1 Discharge at index location: 190 cubic feet per second; corresponding flow-duration frequency: 8 percent | | | | | | | | | | | | |
| 4.0 | 230 | .71 | 2.96 | .87 | 2.41 | .92 | 2.28 | 1.16 | 1.81 | 21.40 | 19,000 | 5.02 |
| 2.8 | 220 | 1.31 | 2.00 | 1.49 | 1.94 | 1.54 | 1.94 | 1.83 | 1.79 | 16.29 | 15,100 | 4.79 |
| 2.2 | 200 | 1.76 | 1.33 | 2.00 | 1.18 | 2.05 | 1.18 | 2.41 | 1.03 | 12.81 | 12,500 | 4.58 |
| 1.2 | 170 | 2.19 | 2.33 | 2.44 | 2.27 | 2.51 | 2.17 | 2.92 | 1.96 | 11.64 | 11,300 | 4.59 |
| 0.1 | 180 | 2.62 | 2.56 | 2.90 | 2.39 | 2.98 | 2.34 | 3.41 | 2.24 | 9.88 | 10,000 | 4.38 |

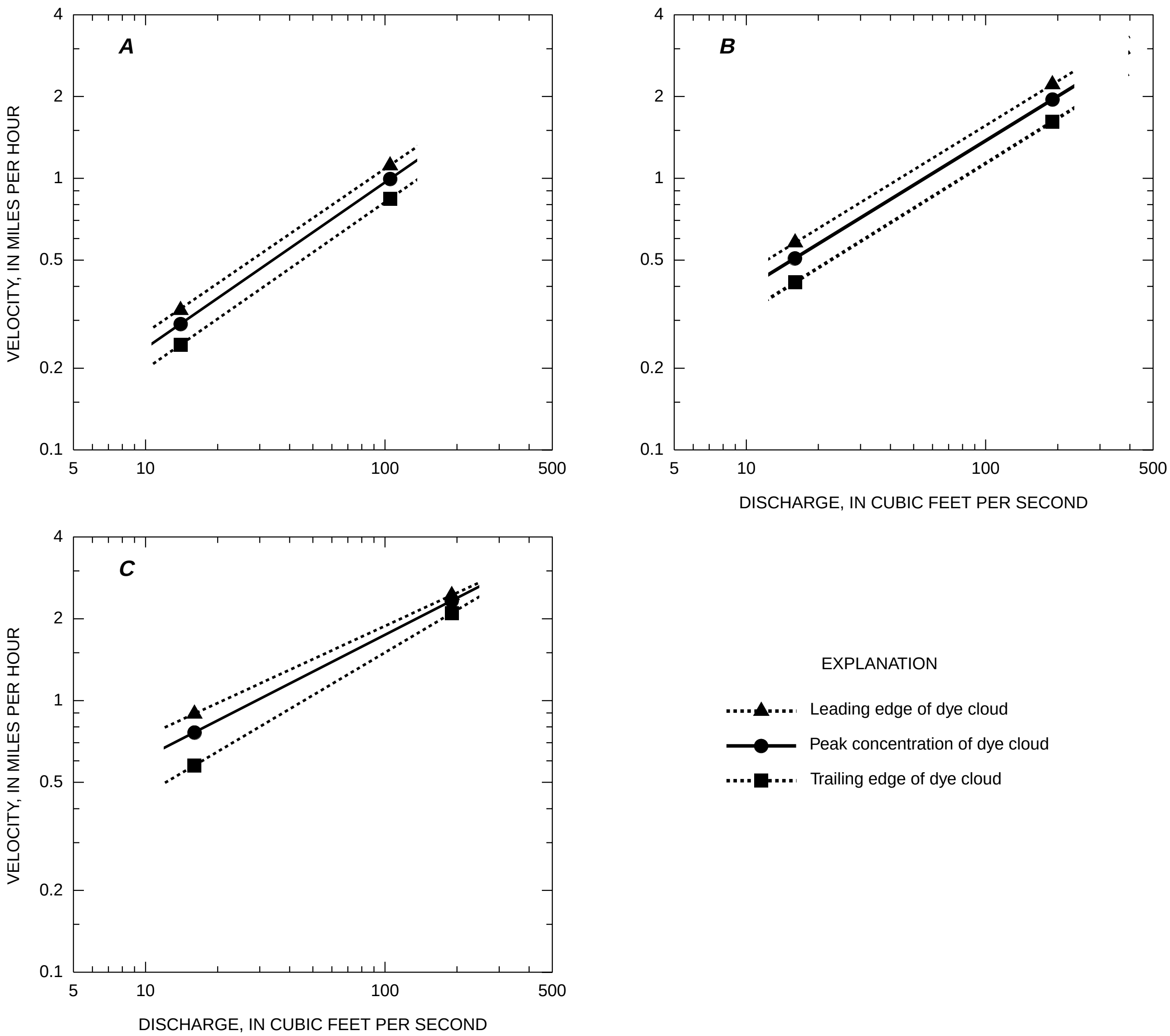


**Figure 18.** Relation of velocity to discharge of Johnson Creek from (A) river mile 10.2 to river mile 6.1, (B) river mile 6.1 to river mile 2.2, and (C) river mile 2.2 to river mile 0.1 to discharge at Johnson Creek at Sycamore (stream-gaging station 14211500).

**Table 11.** Time-of-travel and dispersion data for reaches studied in Amazon Creek

[Index location is station 14169300, Amazon Creek at Eugene, at river mile 21.7.]

| Sampling location: Distance from mouth (mile) | Sampling location: Discharge (cubic feet per second) | Travel time and velocity: Leading edge: Time (hours) | Leading edge: Velocity (miles per hour) | Peak: Time (hours) | Peak: Velocity (miles per hour) | Centroid: Time (hours) | Centroid: Velocity (miles per hour) | Trailing edge: Time (hours) | Trailing edge: Velocity (miles per hour) | Dye curve characteristics: Peak concentration (micrograms per liter) | Unit-peak concentration (micrograms per liter per pound times cubic foot per second) | Area under curve (micrograms per liter times hours) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Injection of 0.060 liters of 20-percent dye solution at 0915 hours on April 21, 1992, at river mile 15.6. Discharge at index location: 1.04 cubic feet per second; corresponding flow-duration frequency: 48 percent | | | | | | | | | | | | |
| 15.0 | 7.61 | 0.92 | 0.65 | 1.33 | 0.45 | 1.66 | 0.36 | 2.52 | 0.24 | 20.96 | 5,420 | 17.22 |
| 14.3 | 10.4 | 4.26 | .21 | 5.08 | .19 | 5.82 | .17 | 7.89 | .13 | 6.03 | 2,310 | 11.63 |
| Injection of 0.020 liters of 20-percent dye solution at 1640 hours on April 20, 1992, at river mile 13.4. Discharge at index location: 1.04 cubic feet per second; corresponding flow-duration frequency: 48 percent | | | | | | | | | | | | |
| 12.8 | 3.10 | 1.97 | .30 | 2.58 | .23 | 3.15 | .19 | 4.88 | .12 | 7.22 | 3,230 | 9.95 |
| Diverted Amazon Creek Channel. River mile indicated measured from the outflow of the Channel at Fern Ridge Lake. Injection of 0.080 liters of 20-percent dye solution at 1620 hours on April 20, 1992, at river mile 3.5. Discharge at index location: 1.04 cubic feet per second; corresponding flow-duration frequency: 48 percent | | | | | | | | | | | | |
| 2.4 | 11.9 | 6.04 | .18 | 7.34 | .15 | 8.65 | .13 | 13.19 | .08 | 3.95 | 1,530 | 11.53 |
| Injection of 0.020 liters of 20-percent dye solution at 1525 hours on May 20, 1992, at river mile 21.7. Discharge at index location: 0.51 cubic feet per second; corresponding flow-duration frequency: 56 percent | | | | | | | | | | | | |
| 20.9 | 1.10 | 4.39 | .18 | 5.48 | .15 | 5.99 | .13 | 8.10 | .10 | 25.47 | 2,370 | 47.86 |
| 20.1 | 1.68 | 12.63 | .10 | 16.10 | .08 | 17.10 | .07 | 23.40 | .05 | 3.01 | 762 | 17.57 |
| Injection of 0.030 liters of 20-percent dye solution at 1200 hours on May 20, 1992, at river mile 20.1. Discharge at index location: 0.51 cubic feet per second; corresponding flow-duration frequency: 56 percent | | | | | | | | | | | | |
| 19.0 | 1.86 | 5.24 | .21 | 5.83 | .19 | 6.45 | .17 | 8.53 | .13 | 15.67 | 2,610 | 26.75 |
| 16.9 | 2.22 | 21.75 | .13 | 26.50 | .10 | 29.12 | .09 | 39.50 | .07 | 2.36 | 493 | 21.27 |
| Injection of 0.100 liters of 20-percent dye solution at 0940 hours on April 29, 1993, at river mile 21.7. Discharge at index location: 4.85 cubic feet per second; corresponding flow-duration frequency: 23 percent | | | | | | | | | | | | |
| 20.9 | 8.12 | 1.40 | .57 | 1.70 | .47 | 1.81 | .44 | 2.33 | .34 | 62.9 | 8,840 | 31.68 |
| 20.1 | 11.4 | 3.61 | .36 | 4.33 | .30 | 4.63 | .28 | 5.86 | .23 | 17.31 | 3,780 | 20.40 |
| 19.0 | 10.6 | 5.67 | .53 | 6.50 | .51 | 6.83 | .50 | 8.45 | .42 | 13.20 | 3,250 | 18.10 |
| Injection of 0.120 liters of 20-percent dye solution at 0845 hours on April 28, 1993, at river mile 16.9. Discharge at index location: 3.50 cubic feet per second; corresponding flow-duration frequency: 28 percent | | | | | | | | | | | | |
| 15.6 | 8.44 | 2.81 | .46 | 3.30 | .40 | 3.46 | .38 | 4.25 | .31 | 34.1 | 5,560 | 27.37 |
| 14.3 | 13.0 | 6.54 | .35 | 7.55 | .31 | 7.97 | .29 | 10.06 | .22 | 9.40 | 2,440 | 17.12 |
| 13.4 | 15.0 | 12.78 | .14 | 13.75 | .14 | 14.52 | .14 | 16.42 | .14 | 2.25 | 2,230 | 4.50 |

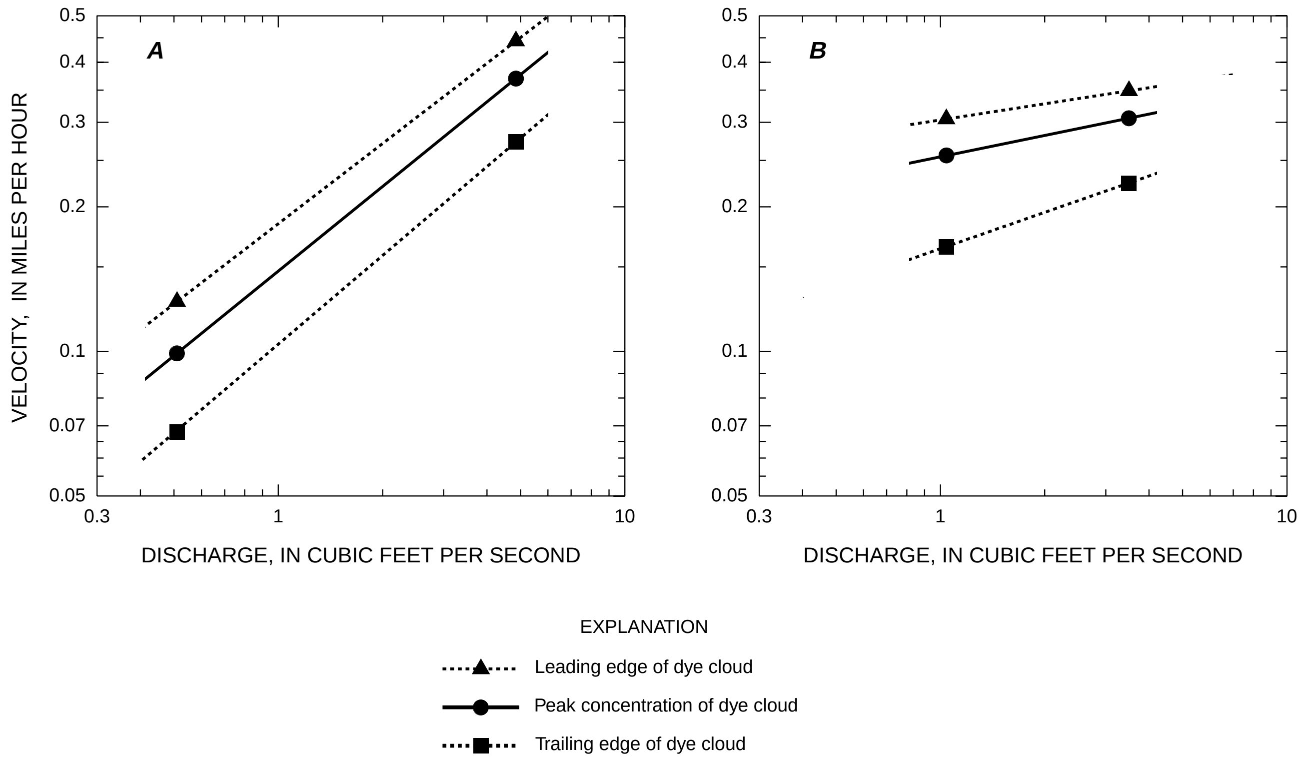


**Figure 19.** Relation of velocity of Amazon Creek from (A) river mile 21.7 to river mile 20.1, and (B) river 15.6 to river mile 14.3 to discharge at the Amazon Creek at Eugene (stream-gaging station 14169300).

$W_r$ is the weight in pounds of dye recovered,
$Q$ is the discharge in cubic feet per second at the cross section,

$A_c$ is the area under the time-concentration curve, in micrograms per liter times hours. The area under the time-concentration curve is calculated by multiplying the concentration of each sample by the time interval for each sample, and summing the subareas.

(2) The recovery ratio is calculated by dividing the weight of dye recovered by the weight of dye injected.

(3) The peak concentration is divided by the recovery ratio; the resulting value represents the peak concentration obtainable, had no dye losses occurred.

(4) The unit-peak concentration is determined using the formula,

$$C_{up} = \frac{QC_{pk}R_r}{W_t} \qquad (3)$$

where
$C_{up}$ is the unit-peak concentration, in micrograms per liter per pound times cubic feet per second [(µg/L)/lb](ft³/s),

$C_{pk}$ is the observed peak concentration, in micrograms per liter (µg/L)
$R_r$ is the recovery ratio, and
$W_t$ is the weight, in pounds of dye injected.

A graph showing the relation of unit-peak concentration to elapsed time to the peak was prepared for each stream. A simple linear-regression technique was applied, using the logarithm of cumulative peak travel time as the independent variable and the logarithm of unit-peak concentration as the dependent variable. For example, the graph showing the relation of unit-peak concentration to elapsed time to the peak for the Clackamas River is shown in figure 20.

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The general form of the equation is:

$$C_{up} = aT^b \qquad (4)$$

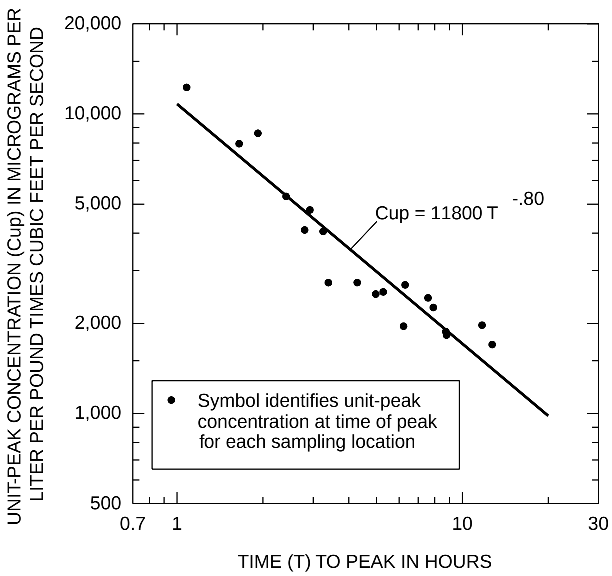


**Figure 20.** Relation of unit-peak concentration of dye to time to peak for the Clackamas River from river mile 22.8 to river mile 0.5.

where

*a* is the unit-peak concentration at an elapsed time of 1 hour,

*T* is the time in hours since injection, and

*b* is the slope of the regression line.

The efficiency of stream dispersal of a solute is defined by the rate of change in the unit-peak concentration with respect to elapsed time (Kilpatrick and Taylor, 1986). When logarithms of the unit-peak concentration and elapsed time to peak are plotted, the slope of the regression line is the indicator of efficiency.

## Results

Streams measured during this study varied in their capacity to disperse a solute, depending on channel characteristics. In a pool-and-riffle channel, pools and eddies serve as retention and mixing areas for a solute cloud and cause a more rapid attenuation of the peak concentration than a stream that flows in a more uniform channel-controlled condition. In a stream that has little variation in velocity, such as in a canal, the solute cloud travels in a compact form. The timespan from the passage of the leading edge to the trailing edge of the dye cloud in a canal will be shorter than for the pool-and-riffle regime, and the peak concentration of the dye cloud will be higher. A meandering stream reach will exhibit a more rapid dispersion of a solute than a straight stream reach, because the velocity across the channel is more varied in the meandering stream and enhances mixing.

Dispersion characteristics also were affected by discharge and are due to variation in channel characteristics and velocities at high and low streamflow. The Molalla River, Calapooia River, Johnson Creek, and Amazon Creek were measured at two significantly different flow-duration frequencies (table 12). Except for Johnson Creek, the slope of the unit-peak concentration curve was greater for the higher flow-duration measurements. The greater slope of the unit-peak concentration curve is attributed to enhanced mixing and retention of dye in the pools and riffles that are more prevalent at lower discharges. As an example, dispersion characteristics for the Calapooia River are shown in figure 21. Data for Johnson Creek indicated a comparable slope for the unit-peak concentration curve for the higher and lower discharge studies; the similarity is attributed to comparable flow conditions over the range of flow-duration frequencies studied. For the streams studied at two significantly different flow-duration frequencies, the intercept (unit-peak concentration at 1-hour elapsed time) of the higher flow-duration frequency measurement was lower. The lower intercept value is attributable to the lower velocity that occurs at lower discharges. Based on flow-duration frequency, trend in the slope or intercept value of the unit-peak concentration curve for the Clackamas River and Mill Creek was not evident. This lack of trend is attributable to similar channel characteristics over the range of discharge studied for the Clackamas River and Mill Creek. Data for the South Yamhill and Yamhill Rivers were combined because a relatively small number of data points were available for each stream. Dispersion was measured at only one discharge in the Willamette, Pudding, and Tualatin Rivers.

The slope of the unit-peak concentration curve ranged from -0.64 (for the average of the two measurements at Johnson Creek) to -0.82 (for the average of the Molalla River measurements). Johnson Creek is an urban stream with a steep gradient and long riffle and run segments. The stream is channelized and straightened. This configuration causes water to flow with a fairly uniform velocity longitudinally and across the channel, resulting in less dispersion than in a more natural, meandering stream. The Molalla River is characterized by a pool-and-riffle channel condition and a meandering, braided channel that results in greater dispersion efficiency.

The intercept value of the unit-peak concentration curve ranged from 7,930 to 18,700 [(µg/L)/lb](ft$^3$/s) for the measured streams (table 12). Data analyzed by Kilpatrick and Taylor (1986) for streams nationwide (fig. 22) indicated a range in the intercept value of 5,000 to 26,000 [(µg/L)/lb](ft$^3$/s). The intercept value is affected by stream gradient and velocity; the steeper, higher velocity streams have intercept values greater than the sluggish, slow-moving streams (Kilpatrick and Taylor, 1986). The intercept values for the streams measured in this study followed this generalization, with the exception of the Tualatin River. The intercept value for the Tualatin River was closer to that of streams with higher gradients.

The unit-peak concentration curve for the Clackamas River shown in figure 20 can be used as an example of the application of such curves. The unit-peak concentration is 3,260 [(µg/L)/lb](ft$^3$/s) at 5 hours after injection of the dye. If 200 lbs of solute is injected into this stream at a discharge of 1,000 ft$^3$/s, the expected concentration 5 hours later would be 652 µg/L, providing the solute is fully conserved and is vertically and laterally mixed in the stream.

The dispersion results for all the streams were aggregated and compared with previous national studies (fig. 22). The unit-peak-concentration data for the streams measured in this study resulted in an equation of:

$$C_{up} = 12,100 \times T^{-0.79} \qquad (5)$$

The standard error of estimate is 0.14 log units, corresponding to -28 to +38 percent. This result was compared to a study by Graf (1986) of several streams in Illinois. For the Illinois study, the equation for unit-peak concentration for all the streams measured that had flow duration frequency greater than 60 percent was:

$$C_{up} = 5,680 \mathbf{x} T^{-0.63} \qquad (6)$$

When compared with the study by Kilpatrick and Taylor (1986), the unit-peak-concentration curve for all the streams measured in this study was below the curve of maximum probable concentration of:

$$C_{up} = 26,000 \mathrm{x} T^{-0.6} \qquad (7)$$

Variability in channel characteristics, such as pool-and-riffle makeup and meandering, affect the dispersive characteristics of a stream reach. Channel characteristics change within a given stream reach and are affected by discharge; as a consequence, these variables are not measured easily or quantified using existing map or field data. Accurate dispersion values should be determined by time-of-travel measurements whenever possible.

## SUMMARY AND CONCLUSIONS

Dye-tracer techniques were used to determine time-of-travel and dispersion characteristics on the Willamette River and its tributaries during low-to-medium streamflow conditions.

The relations between the velocity of the dye cloud and the discharge at an index location were developed for subreaches of the stream reaches studied. The relation of velocity of the peak and leading and trailing edge of the dye cloud to discharge at the index location for the Clackamas River, Molalla River, Calapooia River, South Yamhill River, Yamhill River, Mill Creek, Johnson Creek, and Amazon Creek are shown in this report. A straight-line relation is shown to exist between discharge at the index location and dye-cloud velocity when the variables are plotted logarithmically.

**Table 12.** Summary of dispersion equations for estimating unit-peak concentration of dye and associated standard error of estimates

[ $C_{up} = aT^b$

where

$C_{up}$ is the unit-peak concentration, in units of micrograms per liter per pound per cubic feet per second [(µg/L)/lb](ft$^3$/s);

a is the unit-peak concentration at 1 hour elapsed time, in [(µg/L)/lb](ft$^3$/s);

*T* is the elapsed time to peak, in hours; and

*b* is the slope of the unit-peak concentration curve]

| Stream | River miles | Flow duration in percent[1] | a | b | Number of samples | Standard error of estimate Log units | Percent | |
|---|---|---|---|---|---|---|---|---|
| Willamette River | 161.2-138.3 | 95 | 9,630 | -0.75 | 7 | 0.07 | +18 | -15 |
| Clackamas River | 22.8-0.5 | 68-98 | 10,800 | -.80 | 19 | .08 | +20 | -17 |
| Molalla River | 18.6-1.7 | 81-96 | 10,200 | -.90 | 12 | .08 | +20 | -17 |
| | 18.6-1.7 | 12-13 | 13,300 | -.75 | 8 | .04 | +10 | - 8.8 |
| Calapooia River | 45.4-23.7 | 86 | 8,020 | -.74 | 9 | .08 | +20 | -17 |
| | 45.4-23.7, 19.5-3.0 | 38-46 | 11,500 | -.62 | 15 | .06 | +15 | -13 |
| Tualatin River | 53.8-26.9 | | 11,600 | -.75 | 7 | .11 | +29 | -22 |
| South Yamhill River and Yamhill River | 16.7-11.3,7.2-1.2 8.2-1.3 | 65-75 30-67 | 8,200 | -.72 | 23 | .10 | +26 | -21 |
| Pudding River | | 65 | 15,200 | -.74 | 12 | .05 | +11 | -11 |
| Mill Creek | Salem ditch at Stayton to 11.2 | --[2] | 16,500 | -.73 | 8 | .02 | + 4.7 | - 4.5 |
| | 9.5-0.1 | -- | 11,800 | -.76 | 14 | .05 | +11 | -11 |
| | Shelton Ditch and Mill Ditch | -- | 12,300 | -.69 | 6 | .03 | + 7.2 | - 6.7 |
| Johnson Creek | 10.2-0.1 | 50 | 10,400 | -.63 | 9 | .03 | + 7.2 | - 6.7 |
| | 10.2-0.1 | 8-15 | 18,700 | -.66 | 8 | .04 | +10 | - 8.8 |
| Amazon Creek | 21.7-12.8, including diverted Amazon Creek channel | 48-56 | 7,930 | -.81 | 8 | .08 | +20 | -17 |
| | 21.7-13.4 | 23-28 | 12,000 | -.70 | 6 | .06 | +15 | -13 |
| All streams | | | 12,100 | -.79 | 171 | .14 | +38 | -28 |

[1] Flow duration is the percentage of time in a year when the discharge was equaled or exceeded.
[2] Flow duration not shown because of interbasin transfer.

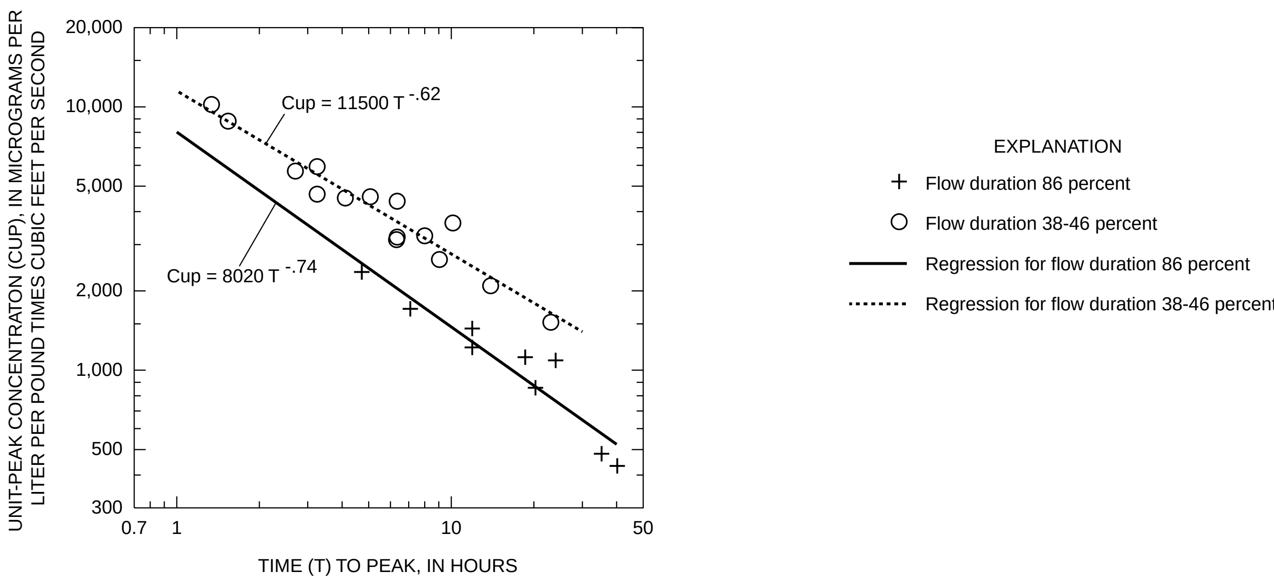


**Figure 21.** Relation of unit-peak concentration of dye to time to peak for the Calapooia River. (Flow duration for index location is the Calapooia River at Holley [stream-gaging station 14172000]).

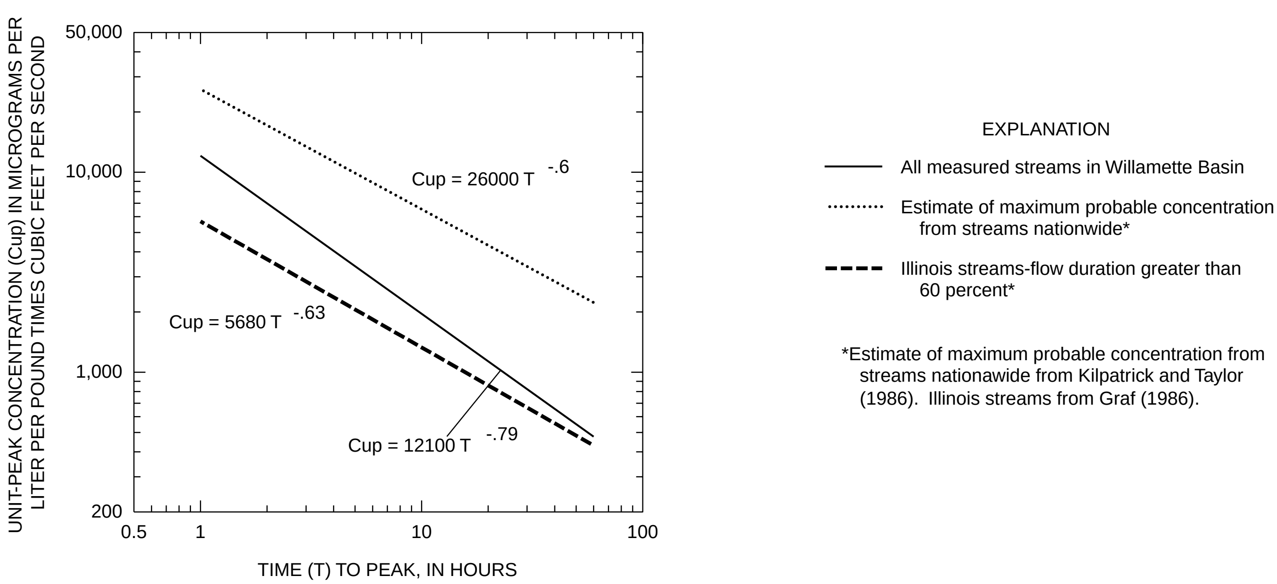


**Figure 22.** Comparison of relation of unit-peak concentration of dye to time to peak for Willamette River Basin streams and other streams.

For the Willamette River, the velocity of the leading edge and peak of the dye cloud was compared with those from a previous study. This comparison indicated that virtually no change in velocity at a given discharge had occurred since 1968.

For the Tualatin River, only the velocity of the peak of the dye cloud was related to discharge at the index location. For the Pudding River, time of travel was measured at only one discharge.

Estimates of travel time of the peak for unmeasured streams (using the relation based on stream discharge and channel slope) are of limited value, because the estimates are only approximately 40-percent accurate. Other factors affect the velocity, including channel shape and pool and riffle depths and lengths, but these parameters are not easily measured or estimated.

For this study, the dispersion results were adjusted to represent the dispersion of a fully conserved solute. Therefore, for a solute that is not fully conserved, losses of the solute incurred through decay or absorption will decrease the peak concentration to less than the concentration estimated from the graphs and equations of this report.

Unit-peak concentration values after 1-hour of elapsed time ranged from 7,930 to 18,700 [(µg/L)/lb](ft$^3$/s) for the measured streams. The slope of the unit-peak concentration curve ranges from -0.64 to -0.82, indicating the relative dispersion efficiency of each stream.

Estimates of dispersion characteristics for stream reaches other than those measured, based solely on similarities of channel and streamflow characteristics, may be unreliable. Estimates of dispersion using a general relation, based on elapsed time, are of limited value because of inexact estimates. Measurements using dye-tracer techniques are advisable to produce reliable dispersion results. In this study, the rate of dispersion appeared to be affected by channel characteristics and streamflow magnitude. Measurements indicated that streams flowing in a pool-and-riffle channel generally had a greater dye-dispersal capacity than streams with more uniform characteristics. The intercept value of the unit-peak-concentration curve also appeared to be affected by physical characteristics of the stream. Variations occurred, however, between streams of apparently similar characteristics.

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