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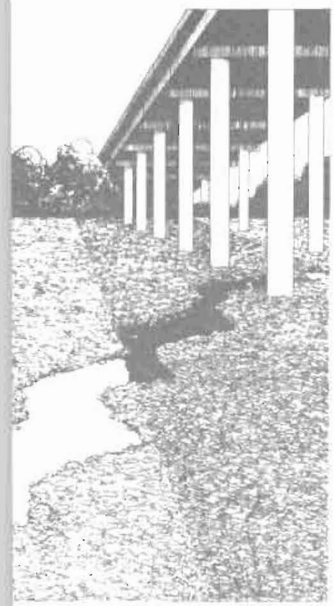

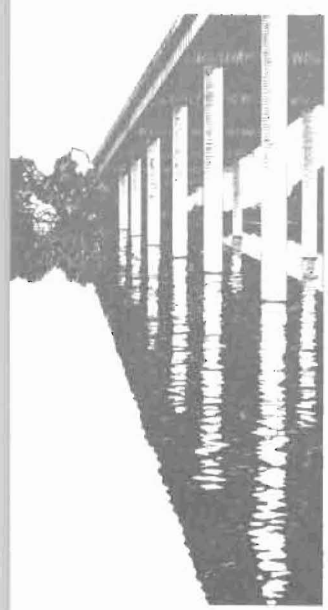

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# CHARACTERIZATION OF WATER MOVEMENT IN SUBMERSED PLANT STANDS

by

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Hydrodynamic processes can reduce the efficacy of chemicals used to control submersed plants by affecting herbicide concentrations, exposure times, and area of containment. Information on water movement within submersed plant stands can be used to develop and evaluate application techniques that maximize herbicide contact time in environments with high water exchange.

The objective of this study was to characterize water movement in a variety of submersed plant stands growing in rivers and flowing-water canals. Flow velocities were measured in and around stands of *Vallisneria americana*, *Potamogeton pectinatus*, and *Heteranthera dubia* in the Holston River, Tennessee, and in stands of *Myriophyllum spicatum*, *P. pectinatus*, *Ceratophyllum demersum*, and *Elodea canadensis* in irrigation canals of central California using electromagnetic velocity meters. Water exchange

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19. ABSTRACT (Continued).

patterns were determined in stands dominated by *M. spicatum* in the Pend Oreille River, Washington, and in stands of *Hydrilla verticillata* in the Withlacoochee River, Florida, using the tracer dye rhodamine WT.

Flow velocities were low (<1 cm/sec) and relatively constant within all of the submersed plant stands, as compared to regions in the water column above, or adjacent to, the stands (15 to 35 cm/sec). Velocities were dampened least in *P. pectinatus*. Half-lives of dye in Pend Oreille River *M. spicatum* stands ranged from 0.3 to 16 hr, and in *H. verticillata* stands in the Withlacoochee River, ranged from 3.7 to 11.4 hr.

Rhodamine WT is an effective tool in measuring water exchange in dense stands of submersed macrophytes. In addition, this dye can be particularly useful in determining potential vertical mixing of herbicides within the plant stands.

# Preface

This study was sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), through the Aquatic Plant Control Research Program (APCRP). Funds were provided under Department of the Army Appropriation No. 96X3122, Construction General. Technical Monitor for the HQUSACE was Mr. James W. Wolcott. The APCRP is managed by the US Army Engineer Waterways Experiment Station (WES) under the Environmental Resources Research and Assistance Programs, Mr. J. Lewis Decell, Manager.

The principal investigator for this study was Dr. Howard E. Westerdahl, Aquatic Processes and Effects Group (APEG), Environmental Research and Simulation Division (ERSD), Environmental Laboratory (EL), WES. The study was conducted and the report prepared by Dr. Westerdahl, Dr. Kurt D. Getsinger, and Mr. W. Reed Green, APEG. Reviews of this report were provided by Ms. Linda S. Nelson, APEG; Mr. Michael D. Netherland, Purdue University; Mr. Kevin Kretsch, Lake Restoration, Inc.; and Dr. Alison M. Fox, University of Florida. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

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The sections of the report concerning the Withlacoochee River were prepared by Drs. Fox and William T. Haller, Center for Aquatic Plants, University of Florida.

This investigation was performed under the general supervision of Dr. John Harrison, Chief, EL; Mr. Donald L. Robey, Chief, ERSD; and Dr. Thomas L. Hart, Chief, APEG.

Commander and Director of the WES was COL Larry B. Fulton, EN. Technical Director was Dr. Robert W. Whalin.

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## Contents

## Conversion Factors, Non-SI to SI (Metric) Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

| Multiply | By | To Obtain |
|---|---|---|
| gallons (US liquid) | 3.785412 | cubic decimetres |
| horsepower (550 foot-pounds (force) per second) | 745.6999 | watts |
| pounds (force) per square inch | 6.89457 | kilopascals |

# CHARACTERIZATION OF WATER MOVEMENT IN SUBMERSED PLANT STANDS

## Introduction

1. Although submersed plants are effectively controlled with herbicides in static water, satisfactory control in environments with significant water movement or exchange (e.g., rivers, streams, canals, large reservoirs, and tidal areas) has been inconsistent (Barrett 1981, Anderson and Dechoretz 1982, Barrett and Murphy 1982, and others). Recent studies suggest that herbicide concentration/exposure time is a critical factor for successfully controlling submersed plants (Westerdahl and Hall 1983, Green and Westerdahl 1988, Van and Conant 1988). Few, if any, conventional herbicide application techniques provide the necessary concentration and/or exposure time required for controlling these plants in high water exchange environments.

2. Hydrodynamic processes, such as water flow, wind mixing, and thermal density gradients, are presumably responsible for inconsistent efficacy following herbicide applications in reservoirs and rivers. The occurrence of these processes can influence herbicide concentrations, exposure times, and area of contaminant.

3. Although water flow and wind mixing would seem to be the most influential parameters affecting herbicide dilution and dispersion, thermal stratification may also be important, particularly in systems where flow velocities are low (Fox et al., in preparation). Dense stands of submersed macrophytes at, or near, the surface can augment the formation of a very warm layer of surface water and much cooler layers of water beneath the plant canopy (Getsinger 1982; Bowmer, Mitchell, and Short 1984; Kunii 1984; Tobiessen and Snow 1984; and others). Thermal stratification can create a physical barrier that may prohibit surface-applied herbicides from mixing below the thermocline.*,**

4. As part of an ongoing project to improve the control of submersed plants in flowing-water systems, studies were conducted to characterize water

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* K. D. Getsinger and W. R. Green. 1989. Unpublished data, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

** Personal Communication, 1989, W. T. Haller, Center for Aquatic Plants, University of Florida, Gainesville, FL.

movement in submersed plant stands growing in high water exchange environments. The objective of these studies was to develop an understanding of water movement in a variety of submersed plant stands in rivers and canals. Once water exchange patterns are characterized, this information (along with herbicide concentration/exposure time data) can be used to develop and evaluate application techniques that maximize herbicide contact time in flowing-water environments.

## Materials and Methods

### Flow meter studies

5. Flow velocities were measured in plant stands in the Holston River near Kingsport, TN (June 1986), and in irrigation and drainage canals of the Sacramento Valley, California (September 1987). Measurements were taken at 0.5-m intervals along transects (longitudinal and cross-sectional) in submersed plant stands using a Montedoro Whitney Model PVM-2A portable velocity monitor (±2 percent accuracy) fitted with an electromagnetic sensor. The velocity sensor was attached to a wading rod (hand-held in place on the bottom) and was aligned parallel to the direction of flow, and perpendicular to the surface of the water. The rod was held at arm's length from the wader to minimize any interference with flow. Velocities were measured, in duplicate, on the time average mode (10-sec interval) at 12-cm increments, from 1 cm below the surface to the bottom.

6. Plant stands in the Holston River were 0.5 to 1.5 ha (5,000 to 15,000 $m^2$) in size, 75 to 85 cm in height, and consisted of wild celery (*Vallisneria americana* Michx.), sago pondweed (*Potamogeton pectinatus* L.), and water stargrass (*Heteranthera dubia* (Jacquin) MacM.). Flow velocities ranged from 20 to 30 cm/sec upstream from the plants. Plant stands in the California canals ranged from 100 to 5,000 $m^2$ in size, 70 to 115 cm in height, and consisted of sago pondweed in the Weyland Lateral Canal and Eurasian watermilfoil (*Myriophyllum spicatum* L.), coontail (*Ceratophyllum demersum* L.), and elodea (*Elodea canadensis* Rich.) in the Biggs Extension Canal. Flow velocities were 15 to 20 cm/sec upstream from the plants.

7. Flow velocity data were analyzed, and contour graphs were produced with the regional variable theory technique called kriging (Delhomme 1978, Robertson 1987) using SURFER (Golden Software, Inc. 1987). The percentage of

the vertical profile of a plant stand within a velocity zone was determined by calculating the area beneath a velocity zone isobar.

8. The effectiveness of using a flow meter was reduced under some field conditions. For instance, water depth >1.5 m created problems for maintaining proper orientation of the sensor, with respect to direction of flow. Also, flow velocities within dense plant stands were often below the detection limit of the instrument (<1 cm/sec). The requirement for greater sensitivity in characterizing water movement in submersed plant stands led to the use of the fluorescent dye rhodamine WT in the later phases of the study.

Dye studies

9. Pend Oreille River. A series of 0.5-ha dye treatments were conducted in submersed plant stands in the Pend Oreille River, Washington, in August 1988. These stands were dominated by Eurasian watermilfoil (*M. spicatum*), interspersed with American watermilfoil (*Myriophyllum exalbescens* Fern.) and various species of pondweeds (*Potamogeton* spp.). Plants were at, or just below, the surface in all of the stands.

10. Three sites were selected for comparative purposes and were located near the river towns of Usk, Cusick, and Ione (Figures 1 and 2). The Calispell River (CR) site was located where plants formed a dense shoreline stand (~20 ha) north of the mouth of the Calispell River (mean depth = 2.13 m). The Lost Creek Bay (LCB) site was situated in a plant-infested, 4-ha cove at the mouth of Lost Creek (mean depth = 1.98 m). The third site, river mile 46 (RM 46) contained dense plants that formed an "island" stand (~3 ha) near the center of the river (mean depth = 1.2 m). These sites represented the types of submersed plant stands that might be targeted for chemical control. Discharge rates from Albeni Falls Dam, on the Pend Oreille River upstream from the plots, ranged from 113 to 170 $m^3$/sec during the studies, or some 50 to 60 percent below the August norm.

11. Shoot biomass was determined by placing a 1,685-$cm^2$ circular frame on the bottom at 10 randomly selected locations within each treatment plot, prior to dye application. All plants within each frame were harvested, washed to remove adhering sediment, and dried at 55° C to a constant weight.

12. The inert, fluorescent dye rhodamine WT was specifically developed for water tracing work and has been approved by the US Geological Survey for use in potable water at concentrations up to 10 $\mu g/\ell$. The detection limit of the dye is 0.01 $\mu g/\ell$, making it a suitable tool for use in water movement studies.

13. Rhodamine WT dye was applied to each plot in a manner that simulated an operational, liquid herbicide treatment. The dye was applied at a rate calculated to achieve 10 μg/ℓ in the entire water volume. The dye solution was injected throughout each plot using a 75-ℓ-capacity, electric Spotlyte Sprayer pump (60 psi,* 12 V) attached to a boom system that was mounted on the bow of a small (4.3-m) aluminum boat. The boat was powered by a 10-hp outboard engine. Five weighted drop-hoses, each fitted with a No. 6 straight-stream nozzle tip, were attached to the boom at 60-cm intervals. This system provided a treatment swath of 2.5 m. The tips of the drop-hoses reached a depth of 45 to 75 cm when pushed through the plant stands.

14. For comparative purposes, dye was applied to the Calispell River plot with two application techniques. One application was made with weighted hoses (described above), while the other application was made, several days later, with unweighted drop-hoses. As opposed to the weighted hoses, the tips of the unweighted hoses reached a depth of only 5 to 10 cm below the surface.

15. Dye was measured in situ using a Turner Design 10-005 field fluorometer, fitted with a high-volume continuous cuvette system. Water was pushed through the fluorometer by a 450-gal/hr electric bilge pump, attached to the end of an opaque hose that was lowered over the side of the sampling boat. Since fluorescence varies with temperature (Smart and Laidlaw 1977), an in-line thermistor was used to measure water temperature.

16. Dye was monitored at fixed points (stations) along transects established perpendicular to the direction of upstream flow within each plot. Plot CR contained nine stations; Plot LCB contained five stations; and Plot RM-46 contained two stations (Figure 2). Readings were taken at 50-cm intervals through the water column at each sampling station, from approximately 3 cm below the surface to 20 to 40 cm above the bottom. Initial readings were taken at 0.5 hr following treatment in Plots CR and LCB, and at 2-hr posttreatment intervals thereafter until readings were below detection (<0.01 μg/ℓ). Since dye dispersion was rapid in Plot RM-46, readings were taken at 0.5 hr following treatment and at 0.5-hr posttreatment intervals until readings were below detection.

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 4.

17. Half-lives for the dye were calculated by regressing natural logarithms of the dye concentration (averaged over depth from all sampling stations within each plot) over all sampling times (Fox et al., in preparation). Contour graphs were produced with the aforementioned kriging technique.

18. Withlacoochee River. In March 1988, two square 2-ha plots were treated with rhodamine WT dye in Lake Rousseau on the Withlacoochee River, Florida (Figure 3). Both of these plots were near secondary channels in the lake and were approximately 1 and 2.5 km upstream of the Cross Florida Barge Canal outflow. Both plots contained dense stands of hydrilla (*Hydrilla verticillata* Royle), which had formed a mat at the surface in Plot 1 and was approximately 1 m below the surface in Plot 2.

19. Rhodamine WT was applied at a rate calculated to achieve 10 $\mu g/\ell$ in the entire water volume. The dye solution was mixed with 2 percent Nalquatic polymer and was delivered to the water column using trailing hoses from an airboat. This technique simulated an operational herbicide/polymer application. Dye was measured using a Turner Design fluorometer (previously described). The concentration of dye was measured at 50-cm intervals from the lake bottom to the surface in the center of the plots, on or near the edges of the plots, and at points downstream of the plot over a period of 2 days.

20. Half-lives for the dye were calculated by regressing natural logarithms of the dye concentrations (averaged over depth from certain points in each plot) over several sampling times. Estimates of water velocity were calculated by tracking the maximum dye concentration downstream of the plots.

## Results of Flow Meter Studies

### Holston River

21. *Vallisneria americana* and *Potamogeton pectinatus*. Figure 4 depicts flow velocity patterns (derived from a longitudinal transect) through stands of *V. americana* and *P. pectinatus*. Velocities were noticeably reduced 0.5 m inside the stands, and this reduction in velocity continued throughout the stand. Bruns et al. (1955) reported that plant distribution and density greatly affected the water movement through submersed plant stands, with dense stands causing water to flow over the top of the plants. Similarly, velocities in this study increased in the upper portions of the water column as the water moved up, over, and around the plant stands.

22. The middepth incoming velocity of ~18 cm/sec was reduced to <5 cm/sec in 90 percent of the *V. americana* stand vertical profile, and to <1 cm/sec in 73 percent of the profile (Table 1). In comparison, the center channel incoming velocity of ~30 cm/sec was reduced to <5 cm/sec in 46 percent of the vertical profile in *P. pectinatus*, and to <1 cm/sec in only 8 percent of the profile. Low and fairly constant velocities within the submersed plant stands have also been reported by other investigators (Marshall 1978, Wenninger 1986, Losee and Wetzel 1988).

23. Although different incoming velocities may have accounted for some of the internal flow variation between the two plants stands, plant morphology and plant density undoubtedly contributed to that variation. During velocity measurements, it was observed that the relatively broad, tapelike leaves of *V. americana* overlapped to form a dense wall of plant material, and that only the uppermost and outermost layer of leaves swayed in the current. In contrast, the narrow leaves of *P. pectinatus* allowed more flow to penetrate the plant stand, as noted by the undulation of leaves (and even entire plants), some 25 cm vertically into the stand.

24. Heteranthera dubia. Incoming flow velocities measured at middepth, 50 cm upstream from the leading edge of *H. dubia* stands ranged from 24.3 to 27.6 cm/sec, while velocities of approximately 32 cm/sec were recorded upstream of open-water locations (Figure 5). Middepth velocities through the plant stands were highly reduced compared with incoming velocities (68 to 99 percent lower), and velocities in the dividing channel were increased 8 to 25 percent.

25. The velocity patterns in and around the *H. dubia* stands demonstrate the alteration of flow regimes by submersed plant stands. Water was apparently deflected away from the stands, decreasing the flow within the plants. Flow increased in the dividing channel, as water was funneled around the plant stands. Flow velocities remained fairly constant (~32 cm/sec) in the main river channel, 50 cm away from the stands.

26. Previous studies have shown that submersed plant growth can result in major alterations of water flow. Stephens (1950) showed that the roughness of a channel was increased 17-fold by a stand of southern naiad (*Najas guadalupensis* (Spreng.) Magnus), reducing the design flow rate by 97 percent. Cave (1981) reported that aquatic plant growth can easily increase roughness and significantly impact hydraulic processes in a flowing system. In addition,

channel cross-sectional area can be drastically reduced in systems infested with submersed plants (Stephens et al. 1963).

California irrigation canals

27. No plants and *Potamogeton pectinatus*. Cross-sectional flow velocity patterns in the Weyland Lateral Canal, with and without plants, are shown in Figure 6. Velocities in the unvegetated portion of the canal exhibited a laminarlike pattern, with the highest velocity zone (>13 cm/sec) near the center of the channel. Velocities <1 cm/sec were primarily restricted to the bottom 12 cm of the water column in the channel.

28. In comparison, velocity patterns in the channel where *P. pectinatus* stands existed were irregular, with a high-velocity zone (13 to 17 cm/sec) above the plants and across the width of the channel. Two regions, occurring above and near the outside edge of the plants, contained velocities >17 cm/sec. In addition, the low-velocity zone (<1 cm/sec) was extended toward the surface (~45 cm from the bottom) and accounted for approximately 50 percent of the velocity measured within the plant stand.

29. *Myriophyllum spicatum*, *Ceratophyllum demersum*, and *Elodea canadensis*. Cross-sectional flow velocity patterns in portions of the Biggs Extension Canal, containing stands of *M. spicatum*, *C. demersum*, and *E. canadensis*, are shown in Figure 7. Consistent with patterns measured in the aforementioned plant stands, velocities were greatest at the surface and the surrounding open-water edges of all three stands, and lowest within the stands. These high velocities, above and around the stands, illustrate the necessity of placing herbicides deep within the stands (where velocities are low) to maximize herbicide contact time with the target vegetation.

30. Water velocity zones, expressed as a percentage of the vertical profile within each plant stand, are shown in Table 2. Velocity zones <5 cm/sec ranged from 92 to 100 percent, with *C. demersum* having the highest percentage. Velocity zones <1 cm/sec ranged from 61 to 71 percent, with *E. canadensis* having the highest percentage. Apparently, these three species (as with *V. americana*) can dampen intrastand velocities more effectively than can *P. pectinatus*, again suggesting that plant morphology plays a role in influencing intrastand flow velocities.

## Results of Dye Studies

### Pend Oreille River

31. *Myriophyllum spicatum* biomass. Mean dry weight (±1 standard error) of *M. spicatum* was 457 (±35) $g/m^2$ in Plot CR, 484 (±49) $g/m^2$ in Plot LCB, and 399 (±45) $g/m^2$ in Plot RM-46. These measurements indicated that plant mass in the plots was comparable, especially Plots CR and LCB. Biomass values from this study were within the range of mean *M. spicatum* biomass reported from other studies conducted along the Ione to Calispell stretch of the river (WATER Environmental Services, Inc. 1986, 1987). These biomass values were indicative of dense *M. spicatum* stands.

32. Vertical dye distribution. Vertical patterns of dye concentration over time in the treated plots are presented in Figures 8-11. Following surface injection with unweighted hoses, dye was concentrated in the upper portion of the water column in Plot CR during the first few hours posttreatment (Figure 8). These high levels of dye (21 to 91 $\mu g/\ell$) were measured primarily in stations nearest shore (3, 6, and 9) and stations along the center transect (2, 5, and 8). Dye penetrated the lower depths and existed over a longer period of time in the downstream portion of the plot (Stations 7-9).

33. Previous dye studies have indicated that thermal stratification can interfere with the mixing of dye (and possibly herbicide) in the water column.*,** If a herbicide is isolated in certain layers of the water column, reduced efficacy could result. For instance, if a contact-type herbicide is restricted to the top portion of the water column, then a top growth burnoff of the target plants would occur. A systemic herbicide, isolated in the surface waters, could also cause a top growth burnoff, since the chemical would be highly concentrated around the tops of the plants, disrupting translocation of the active ingredient.

34. A slight difference in water temperature from surface to bottom (~1° C) was measured during the study in Plot CR (as well as in Plots LCB and RM-46). This extent of stratification may have contributed to the incomplete mixing of the dye. Water flow influenced the mixing process as well, by transporting dye from the plot before complete mixing could occur. Dye

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* K. D. Getsinger and W. R. Green, 1989, op. cit.
** Personal Communication, 1989, W. T. Haller.

transport out of the plot was documented by dye concentrations of 8 to 9 μg/ℓ (in the top 50 cm of the water column), at 4 hr posttreatment, approximately 150 m downstream from the northern edge of the plot.

35. In contrast to the subsurface injection technique, dye was more evenly distributed through depth in Plot CR following the weighted-hose (deep-injection) application, particularly in the downstream two thirds of the plot (Figure 9). Although low levels of dye (<1 μg/ℓ) were recorded near the bottom using this deep-injection technique, higher concentrations (over a greater time interval) occurred in the mid and lower depths of the water column than were found using the surface injection method. The 45- to 75-cm deep-injection points allowed the dye to quickly penetrate the plant canopy and mix to depths >1.5 m, while moderating the occurrence of high dye concentrations found in the surface water.

36. Similar to the surface-injection treatment, water flow moved dye out of the plot in a downstream (or northerly) direction following the deep-injection treatment. Dye concentrations of 3.5 to 8.0 μg/ℓ (in the top 1.5 m of the water column) were recorded at 4 hr posttreatment, 150 m downstream from the northern edge of the plot.

37. Several narrow channels (1 to 2 m wide by 10 to 20 m long) of open water (no plants present) existed in the plant stands in and around Plot CR. Posttreatment measurements revealed that dye was accumulating in these areas. For example, at 6 hr posttreatment, dye concentrations averaged 0.7 μg/ℓ in the top 1 m of the water column on the vegetated sides of a channel, whereas the top 1 m of the water inside the channel averaged 4.7 μg/ℓ. This phenomenon was noted at several channels throughout the downstream half of the plot, and occurred in both the surface- and deep-injection treatments.

38. Dye was distributed over greater depths and for longer periods of time in Plot LCB (a deep-injection treatment), especially in the northeastern portion of the plot (Figure 10). Plot LCB was situated in a cove and was partially isolated from the main river current. These conditions resulted in less water movement and exchange in this plot than would occur in a main river plot (i.e., Plots CR and RM-46).

39. Dye readings taken throughout the posttreatment period at the outside edges of LCB suggested that water was moving in a slow, southeasterly direction, eventually reentering the northbound current of the river. Presumably, the dense plant stands in the cove deflected some of the riverflow and contributed to the slow water movement in Plot LCB.

40. Vertical patterns of dye concentration in Plot RM-46 are shown in Figure 11. Dye penetrated the stand at station 1, where plants were approximately 30 cm below the surface. However, dye did not penetrate as well at station 2, where plants formed a surface mat. The plant mat inhibited penetration of the injection hoses into the stand, resulting in high concentrations of dye in the surface water at this station.

41. Dye half-lives. Half-lives of dye for each plot are presented in Table 3. Plot LCB had the slowest rate of dye dissipation ($t_{1/2}$ = 16 hr), followed by Plot CR ($t_{1/2}$ = 2.0 hr, surface injection; $t_{1/2}$ = 2.3 hr, deep injection) and Plot RM-46 ($t_{1/2}$ = 0.3 hr).

42. Van and Conant (1988) reported that under laboratory conditions Eurasian watermilfoil was controlled when exposed to 1.0 mg/ℓ diquat for only 1 hr, while hydrilla was controlled at the same dose with a 12-hr contact time. In other laboratory studies, Green (1989) showed that Eurasian watermilfoil was controlled when exposed to endothall at 5 mg/ℓ for 12 hr and was severely injured when exposed to 3 mg/ℓ endothall for 12 hr. These concentration/exposure time studies suggest that control of hydrilla and/or Eurasian watermilfoil may be possible in situations with a water exchange pattern similar to that found in Plot LCB. Water exchange in the other two plots (particularly RM-46) was probably too rapid to provide sufficient herbicide contact time for acceptable plant control.

Withlacoochee River

43. Vertical dye distribution. Vertical profiles of dye concentrations found in the treated plots are presented in Figure 12. In Plot 1, the dye was most concentrated at the water surface immediately after application with little penetration below 1 m. Lumps of dye-colored polymer were observed adhering to hydrilla plants near the water surface, with dye being released and flowing downstream in a westerly direction.

44. Within 5 hr, the surface concentration of dye was less than one sixth the maximum concentration, and only 0.02 μg/ℓ of dye was found 22 hr after treatment. Dye concentrations in the middle of the western edge of the plot were similar to those found in the center of the plot. The relatively fast, horizontal movement of water through the topped-out hydrilla in Plot 1 prevented any significant penetration of dye into the hydrilla stand.

45. Although mean dye concentrations at the centers of each plot were similar (2.7 μg/ℓ in Plot 1 and 2.2 μg/ℓ in Plot 2), the maximum value in Plot 2 was only a third of that in Plot 1. Since the dye was not confined to

the surface layer of the water in Plot 2, it was more evenly distributed throughout the water column. This difference in vertical distribution of the dye was probably caused by the lack of topped-out hydrilla in Plot 2.

46. Dye measurements were taken within an hour of application in a circle around Plot 2, and surprisingly, maximum values were found on the east side of the plot. Subsequent dye readings taken at this position showed similar values to those taken from the center of the plot. The easterly movement of the dye, opposite to the general flow in the river, was probably the result of a localized eddy in the cove in which the plot was situated.

47. Dye half-lives. Half-lives of dye for each plot are shown in Table 4, with those in Plot 1 being much less than those in Plot 2. Although the half-lives were based on data from only four or six sampling times, the $r^2$ values for the regressions (Table 4) indicate that a reasonable level of confidence can be placed in these results. These water exchange patterns suggest that plant control might be achieved using a contact herbicide in Plot 2.

48. Water velocity. The points at which the maximum dye concentrations were recorded on the day after application are indicated in Figure 3. Approximate water velocities were calculated from these positions (Table 5). The water velocity was 1.2 cm/sec in Plot 1 and 0.9 cm/sec in Plot 2, and, as shown previously, these velocities are typical of flows found in submersed plant stands. Since the velocities calculated with the dye were near the detection limits of most commercially available flow meters, rhodamine WT may provide a means of measuring low flows in submersed plant stands.

49. Low dye concentrations found at point Max 22 (Figure 3), and the inability to detect similar values in the canal outlet later that day, indicated that the main dye pulse from Plot 1 had already entered the canal (which was not examined) early on the second day posttreatment. If this were the case, then the water velocity from Plot 1 would have been even faster than 1.2 cm/sec.

## Conclusions and Recommendations

### Conclusions

50. Results from this study have shown that dense stands of submersed plants substantially alter water movement in lotic systems. The physical structure and height of plants, as well as the aerial extent of the plant stand, can influence water velocities. While velocities over and around

submersed stands can be relatively high (15 to 35 cm/sec), intrastand velocities are quite low (<1 cm/sec).

51. Electromagnetic flow meters can be used to characterize linear water flow in and around submersed plant stands when velocities are >1 cm/sec. However, low intrastand velocities (<1 cm/sec) and water depth >1.5 m can make the use of these meters impractical in some field situations.

52. The fluorescent dye rhodamine WT can also be used to determine water movement and to characterize water exchange patterns in submersed plant stands. This technique is most useful in measuring water exchange in dense stands of submersed plants where water velocities are <1 cm/sec. In addition to determining water exchange patterns, rhodamine WT can be used to compare the effectiveness of various herbicide application techniques. This method is particularly useful in determining potential vertical mixing of herbicides in submersed plant stands. The slow water movement within submersed plant stands may provide adequate exposure time for contact-type herbicides to control target vegetation, if the chemical can be properly distributed through the water column.

53. The combination of intrastand water exchange information and results from herbicide concentration/exposure time studies can provide a tool for predicting the efficacy of herbicides in flowing-water systems. However, until clear relationships between the dissipation of rhodamine WT versus the dissipation of aquatic herbicides are established, the use of this inert dye will only predict the maximum possible persistence of biologically active herbicides within plant stands.

Recommendations

54. The recommendations suggested by this study include the following:

a. Water exchange patterns should be characterized in submersed plant stands prior to herbicide treatment, if high water exchange in the treatment area is suspected.

b. The fluorescent dye rhodamine WT is recommended for use in characterizing water exchange patterns in submersed plant stands.

c. The relationships between the dissipation of rhodamine WT and aquatic herbicides in submersed plant stands should be developed.

d. Dye studies, using rhodamine WT, should be conducted to determine the effects of thermal stratification, stage of plant growth, and various application techniques on the distribution of herbicides in the water column.

e. The relationship between areal size of submersed plant stands, stage of plant growth, water exchange patterns, and herbicide efficacy should be developed.

f. Herbicide concentration/exposure time studies should be continued to identify the most effective combinations of chemical concentration and exposure time at various flow velocities.

g. Techniques should be developed and evaluated to apply herbicides within submersed plant stands in flowing water, taking into consideration the hydrodynamic processes that occur in and around those stands. These techniques should include various types of formulations and methods of application.

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Table 1

Flow Velocity Patterns in Vertical, Longitudinal Profiles of *V. americana* and *P. pectinatus* Stands in the Holston River June 1986

| Species | Velocity cm/sec | Vertical Profile percent |
|---|---|---|
| *V. americana** | <9 | 100 |
| | <5 | 90 |
| | <1 | 73 |
| *P. pectinatus*** | <21 | 100 |
| | <17 | 98 |
| | <13 | 87 |
| | <9 | 74 |
| | <5 | 46 |
| | <1 | 8 |

* Middepth, center channel incoming flow velocity ~18 cm/sec.
** Middepth, center channel incoming flow velocity ~30 cm/sec.

Table 2

Flow Velocity Patterns in Vertical, Cross-Sectional Profiles of *M. spicatum*, *C. demersum*, and *E. canadensis* Stands in the Biggs Extension Canal, September 1987*

| Species | Velocity cm/sec | Vertical Profile percent |
|---|---|---|
| *M. spicatum* | <9 | 100 |
| | <5 | 92 |
| | <1 | 68 |
| *C. demersum* | <5 | 100 |
| | <1 | 61 |
| *E. canadensis* | <9 | 100 |
| | <5 | 97 |
| | <1 | 71 |

* Middepth, center channel incoming flow velocities were 15 to 20 cm/sec.

Table 3

Regression Equations for the Dissipation of Dye from Plots in the Pend Oreille River, August 1988

| Plot | Stations | Regression Line* $\ln C_t - \ln C_o$ | $r^2$ percent | Half-Life hr |
|---|---|---|---|---|
| CR** | 1-3 | y = 1.43 - 1.10t | 98 | 0.6 |
| | 4-6 | y = 1.16 - 0.46t | 95 | 1.5 |
| | 7-9 | y = 1.07 - 0.21t | 95 | 1.3 |
| | 1-9 | y = 1.10 - 0.35t | 99 | 2.0 |
| CR† | 1-3 | y = 1.46 - 1.51t | 87 | 0.5 |
| | 4-6 | y = 1.09 - 0.61t | 87 | 1.1 |
| | 7-9 | y = 1.07 - 0.21t | 95 | 3.8 |
| | 1-9 | y = 0.77 - 0.30t | 95 | 2.3 |
| LCB† | 1-5 | y = 0.96 - 0.04t | 98 | 16.0 |
| RM-46† | 1-2 | y = 1.48 - 2.31t | 90 | 0.3 |

* $\ln C_t = \ln$ (dye concentration at time t); $\ln C_o = \ln$ (dye concentration at time o).
** Surface injection.
† Deep injection.

Table 4

Regression Equations for the Dissipation of Dye from Plots in the Withlacoochee River, March 1988

| Plot | Position | Regression Line* $\ln C_t - \ln C_o$ | $r^2$ percent | Half-Life hr |
|---|---|---|---|---|
| 1 | Center | y = 1.20 - 0.18t | 97 | 3.7 |
| 1 | Western edge | y = 1.31 - 0.15t | 92 | 4.6 |
| 2 | Center | y = 0.60 - 0.06t | 93 | 11.4 |
| 2 | Eastern edge | y = 0.94 - 0.10t | 97 | 6.7 |

* $\ln C_t = \ln$ (dye concentration at time t); $\ln C_o = \ln$ (dye concentration at time o).

Table 5

Estimates of Water Velocities in Hydrilla Stands in the Withlacoochee River, March 1988

| Plot | Time Interval hr | Distance km | Velocity cm/sec | Maximum Dye Concentration at Surface µg/ℓ |
|---|---|---|---|---|
| 1 | 22.0 | 0.93 | 1.2 | 0.18 |
| 2 | 21.0 | 0.76 | 1.0 | 0.75 |
| 2 | 7.5 | 0.26 | 0.9 | 0.40 |

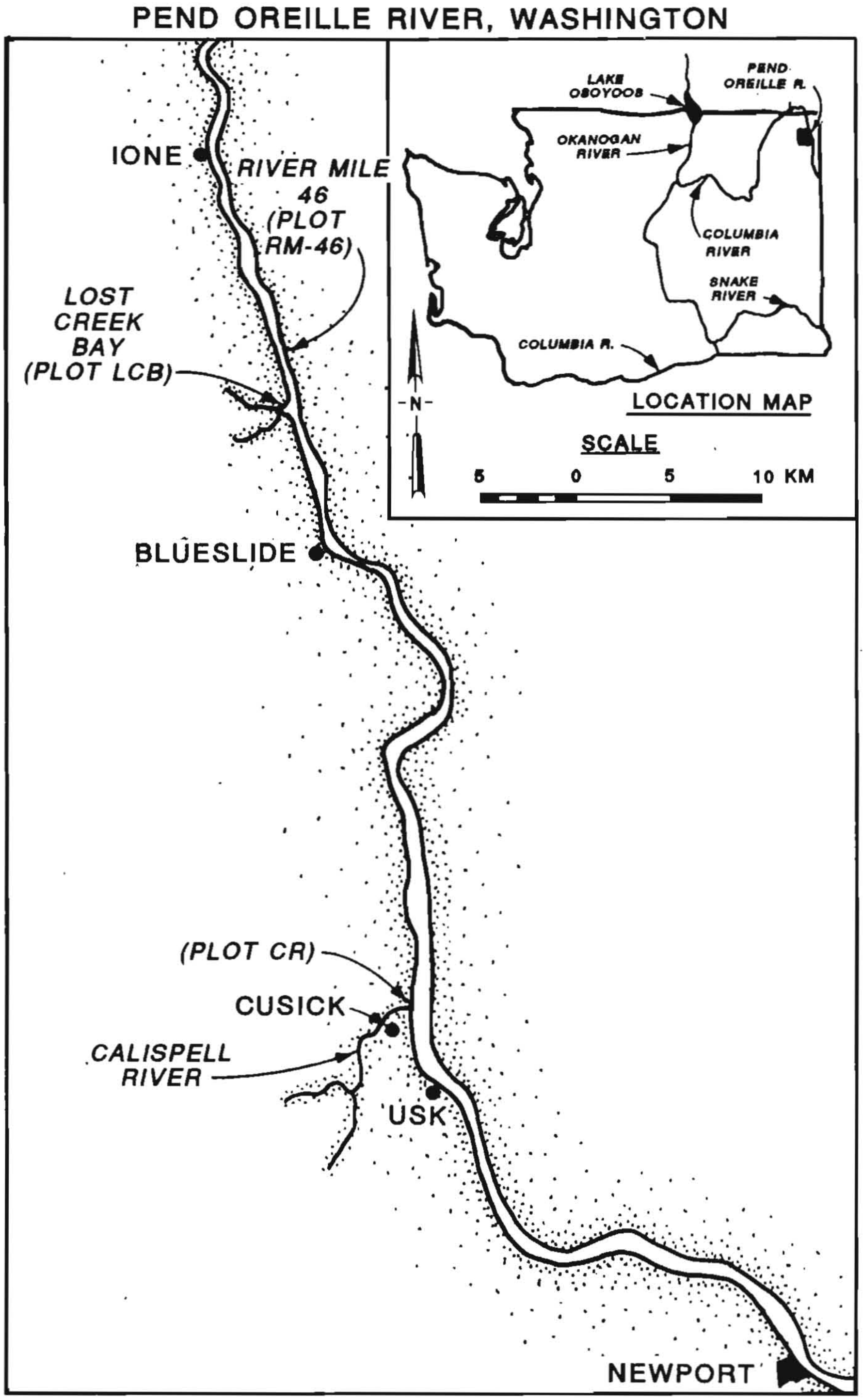



Figure 1. Pend Oreille River, Washington, study sites

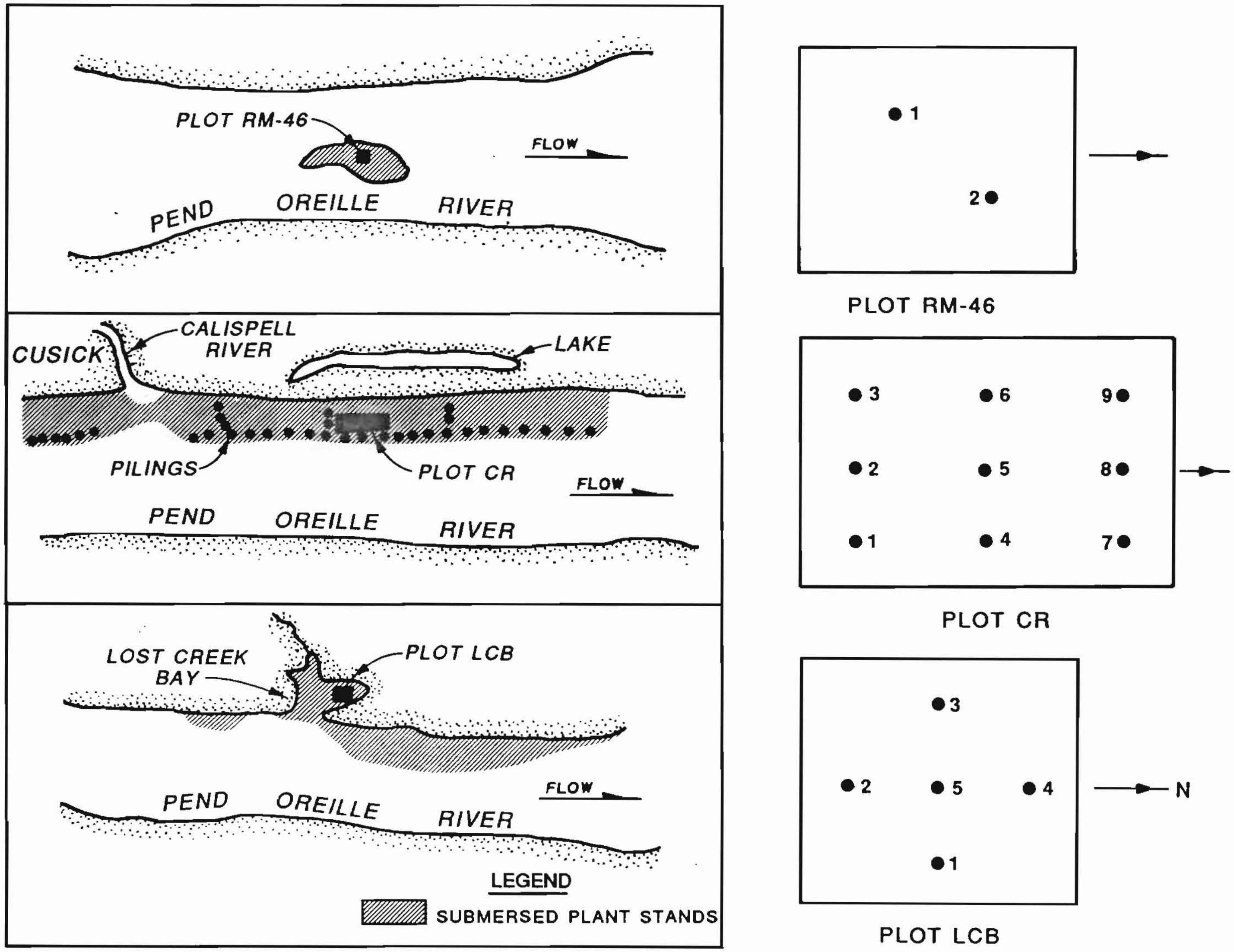



Figure 2. Plot locations on the Pend Oreille River. Numbers in open boxes represent dye monitoring stations

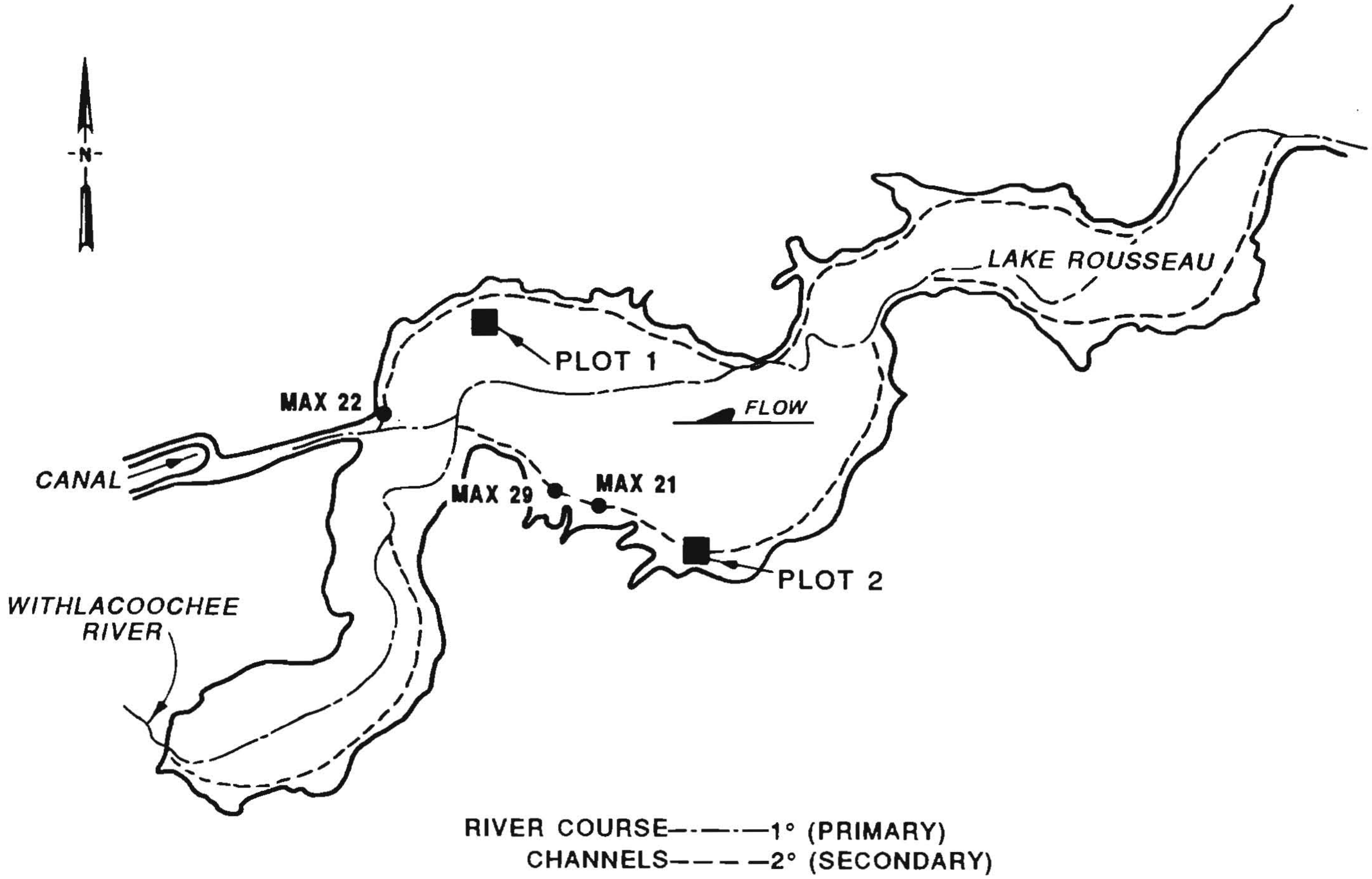
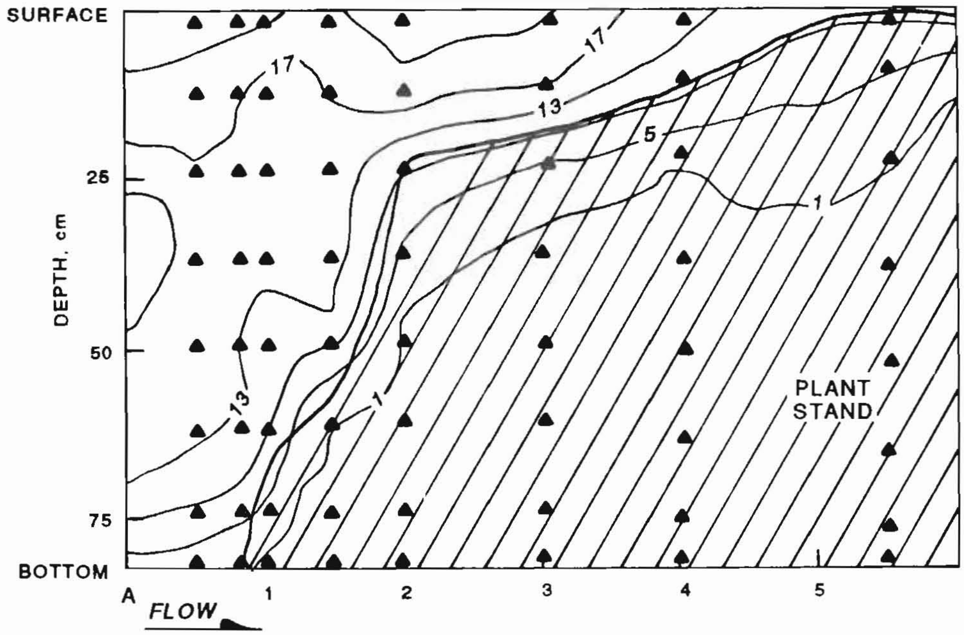
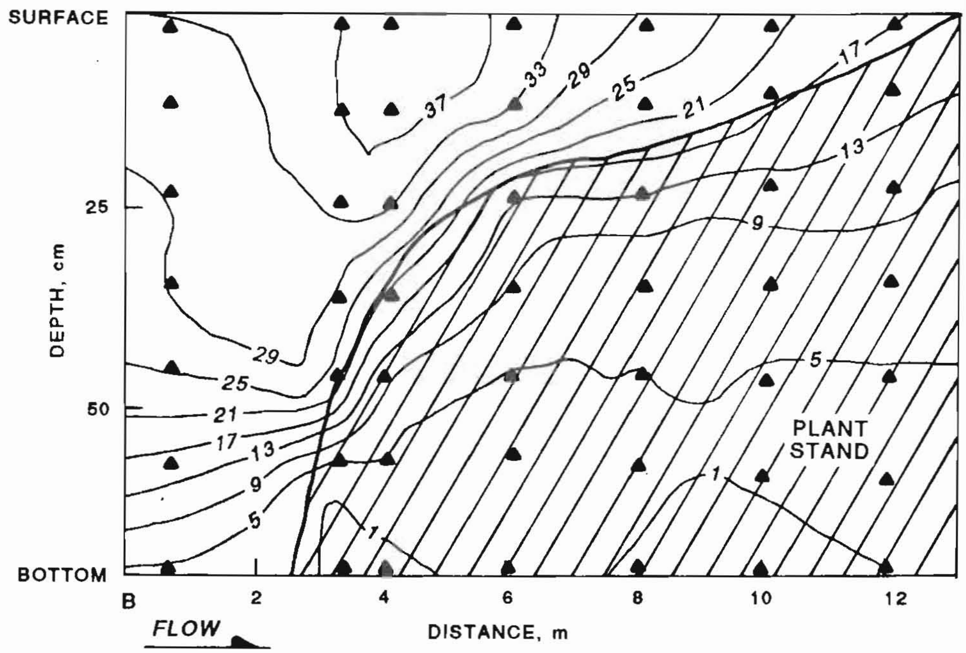



Figure 3. Withlacoochee River, Florida, study sites and plot locations showing positions of maximum dye concentrations at 21, 22, and 29 hr posttreatment (MAX 21, etc.)




a. *Vallisneria americana*




b. *Potamogeton pectinatus*

Figure 4. Longitudinal section of flow velocity patterns in plant stands in the Holston River (▲ = sampling locations; isobars - velocity, cm/sec)

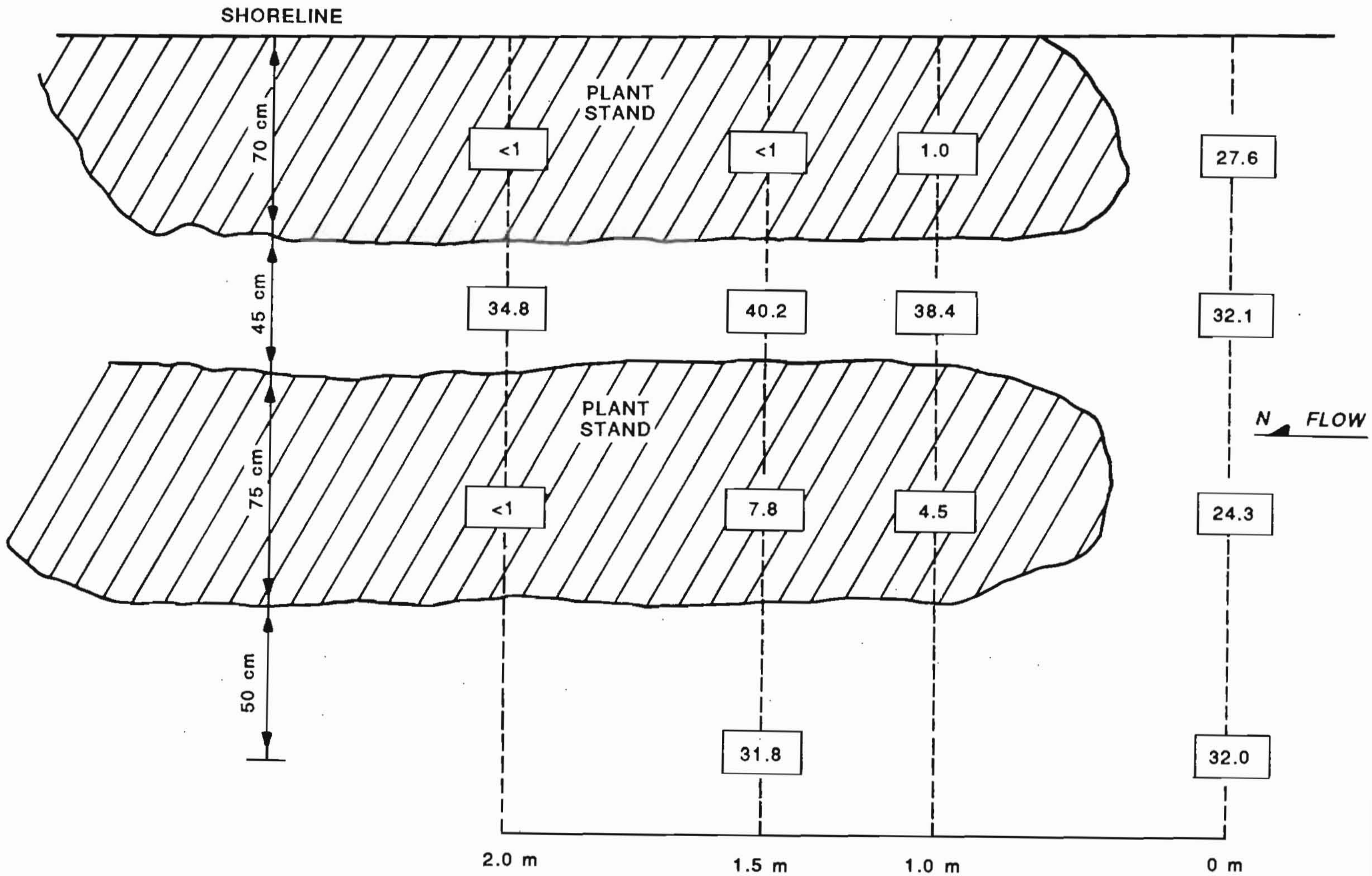
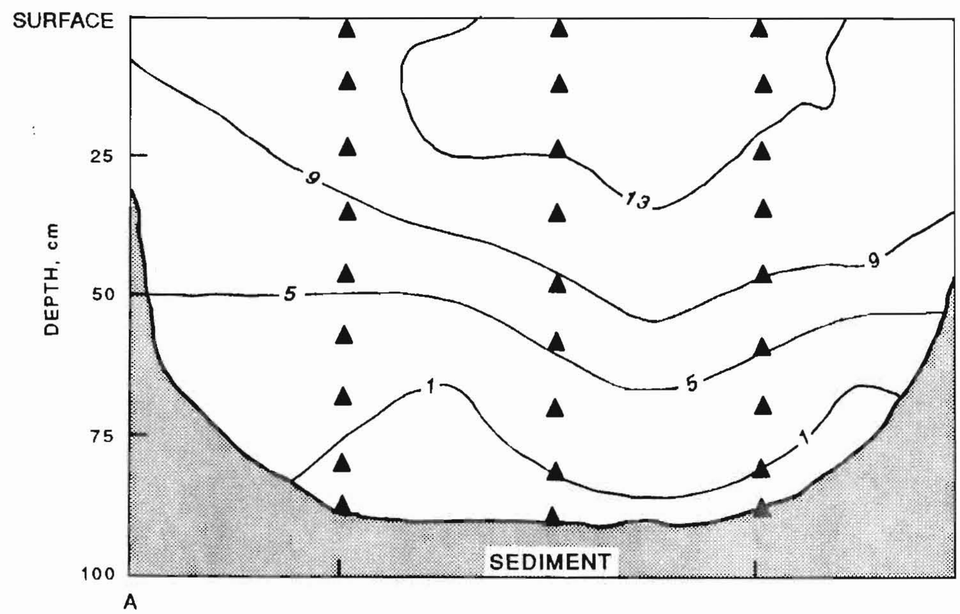
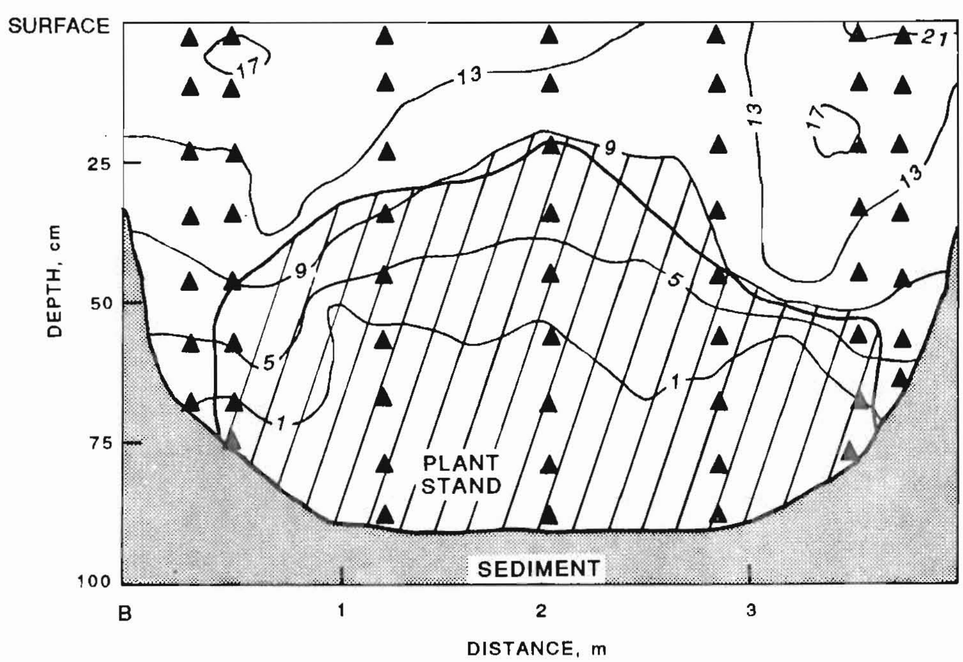



Figure 5. Surface view of *H. dubia* stands in the Holston River. Numbers within boxes are velocity values (cm/sec) taken at middepth




a. No-plant area




b. *Potamogeton pectinatus*

Figure 6. Cross section of flow velocity patterns in areas of the Weyland Lateral Canal (▲ = sampling locations; isobars = velocity, cm/sec)

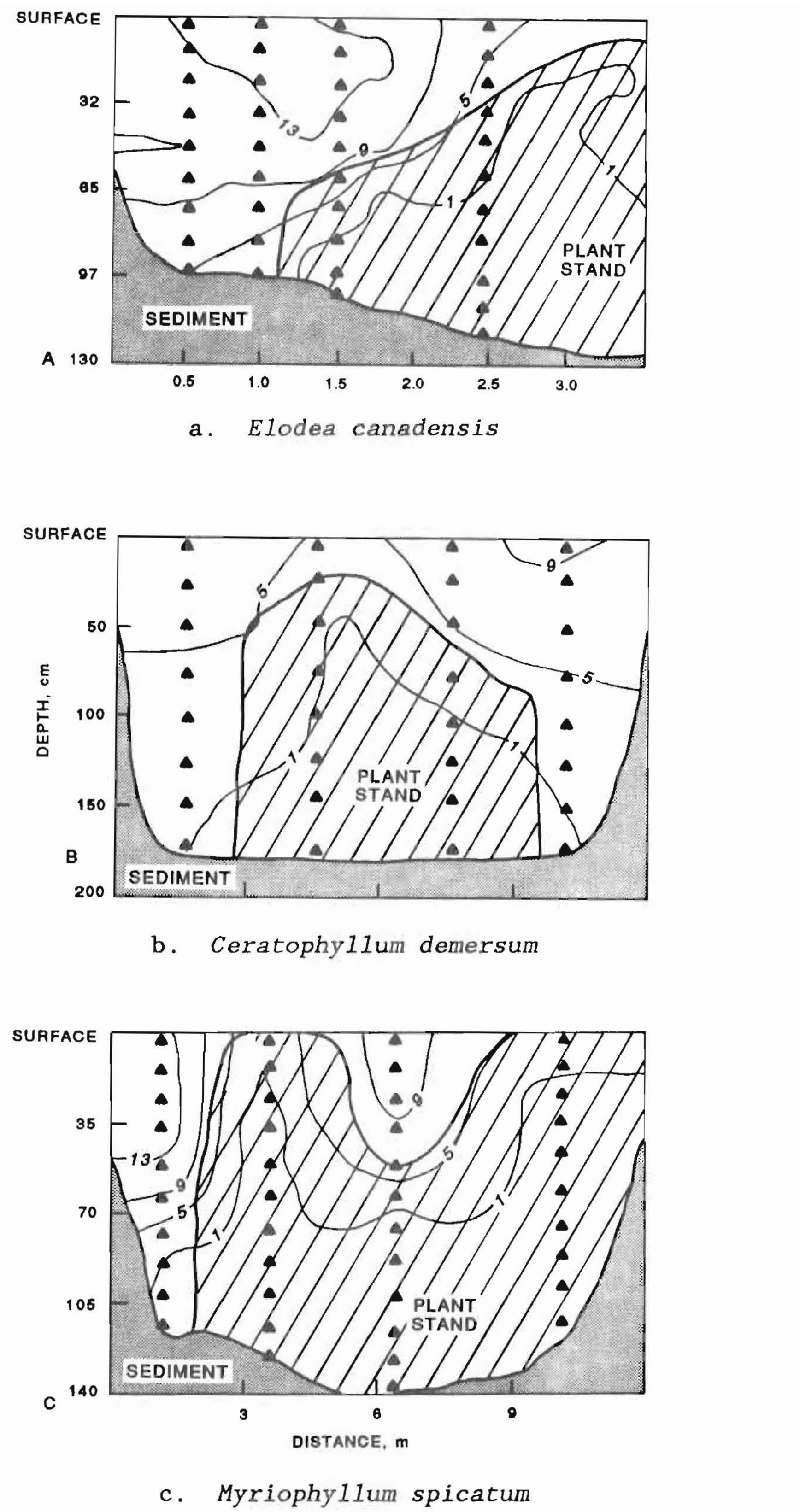



Figure 7. Cross section of flow velocity patterns in plant stands in the Biggs Extension Canal (▲ = sampling locations; isobars = velocity, cm/sec)

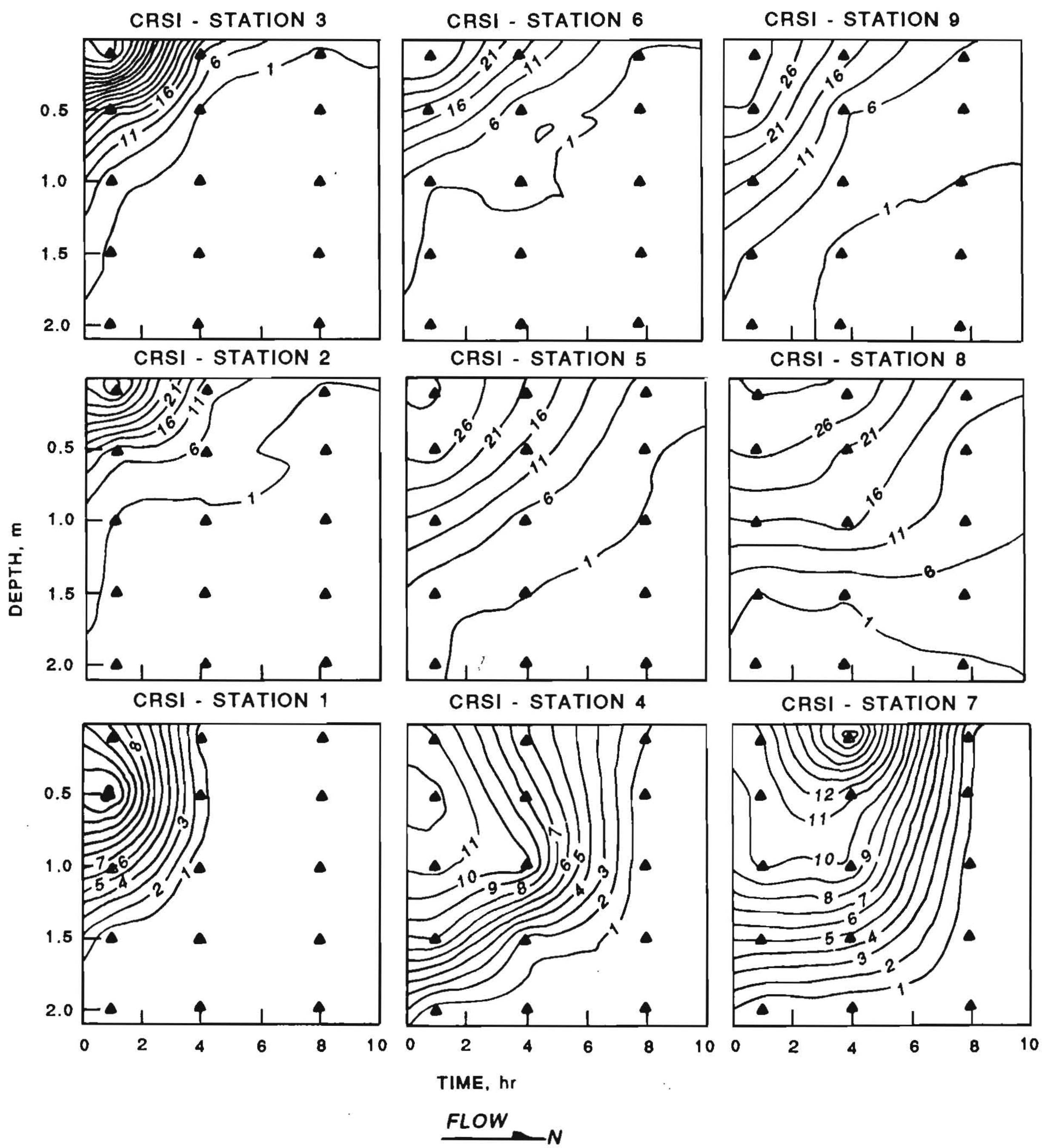



Figure 8. Vertical profiles of dye following surface injection in the Calispell River plot, Pend Oreille River (▲ = sampling depths and times; isobars - dye, $\mu g/\ell$)

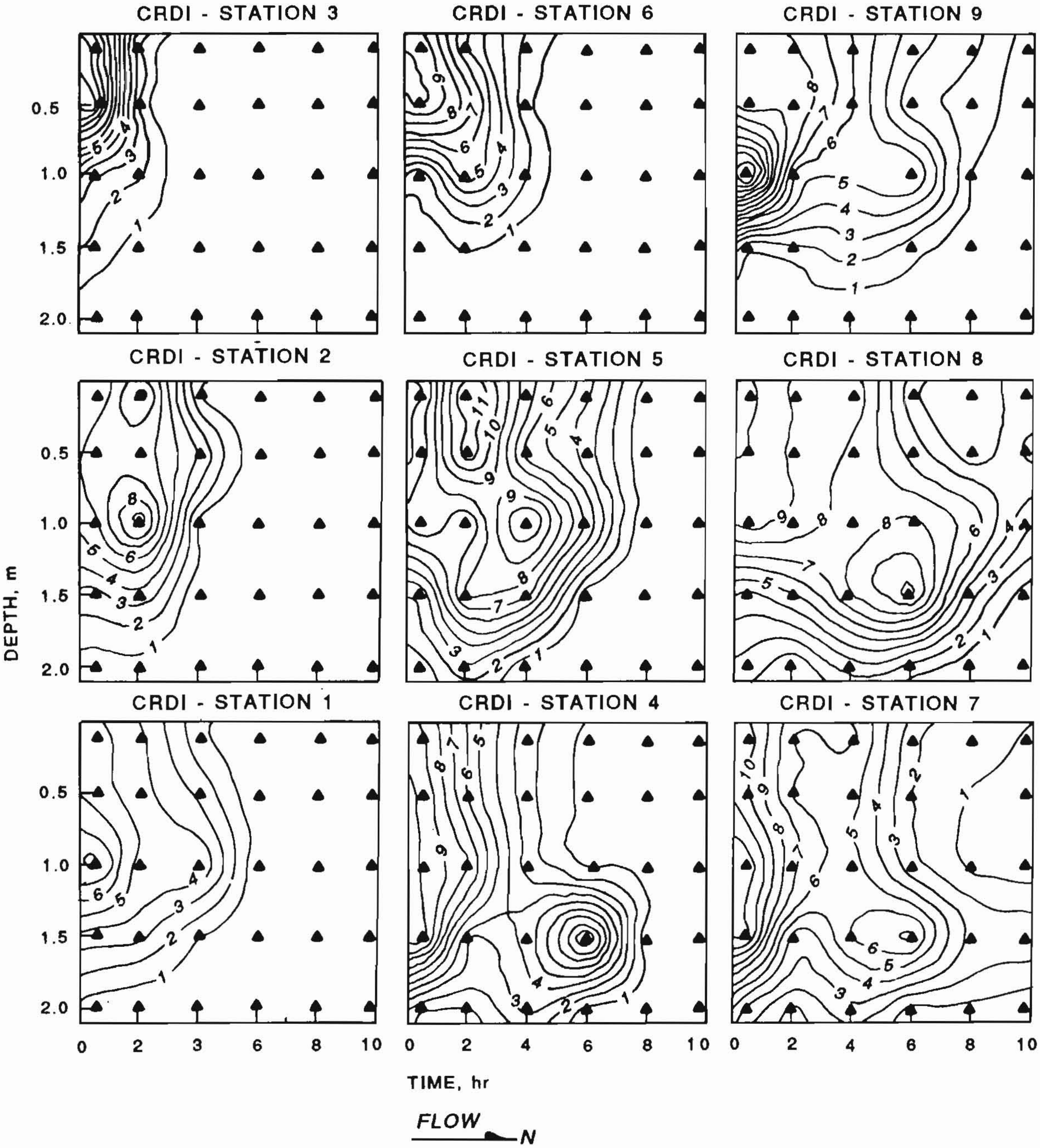



Figure 9. Vertical profiles of dye following deep injection in the Calispell River plot, Pend Oreille River (▲ = sampling depths and times; isobars = dye, $\mu g/\ell$)

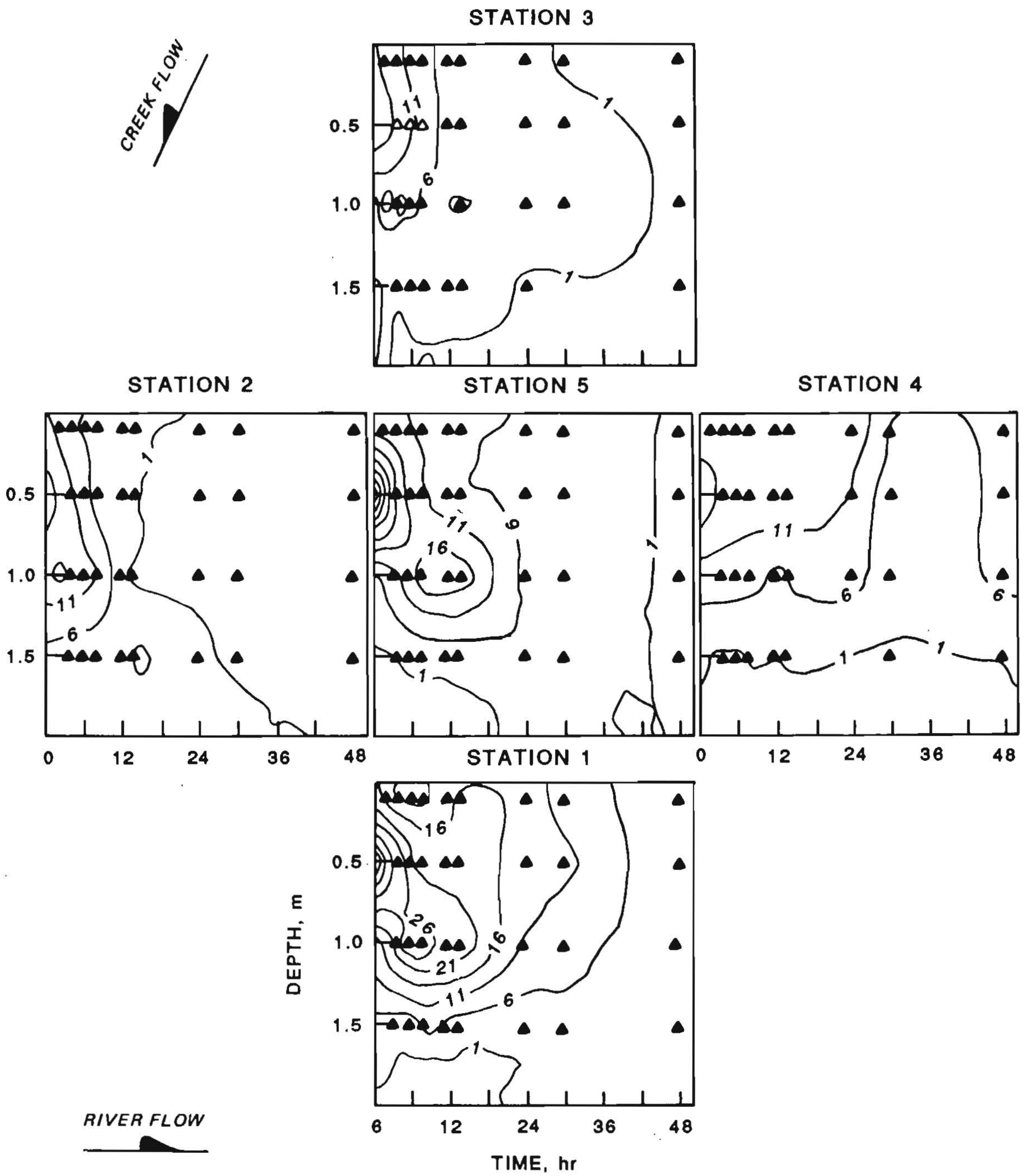



Figure 10. Vertical profiles of dye following deep injection in the Lost Creek Bay plot (▲ = sampling depths and times; isobars = dye, μg/ℓ)

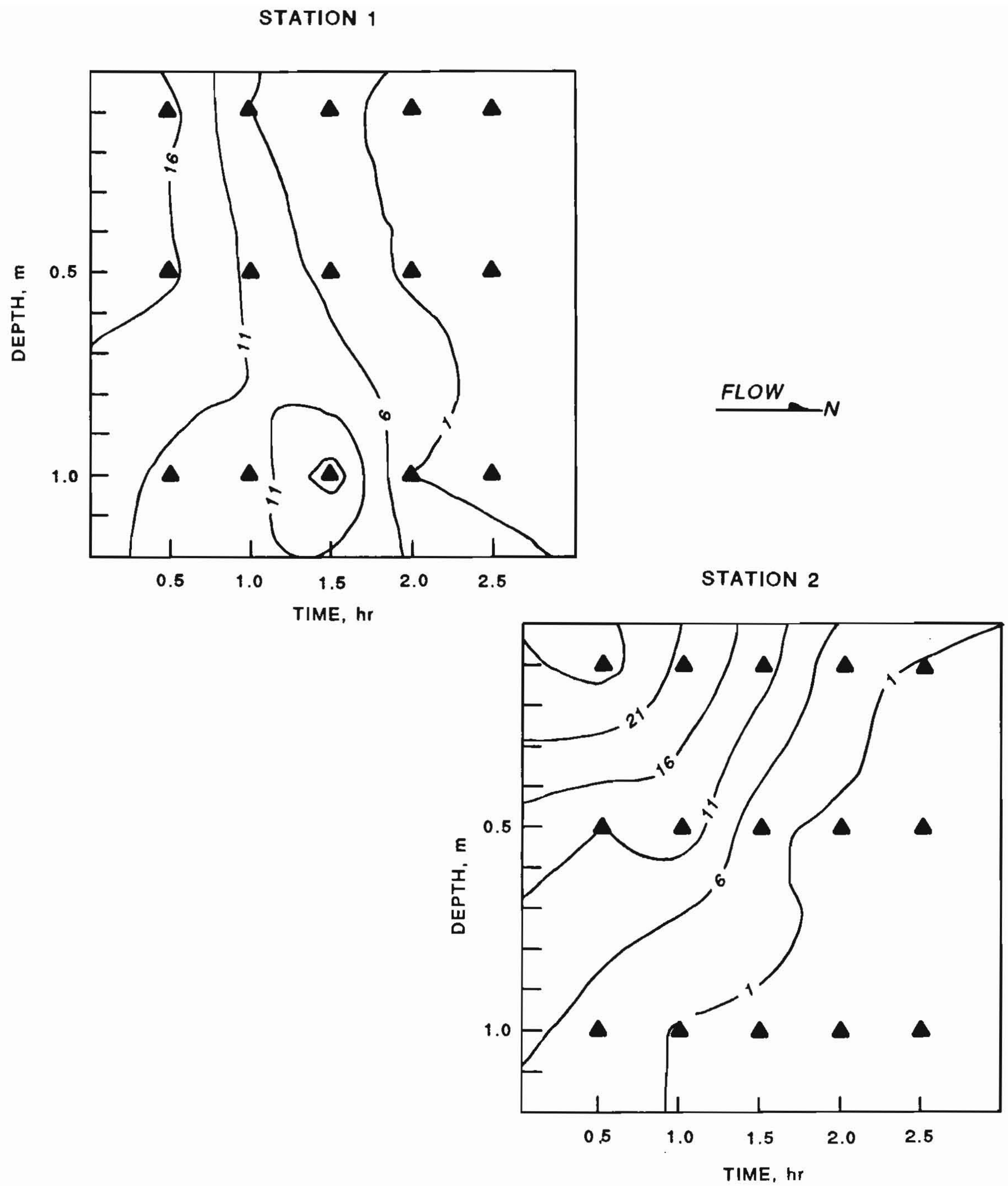



Figure 11. Vertical profiles of dye following deep injection in the river mile 46 plot, Pend Oreille River (▲ = sampling depths and times; isobars - dye, $\mu g/\ell$)

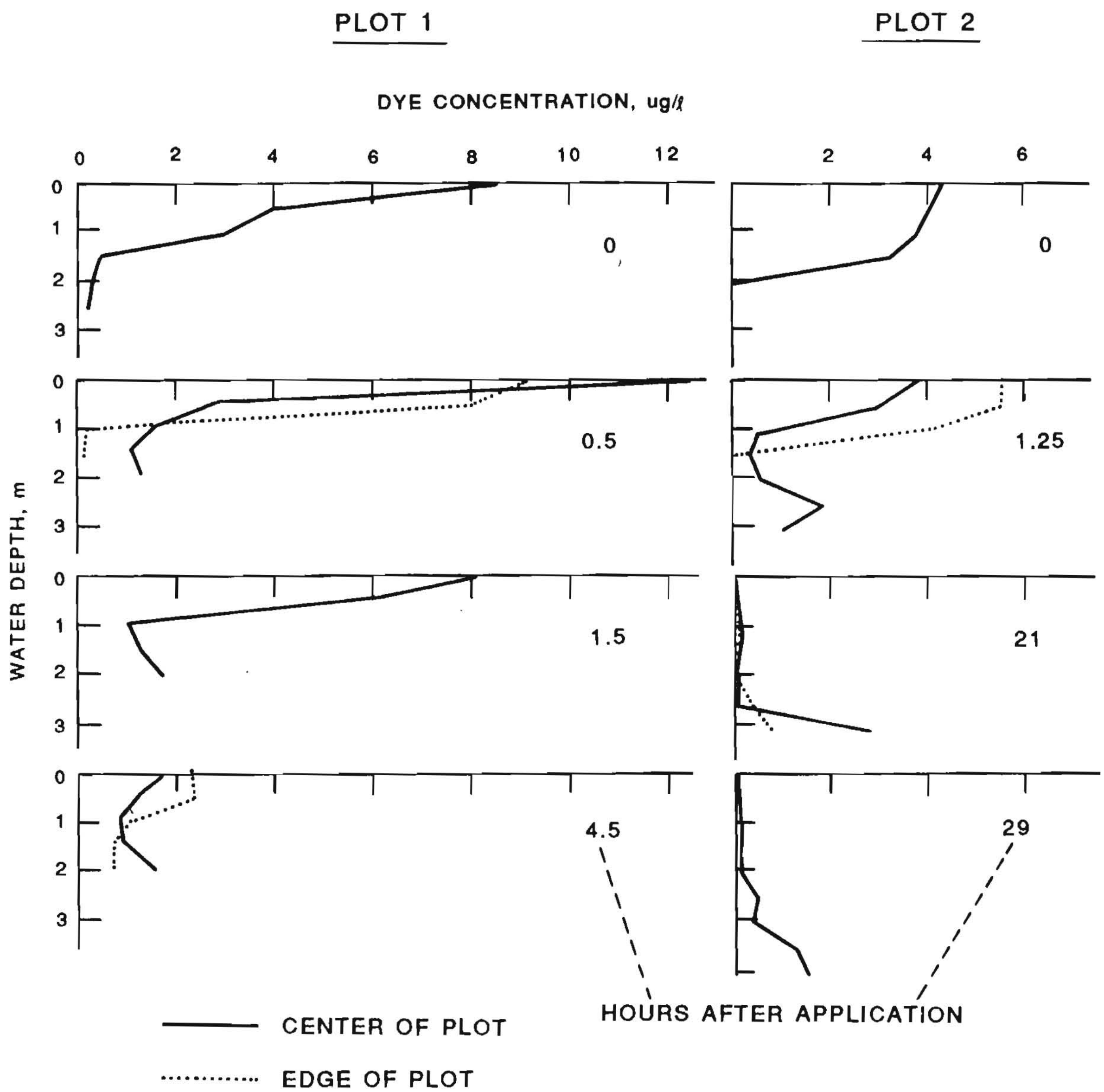



Figure 12. Vertical distribution of dye at the center and western edge of Plot 1 and at the center and eastern edge of Plot 2, between 0 and 29 hr posttreatment, Withlacoochee River