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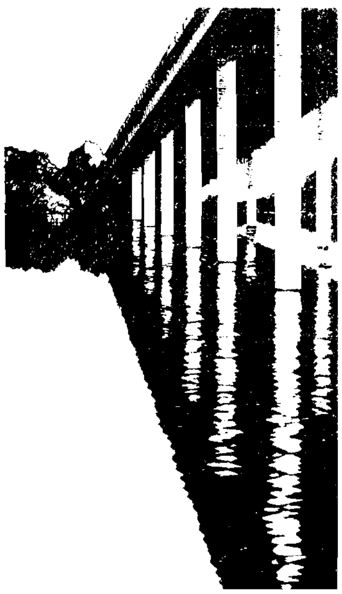

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CHARACTERIZATION OF WATER EXCHANGE IN HYDRILLA-INFESTED TIDAL CANALS OF THE CRYSTAL RIVER, FLORIDA

by

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The freshwater, tidal canals of the Crystal River, Florida, have been infested with hydrilla (*Hydrilla verticillata* Royle) for over two decades. The efficacy of herbicide application in this system has been unpredictable, often resulting in inconsistent hydrilla control. The objectives of this study were to compare the influence of tides, vegetation, and season on water exchange in dead-end canals and to evaluate herbicide efficacy in the canals as predicted by water exchange patterns.

The fluorescent dye Rhodamine WT was used in four dead-end canals to estimate rates of water exchange and to characterize water movement during different tidal cycles. The behavior of the nonadsorptive dye indicated the maximum persistence of a chemical applied to the hydrilla-infested canals. The conditions under which dilution rates were slowest were identified. These conditions were predicted to be the optimum times for the application of herbicides, providing maximum herbicide exposure to the plants.

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Contrary to predictions of a water exchange model based on water level data, there were no significant differences in the rates of dissipation of dye on spring and neap tides.

Significant differences in rates of dilution were observed between dye treatments made in the summer, winter, and fall. With only two exceptions, there were no significant differences within a season. A high density of vegetation significantly prolonged the rate of dye dilution in winter but not in summer, when rates of water exchange or dye dilution were greatest.

The relative temperatures of the water in the canals and in the adjacent Three Sisters Springs varied with season, as did the difference in temperature between the top and bottom of the water column. Seasonal differences in the vertical distribution of dye were also observed. A hypothesis to explain the effects of water temperature on circulation patterns and rates of tidal dissipation in the canals was proposed.

Applications of endothall in the fall of 1987 and 1988 provided good hydrilla control over several months. A treatment in March 1988 was less effective, and regrowth was rapid. Fluridone applied in October 1988 caused severe chlorosis of shoot tips but did not reduce the amount of vegetation.

Based on the results of this study, herbicide use should be restricted to fall and springtime, when water in the canals and springs is isothermal. Summer plant control should be limited to mechanical harvesting. In addition, information derived from this study can be used as a preliminary guide for controlling hydrilla in other tidally influenced, spring-fed canal systems of the Southeast.

PREFACE

The study reported herein was performed under a cooperative agreement between the US Department of Agriculture and the US Army Engineer Waterways Experiment Station (WES). Funds for the study were provided by the US Army Corps of Engineers (USACE) and the US Army Engineer District (USAED), Jacksonville. The work was conducted as part of the Aquatic Plant Control Research Program (APCRP) (Appropriation No. 96X3122, Construction General). The APCRP is sponsored by the USACE and is assigned to the WES under the purview of the Environmental Laboratory (EL). The USACE Technical Monitor for APCRP is Mr. James W. Wolcott.

The research described in this report was a collaborative effort between the WES and the University of Florida (UF), Institute of Food and Agricultural Sciences, Center for Aquatic Plants. This report was prepared by Drs. Alison M. Fox and William T. Haller of the UF Center for Aquatic Plants and Dr. Kurt D. Getsinger and Mr. W. Reed Green of the Aquatic Processes and Effects Group (APEG), Ecosystem Research and Simulation Division (ERSD), EL. Principal investigator for the WES was Dr. Getsinger. Dr. William C. Zattau and Mr. Michael Dupes served as points of contact at the USAED, Jacksonville. Technical reviews of the report were provided by Dr. Howard E. Westerdahl and Mr. Ross Hall, EL.

The research and data analyses were performed by the authors. Technical assistance was provided by Ms. Margaret Glenn, Dr. Joe Joyce, and other personnel of the UF Center for Aquatic Plants. Appreciation is expressed to Messrs. Tom Dick, Greg McClain, and other personnel of the Florida-Citrus County Aquatic Plant Management Program for providing herbicide applications and field assistance during the study. The report was edited by Ms. Jessica S. Ruff of the WES Information Technology Laboratory.

This investigation was performed under the general supervision of Dr. John Harrison, Chief, EL, and Mr. Donald L. Robey, Chief, ERSD, and under the direct supervision of Dr. Thomas L. Hart, Chief, APEG. Mr. J. Lewis Decell was Manager of the APCRP at WES.

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

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CONTENTS

CHARACTERIZATION OF WATER EXCHANGE IN HYDRILLA-INFESTED TIDAL CANALS OF THE CRYSTAL RIVER, FLORIDA

PART I: INTRODUCTION

Background

1. The spring-fed, freshwater, tidal canals of the Crystal River, Florida, have supported an extensive growth of hydrilla (*Hydrilla verticillata* Royle) for over 20 years. This high-use area has required extensive use of herbicides and mechanical harvesting to keep the canals navigable for recreational boating. The efficacy of herbicide applications has been unpredictable, often resulting in less than desired levels of hydrilla control.

2. Control of submersed plants in tidal areas, or any flowing water system, is directly related to herbicide concentration and exposure time. In addition to biological and physical processes of uptake and degradation, herbicide concentrations and exposure time will be affected by water exchange patterns within submersed plant stands. The persistence and dissipation of herbicide residues have been studied in rivers and canals with unidirectional flow (O'Loughlin and Bowmer 1975; Fox, Murphy, and Westlake 1986; Mitchell 1986). In artificial channels, such as drainage and irrigation canals, residue movements may be predicted using hydrological and engineering principles (O'Loughlin 1975), although the presence of vegetation may influence these flow patterns (Stephens et al. 1963).

3. Herbicide residues have not been studied in the bidirectional water movement of dead-end tidal canals. Water exchange patterns in such systems can be influenced by flow, tides, wind, vegetation density, and thermal stratification. After patterns of water exchange have been characterized in the Three Sisters Canals, this information can be used to evaluate suitable herbicide application techniques, time of application, and choice of herbicides in this system, as well as other tidally influenced systems.

4. Soluble tracer dyes are regularly used by engineers in flowing-water systems to determine the velocity and movement of water (Feuerstein and Selleck 1963, Pilgrim and Summersby 1966, Johnson 1984) and to trace the dilution of effluents. The fluorescent dye Rhodamine B has been used to simulate the movement of herbicide residues in canals (Demint 1970) and lakes

(Langeland and DeMont 1986), but this dye has the disadvantage of being readily adsorbed onto sediments (Smart and Laidlaw 1977). Fluorescent dyes have been used to trace water movements in bays and estuarine tidal systems to determine the flushing rate of pollutants released from adjacent urban areas (Paul 1978).

5. Rhodamine WT, which is resistant to adsorption, was specifically developed for water tracing work. This dye has been reviewed by the US Environmental Protection Agency and the US Food and Drug Administration, and has been approved by the US Geological Survey for use in potable water at concentrations up to 10 $\mu g/\ell$. Rhodamine WT is not toxic at normal use levels and has been tested on fish, oyster eggs, and aquatic invertebrates (Smart and Laidlaw 1977). The detection limit of Rhodamine WT is 0.01 $\mu g/\ell$, or 1,000 times less than the application rate for potable water, making it an ideal tool for use in water movement/dilution studies. Direct and accurate measurements of dye concentration can be made in the field using a fluorometer. Environmental factors that can affect the measurement and persistence of Rhodamine WT have been extensively reviewed (Smart and Laidlaw 1977).

6. The purpose of this study was to determine general water movement in the hydrilla-infested Three Sisters Canals and to predict optimum times and methods of herbicide applications for controlling hydrilla in that system. A better understanding of water movement characteristics in these canals may result in more predictable hydrilla control, which would reduce the amount and cost of herbicides used in future treatments. In addition, these canals may be suitable as an experimental system for studying aquatic plant management techniques related to tidally influenced water bodies on a regional and/or national scale.

Objectives

7. The objectives of this study were to (a) characterize general water exchange in four of the Three Sisters Canals and determine whether these canals could be treated as experimental replicates; (b) compare the influence of tidal cycles, vegetation density, and time of year on general water exchange in the canals; and (c) evaluate the efficacy of herbicides applied to the canals under optimal conditions for controlling hydrilla, as predicted by water exchange patterns.

Study Site

Three Sisters Canals

8. The Three Sisters Canal system is a series of five dead-end canals in the eastern headwaters of the Crystal River, Florida (Figure 1). These canals were constructed in the 1950s to provide water frontage for housing development. The movement of the freshwater in these canals, as in the whole Kings Bay area, is influenced by springs and the tidal cycles which ebb and flow along the 8-km river, connecting the headwaters to the Gulf of Mexico.

9. This study was confined to four similar canals (approximately 420 m long, 24 m wide, and 2 to 4 m deep at high tide) labeled A through D, from west to east (Figure 2). There are several large springs in and near the canals which ultimately flow to Kings Bay, most importantly the Three Sisters Springs in the header canal opposite Canal B. The clarity, high nutrient content, and relatively constant temperature (22° to 24° C) of the spring water make these canals an ideal habitat for hydrilla, which has formed a monoculture and dominated other submersed species.

Tides

10. Kings Bay typically has a synodic, semidiurnal tidal pattern which lags behind that in the Gulf of Mexico, at the mouth of Crystal River, by 1.5 to 2 hr. There is normally an interval of about 12.5 hr between high tides (one tidal cycle). The times and heights of tides can be predicted (Macmillan 1966), and in the 29-day lunar cycle two types of tide can be recognized--neaps and springs. The range in water height between high and low tides is small for neap tides and large for spring tides. These tides are respectively related to the quarters and syzygies (full and new) of the moon. The predicted tides in Kings Bay for September 1987 are presented in Figure 3. More complex patterns of greater and lesser springs and neaps occur throughout the year, related to the solstices and equinoxes.

11. The reduction in tidal range on a neap tide, when a smaller proportion of the canal volume would be exchanged between high and low tides, would be expected to result in a slower exchange of water from the canals than during a spring tide.

12. A feature of the neap tides in Kings Bay is that the range of one of the daily tidal cycles is reduced much more than the other so that in an extreme case (September 16, Figure 3) there is effectively only one tidal cycle in 24 hr. This factor might be expected to reduce the rate of water

exchange in the canals by approximately 50 percent in comparison to a spring tide.

13. The times of the tides in the Three Sisters Canals could be predicted by the Kings Bay tide tables, but water heights in the canals were more variable than predicted by the tables.

PART II: MATERIALS AND METHODS

Measurement of Canals, Tides, and Water Volumes

14. Mean dimensions of each canal are listed in the tabulation below. The lengths of the canals were calculated from a 1985 aerial photograph taken by the Florida Department of Transportation. Ground measurements of well-defined lengths of road were used to verify the scale of the photograph. Canal widths were measured from a boat at nine transects along each canal, and depths were measured at 1-m intervals across the transects.

15. Water levels (tides) at the heads of Canals A and D were continuously charted on Steven's Type F recorders, which were mounted on stands erected at the sides of the canals. Results from both recorders were identical.

16. The state of the tide was estimated for each set of depth measurements so that they could be corrected to a datum point that was fixed on the tide gage in Canal A. Cross-sectional areas at each transect were calculated at the datum level from the width and depth data, and total volumes were estimated using the distances between each transect from the aerial photograph. Water volumes at any tide level could be calculated using the surface areas, since the difference in water level from the datum was known.

17. Depth profiles along the center line of each canal were obtained with a fathometer attached to an airboat. Examples of these, with the canals in a relatively unvegetated state, are presented in Figure 4.

	Canal			
Dimension*	A	B	C	D
Length, m	428	426	414	416
Width, m	23.3	24.7	23.2	23.8
Surface area, m^2	9,903	10,458	9,610	9,865
Depth, m	1.80	1.91	2.08	2.23
Volume, m^3	17,172	20,132	20,136	22,120

* Mean canal dimensions calculated from nine width and depth transects on each canal, corrected to the datum water level on Canal A.

Dye Application and Monitoring

18. Rhodamine WT has a specific density of 1.2 and is received from the manufacturers (Crompton and Knowles) in a 20-percent solution. To achieve a specific density of 1.0 and to ensure rapid mixing in water, the dye was mixed in a 1:1 ratio with methanol. This mixture contained 120,000 mg of dye per liter.

19. The total amount of dye/methanol mixture needed to treat a canal (usually 1,200 to 1,800 ml/canal) was measured with a graduated cylinder and divided equally between two 1-ℓ polyethylene bottles. Half of the dye was added to 227 ℓ of water and mixed in a stainless steel tank onboard an airboat. This tank-mix was injected into the suction side of a 227-ℓ/min, gasoline-powered, centrifugal pump at a rate of 5 ℓ/min. Make-up water for the pump was obtained with a suction line drawing water from the canal. After the dye was mixed and drawn through the pump it was injected into the canal by a manifold of four trailing, weighted hoses of different lengths mounted on the airboat.

20. The airboat was driven the length of the canal in 15 min; thus, three complete trips along the canal could be made in 45 min to empty the tank. The total dye application, from two tank mixes, was completed in 6 passes in 90 min.

21. Rhodamine WT dye was applied to the entire water volume of each canal at, or just after, a low tide at a rate calculated to achieve approximately 10 μg/ℓ at the subsequent high tide. This application rate produced a distinct red coloration in the clear water of the canals. In the first six dye applications, a polyvinyl chloride (PVC) pipe was also used to inject the dye mixture into shallow waters, under boats and docks (Figure 5). The PVC pipe was considered unnecessary in subsequent treatments, after finding that lateral water movement was sufficient to mix the dye throughout a treated canal.

22. Dye was monitored using a Turner Designs Model 10-005 field fluorometer fitted with a 10-020 high-volume continuous-flow cuvette system and the appropriate filters and light source for detecting Rhodamine WT. The fluorometer was calibrated at a known temperature in the laboratory, in the range of 0 to 30 μg/ℓ of dye, following the manufacturer's instructions. Water was circulated through the fluorometer with a 378 ℓ/hr-capacity bilge pump, attached to the end of a 5-m-long hose (20-mm diameter), which was

marked in 0.5-m intervals. Dye readings were taken until Rhodamine concentrations consistently fell below the detection level of 0.01 μg/ℓ.

23. A temperature probe was also attached to the hose, and water temperature was recorded concurrently with each reading from the fluorometer. Fluorescence of Rhodamine WT decreases with an increase in temperature; therefore, a correction with the calibration temperature is necessary to determine actual dye concentrations. The temperature correction equation was taken from Smart and Laidlaw (1977):

$$F_c = F \exp\left[-0.027(t_c - t)\right] \quad (1)$$

where

F_c = fluorescence at the calibration temperature (t_c)

F = fluorescence at the sample temperature (t)

24. Dye treatment dates and comparisons between canal treatments are listed in Table 1. Specific dye treatments are indicated by the canal name (A, B, C, or D) and a subscript of the number of times that a canal has been treated (e.g., A_3 = third treatment in Canal A). In the first eight treatments (A_1 - D_2), the dye was monitored at high tides at three points across the five transects (Figure 2). Readings were taken at 0.5-m depth intervals at each point, starting at 0.5 m from the canal bottom and finishing just below the water surface. The total depth was measured at each point to ensure that the hose and bilge pump were not dropped into the sediment.

25. Data from the three points across the transects could not be analyzed as treatment replicates since they were affected by only one treatment, and hence were merely sampling replicates. This fact limited their importance in the statistical analyses. For the eight initial treatments, rates of dye dilution calculated using the data collected from all three points across the transects were compared with dilution rates calculated using data from only the center points on the transects. There were no significant differences in these dilution rates. Thus, in all subsequent treatments the dye was measured only at the center point on each transect.

26. Transparent, 115-ℓ polypropylene bags, suspended from floating frames, were filled with dye-treated water and anchored in the canals during some of the dye treatments. These bags were open at the surface and acted as

enclosures that prevented water exchange. The concentration of the dye in the bags was measured daily, for about a week, to determine any loss of dye due to photochemical or microbial action.

27. For the baseline comparison of the four canals (to determine if canals could be used as replicates), a dye application was made to each canal during a spring tidal cycle in late August or early September on the dates indicated in Table 1. At this time the canals were reasonably free of vegetation, which had been removed by repeated applications of endothall and mechanical harvesting. Since it was not known how much cross-contamination of dye might occur between canals, each canal was treated separately.

Vegetation Monitoring

28. Periodically, fathometer tracings were recorded showing longitudinal sections down the centers of the canals (similar to those in Figure 4). After delineating the stands of vegetation, the fathometer recordings were traced on parchment. The areas of vegetation and open water were separated and weighed. From these weights the approximate percentages of vegetation in the longitudinal sections were calculated.

Data Analysis

29. Statistical analyses of the dye data were carried out using the SAS statistical package (SAS Institute 1985). The use of the term significant has been restricted to statistically tested relationships showing a significant difference where $P < 0.05$.

30. For comparisons of changes in dye concentration with time between pairs of canals, data from all depths and transects 2, 3, 4, and 5 within each canal were pooled and used in an analysis of variance (ANOVA). This compared the mean dye concentrations per canal and sampling time.

31. The overall changes in the concentrations of dye in each canal occurring with time appeared to follow an exponential curve (e.g., Figure 6) that would have an equation of the form

$$\frac{C_t}{C_o} = e^{-a(t)} \qquad (2)$$

where

C_t = dye concentration at time t

C_o = initial dye concentration

a = coefficient of the rate of

dilution determined by $\frac{\text{water exchange per unit time}}{\text{total water volume of the canal}}$

32. By taking the natural logarithm of the dye concentrations, a linear relationship would be expected, of the form

$$(3) \quad \log_e C_t = \log_e C_o - a(t)$$

From this equation, the half-life ($t_{1/2}$) is

$$t_{1/2} = - \frac{\log_e(0.5)}{a} \qquad (4)$$

33. Thus, for initial canal comparisons, data from each of the canal treatments (A_1, B_1, C_1, D_1) were subjected to an analysis of variance, after a $\log_e$ transformation, with the factors TREAT (treatment = A_1, B_1, etc.) and TIME (sampling time) and the TREAT*TIME interaction being tested.

34. Since the initial concentrations were determined by the amount of dye applied and the canal water volume, and were not always as close to 10 $\mu g/\ell$ as intended, the comparisons of absolute dye concentrations per canal were not of interest. Only differences in the rate of dilution (a in the linear equation, Equation 3) and the TREAT*TIME interactions were considered important.

35. Unless two canals were treated simultaneously, dye concentrations were not necessarily measured at the same number of hours after treatment. For some ANOVA comparisons, so that only data from samples taken at similar times after treatment were compared, data from some sampling periods were disregarded.

36. Linear regressions of dye concentration against time were also calculated to determine if the data fitted the linear model and to provide dilution rates and half-lives for simplified comparisons (Table 2). In later analyses the same statistical procedures were applied to the data from each canal to compare the rates of dilution from different transects (TRANSECT) and water depths (DEPTH).

37. Data were not used in these analyses from the first high tide sampling period, nor from transect 1. There was greater variation in the data from the first high tide sampling period than from subsequent sampling times. This was caused by insufficient mixing during the short time period of flood tide following the application. In addition, small isolated patches of concentrated dye created "hot spots" that frequently occurred at this stage. These hot spots were due to temporary high concentrations of dye produced by the application pole and/or trailing hoses when they were caught in vegetation, etc.

38. Great variations were noted in the mean concentrations of dye between different sampling periods at transect 1, resulting in very low regression coefficients (R^2). This variability was related to the differences in water levels at high tide (particularly in neap cycles) and the effect these differences had on the intrusion of untreated water from the Three Sisters Springs and header canal.

PART III: RESULTS AND DISCUSSION

Dye Dissipation

Dye stability

39. The dilution of dye in the polypropylene bag enclosures differed from that in the open water (Table 3). These results indicated that decomposition of the isolated dye solution was negligible over a 2-week period. Therefore, the dissipation of dye from the canals was presumably the result of water exchange and not photodegradation or microbial degradation, verifying published characteristics of the dye.

Cross-contamination between treated canals

40. Cross-contamination might have been expected if dye-treated water, leaving a canal on an ebb tide, flowed back into an adjacent canal on the following flood tide. This would have affected an untreated canal on the downstream (west) side of a treated canal (e.g., dye moving from C to B).

41. Dye readings taken in untreated Canal B, 1 to 6 days after treatment of Canals A and C, are presented in Table 4. Dye concentrations in Canal B were small compared to those in Canals A and C at the same sampling times.

42. From these results it was determined that adjacent canals should not be treated with dye simultaneously. However, in two nonadjacent canals treated simultaneously, cross-contamination would probably have little effect on dye half-lives.

Variance within canals

43. Horizontal. It was expected that the rates of dye dilution would be slower in the transects toward the head of a canal (4 and 5) than in those nearer the mouth. Dye-treated water at the head of a canal would be less likely to come into contact with, and be diluted by, the incoming untreated water. Furthermore, past herbicide treatments were observed to be effective in the head of a canal, often causing no damage to plants near the mouth.

44. In all treatments, significant differences in dye concentrations occurred between the transects when averaged over all sampling times. Table 5 indicates the differences in mean concentrations (calculated over all sampling times) between transects 2 and 5, with significantly more dye at the head of the canals. The only pattern that emerged from these data was that for most

of the winter treatments (A_4, B_2, C_2), the ratios of concentrations at transect 5/transect 2 were lower than at other times of the year.

45. Similarly, the interactions of TIME*TRANSECT were only significant for the winter treatments. Generally, the R^2 values of the regressions calculated for each transect of these treatments (Table 6) improved toward the head of the canal. However, the half-lives did not necessarily increase with distance from the canal mouth.

46. Vertical. For all treatments except A_5 and D_2, significant differences were noted between dye concentrations (averaged over all sampling times) in the top and bottom halves of the water column. These top and bottom concentrations and the ratios top/bottom are presented in Table 7. The TIME*DEPTH interaction was significant in five treatments: A_4, B_2, C_1, C_3, and C_4. No relationship was noted between these significant interactions and either season or vegetation density.

47. There was a clear relationship, however, between season and the vertical distribution of the mean dye concentrations (Table 7). In all summer treatments, the concentration of dye was greatest in the top half of the water column. For the summer treatments that had significant DEPTH*TIME interactions (C_1, C_3, C_4), the fastest dilution rates were at the bottom.

48. In winter, fall, and spring, the greater concentrations of dye occurred in the bottom half of the water column. In Treatment A_4 (winter), the rate of dilution was significantly faster from the surface water. However, the dilution rate was significantly faster from the bottom of the water column in treatment B_2 (winter) even though the mean concentration was higher there as well.

49. No consistent relationship was noted between the vertical distribution of maximum dye concentrations and the density of vegetation.

Variance between canals

50. Pair-wise comparisons of data from the initial canal treatments (A_1, B_1, C_1, D_1) indicated that significant differences in rates of dilution of dye occurred only between Canals B and C. Linear regression lines for these treatments are illustrated in Figure 7, and the equations are listed in Table 2.

51. These results showed that the four canals could be used as replicates, provided that comparisons were not made between Canals B and C. This limitation was acceptable since, based on the cross-contamination data, only alternate pairs of canals were to be treated simultaneously.

Factors Influencing Water Exchange in Canals

Tides

52. Prior to comparing rates of dye dilution in the canals on spring and neap tides, it was necessary to establish that there were significant differences between these tidal cycles in the rise and fall of water levels. Water levels recorded after the dye applications are shown in Figure 8. For eight tidal cycles after each treatment, the sums of rises and falls in water levels (rise = positive change in water level between high and low tide, fall = negative change in water level between high and low tide) were calculated (Table 8). T-tests, comparing the spring and neap tide rises and falls in water level, showed that there were significant differences in water exchange between the two types of tidal cycle. However, results from eight dye treatments (Table 9) showed that rates of dye dilution were not affected by different tidal cycles.

Vegetation

53. Rates of dye dilution differed significantly between canals with sparse and dense vegetation in a winter treatment, but not in summer treatments (Table 10). Reductions in water exchange in densely vegetated canals had been anticipated since reductions in unidirectional water velocity occur in submersed plant beds (Marshall 1978, Getsinger 1988). This spatial differentiation of water movement might have resulted in dye being retained in the hydrilla stands and not mixing with the rest of the water column. Although water above the vegetation would move and be exchanged during the tidal cycles, the prolonged retention of dye in the hydrilla stands was expected to extend the overall dye half-life in a densely vegetated canal.

54. This mechanism of dye retention may have occurred in the winter treatment of a densely vegetated canal (C_2), which had a significantly longer dye half-life than the sparsely vegetated canal (A_4). However, the results of comparisons C_3/A_6 and C_4/A_7 indicate that the time of year had an effect on dye dilution rates that was greater than the effects of vegetation.

55. The fact that vegetation could reduce rates of dye dilution in winter, but not summer, may indicate important differences in water exchange patterns and circulation in the canals between the seasons.

Season

56. Comparisons of treatments A_1 and A_3 showed that there was a highly significant TREAT*TIME interaction. The difference in rates of dye dilution

(10×) increased the half-life of the dye from 12 hr in A_1 (August) to 5 days in A_3 (early October). Subsequent dye treatments (B_2/D_2, A_4/C_2, Table 11) during late October and December produced dye half-lives intermediate to those of August and early October.

57. In the subtropical climate of Florida, the four seasons do not correspond to the traditional dates defined by the equinoxes and solstices. An environmental factor that varied between seasons, and most likely influenced water circulation patterns and dye half-lives, was water temperature. Despite the relatively constant temperature (±1.0° C) of the water issuing from the springs, it was observed that water temperatures within the canals could vary up to 12° C between seasons and up to 4° C through the water column.

58. Typical examples of seasonal variations in water temperature are shown in Figure 9. These data were collected from the same transect (2), in the same canal (A), at approximately 1515 to 1800 hr in June, October, and December. Springtime water temperatures were in a range of values intermediate to those of winter and summer. Unlike fall, vertical temperature stratification was usually maintained in the springtime.

59. Table 11 presents all direct comparisons between treatments made in each of the seasonal periods defined by water temperatures. Seasonal comparisons were made only between treatments under the same tidal and vegetation conditions. In Table 12, all treatments and half-lives have been sorted between tide, vegetation, and season for easy reference.

60. Dye half-lives measured in summer, fall, and winter were compared using t-tests. These tests confirmed the results of the treatment comparisons shown in Table 11--that rates of dye dilution were significantly different between these three seasons. Springtime treatments (A_5/B_3) had half-lives that were not significantly different from those of the winter or fall.

61. It is likely that the water temperature regimes in the canals may influence patterns of water exchange in two ways: (a) depending on the relative temperature of the canal water in relation to 23.3° C spring water, which on an incoming tide would flow from the Three Sisters Springs, and (b) depending on the relative water temperatures at the surface and bottom of the canal, i.e., the degree of thermal stratification.

Effects of Water Temperature Regime on Water Exchange

62. Figure 10 illustrates how water temperature regimes may affect the dissipation of dye from a canal during the first tidal cycle after treatment. During summer, water issuing from the Three Sisters Springs is colder than that in the canals. On a flood tide, the cold, dense water from the springs will be pushed along the bottom of the header canal into the dead-end canals, and will slide beneath the warmer (less dense) canal water. Thus, at high tide, a wedge of cooler spring water will be under the warmer dye-treated water.

63. On the ebb tide, the water flow from the springs is reversed (i.e., water flows from the springs into the header canal). As a result, water leaving the dead-end canals will be removed from the upper part of the water column, due to the head of pressure at the bottom of the canal mouth created by the flowing springs. Thus, the dye-treated, warmer canal water will leave the canal faster than the cooler water of spring origin. The temperature stratification will tend to reduce mixing between the dye-treated canal water and untreated spring water. This process will be repeated on subsequent tides, resulting in a circulation pattern of water exchange.

64. In the winter a reverse circulation pattern occurs, resulting from the temperature differences between the cooler canal water and the relatively warmer spring water. Winter half-lives are not as short as those in summer. This may be related to the head of pressure from the spring during the ebb tide being equal at the bottom and surface of the water column (rather than being concentrated at the bottom of the canal as seen in summer). Thus, water leaving the canals would include some of the untreated surface water, not just the underlying dye-treated water. This type of circulation pattern would reduce the rate of loss of dye-treated water from the canals.

65. In the fall, a transition stage occurs between the summer and winter temperature regimes, resulting in isothermal conditions. In these isothermal conditions the spring water will move as a front, throughout the water column, into the dead-end canals on a flood tide. The dye-treated water will be pushed back into the canal with little mixing and dilution except at the interface of the two water blocks. The reverse will occur on the ebb tide so that on the next high tide the dye-treated water will return to about the same position it occupied on the initial high tide.

66. In theory, as long as fall isothermal conditions (which may last several weeks) are maintained, the concentration of dye in the canals would not decrease. However, in practice, diurnal variations in the canal water temperature, mixing at the canal/spring water interface, and dilution by water issuing from any springs within the canals would reduce the dye half-life.

67. Water temperature and exchange patterns were less well defined in the springtime than in the other seasons. In late March 1988, isothermal conditions were observed but persisted for only a few days. Warming air conditions rapidly transformed the canals to a summer temperature regime. The dye half-lives of treatments made at this time (A_5 = 62.1 hr, B_3 = 64.9 hr), which were intermediate to those of fall and summer, reflected this transition in water temperature regimes. Springtime is a short season in Florida, with highly variable weather conditions that are not conducive to predictable and stable water temperature regimes. Thus, it may prove difficult to clearly define springtime water circulation patterns in the canals and to predict optimum times for herbicide applications.

68. Some evidence to support the proposed water circulation patterns for summer, winter, and fall was apparent in the analyses of vertical variations in dye concentration. As shown by the top/bottom dye concentration ratios (Table 7), most dye was distributed near the water surface in summer, and toward the canal bottom in winter.

69. Based on the water circulation patterns proposed for isothermal conditions, the top/bottom dye concentration ratios of fall treatments would be expected to approach 1. In fact, these ratios, while consistent within each season, were smaller for treatments in fall than for those in winter.

70. Comparisons of dye concentrations at transects 1 and 2 recorded at low tides with those found at the subsequent high tides should also provide valuable information on the water circulation patterns. This information is available for a summer treatment (A_1), and it is anticipated that winter and fall data may be collected in future experiments in Crystal River in 1989.

71. A further method of testing these circulation hypotheses would be to inject dye, over a flood tide cycle, directly into the water issuing from the Three Sisters Springs. Tracking the movement of this dye-treated water throughout the flood and subsequent ebb tide should show the reverse distribution of dye to that illustrated in Figure 10.

Water Exchange and Herbicide Efficacy

Endothall

72. Taking advantage of the long half-life of the dye in treatment A_3, Canal A was treated with endothall on the neap tide of 14 October 1987. The liquid endothall formulation, Aquathol K, was applied to achieve a mean concentration of 3 mg/ℓ of endothall in the water column. This is the maximum endothall concentration permitted for hydrilla control in Florida.

73. This treatment provided adequate hydrilla control, as fathometer tracings showed a reduction in the percentage of vegetation in the longitudinal section from 97 percent pretreatment to 18 percent 13 days posttreatment. This treatment also had a reasonably long-lasting effect on the hydrilla since the amount of vegetation was only 15 percent 57 days after treatment (Figure 11) and 23 percent 66 days after treatment (Table 13).

74. Two weeks later, Aquathol K was applied with the dye to Canals B and D. Hydrilla was reduced from 92 to 53 percent 12 days after treatment in Canal B. A month later, hydrilla was reduced to 17 percent, but recovered to 99 percent by mid-March. In Canal D, which had a significantly shorter dye half-life, there was only a slight reduction in vegetation, from 70 to 50 percent of the longitudinal transect.

75. In an attempt to use the predicted long dye half-lives during the springtime water temperature regime, concurrent applications of endothall and dye were made to Canals A and B in March 1988. Equal rates of Aquathol K and the granular endothall formulation, Aquathol, were applied to Canal A to achieve 3 mg/ℓ endothall. This treatment reduced the amount of hydrilla by approximately 50 percent within a month (Table 13), but regrowth was rapid within the next 6 weeks. Similar results were noted in Canal B, where only the liquid formulation of endothall was applied. Substantial mechanical harvesting was required at the end of May to remove rapid hydrilla regrowth.

76. The springtime herbicide treatments were probably less effective than those made in the fall because of the shorter exposure period to the herbicide, indicated by the shorter dye half-lives. Only short-term hydrilla control was achieved since the subsequent summer conditions (long days and warmer temperatures) were suitable for rapid regrowth.

77. In October 1988, further concurrent applications of endothall (liquid and granular) and dye were made to Canals A and B and part of the header canal. Within 3 weeks the hydrilla in Canals A and B had been reduced

from 100 percent to approximately 20 percent of the longitudinal cross section. However, regrowth under the mild winter conditions was substantial by mid-January.

Fluridone

78. Fluridone (aqueous suspension and 5P pellet formulations) was applied to Canals C and D and the bypass canal (east of Canal D) in October 1988. Despite the appearance of good symptoms of fluridone uptake by the hydrilla in both Canals C and D, there was no apparent reduction in the amount of hydrilla. Eventually, at 12 weeks posttreatment, mechanical harvesters had to be used to provide access to these canals.

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

79. The results of this study clearly show that important information on the movement of water in tidal canals can be obtained using fluorescent dyes. The ease and speed of data collection after applications of Rhodamine WT enable multiple treatments to be conducted under a wide range of environmental conditions. Dye studies, similar to those conducted in the Crystal River, could be used to measure bulk water movement in other tidally influenced canals of Florida, as well as in various coastal regions of the Nation.

80. The use of the nonadsorptive dye provides a maximum half-life for any water-soluble chemical that might be added to the canals. Compared to the dye, most herbicides would have a shorter persistence time in the water as a result of adsorption onto organic materials, plant uptake, and microbial or other degradation. The use of dye in this study was intended only to provide information on the water movement in the canals, not to simulate the behavior of biologically active herbicides. This difference in the persistence of dye and herbicides was one reason why dye half-lives could not be used to predict directly the efficacy of herbicide applications.

81. Based on current herbicide efficacy information, dye studies can show conditions in which herbicide applications would be of little or no use. For example, a herbicide requiring a 24-hr contact time at its maximum concentration would be of no value in a water body with a 12-hr dye half-life, such as the Three Sisters Canals in summer.

82. Based on the available results of concurrent herbicide/dye applications, herbicide efficacy at various rates of water exchange could be estimated empirically. For example, the speed and efficacy of plant control obtained from herbicide applications made during periods of minimum water exchange (i.e., in fall, when dye half-lives were longest) should indicate whether control might be possible, were water exchange slightly more rapid. Fall treatments of canals with endothall were very successful and indicated that an early winter endothall treatment (i.e., treatment B_2 when the dye half-life, 60 hr, was considerably longer than in the summer) might be effective. As predicted by the significantly shorter dye half-life (37.7 hr), the simultaneous herbicide treatment D_2 had little effect on the hydrilla.

83. The distinct symptoms of fluridone uptake on hydrilla following the October 1988 treatment suggested that control might be possible if the persistence of the herbicide could be extended. If application methods can be devised (e.g., split treatments, use of slow-release pellets, etc.) so that fluridone is effective in the Three Sisters Canals after a fall or springtime application, hydrilla control may extend for longer periods than has been seen with endothall. Successful fluridone treatments in the canals should reduce the hydrilla management necessary over the year immediately after application. In addition, successful treatments over several years might reduce annual tuber production by hydrilla. Once the tuber stock in the sediments was reduced, more desirable native species might be able to compete with hydrilla and colonize the canals.

84. Assuming that herbicide efficacy can now be reasonably predicted in the Three Sisters Canals, long-term hydrilla management policies can be based on at least three factors: economics, public reaction, and impact on manatees.

85. The relative annual costs of mechanical harvesting and various herbicides will depend not only upon the rapidity of regrowth (and hence the number of treatments needed a year) but also the formulation and concentration of herbicide required. The October 1988 application of endothall granules and liquid was more expensive per acre than the similar (but, at that concentration, ineffective) treatment of fluridone.

86. Although mechanical harvesting can provide immediate plant control, it has to be restricted to the centers of the canals due to boat and dock obstructions. This results in thick surface mats of hydrilla remaining throughout the summer surrounding boats, docks, and swimming areas. This not only leads to the dissatisfaction of residents, but may result in illegal homeowner applications of herbicides. Copper sulphate, most likely to be used under such circumstances, is banned from winter use in the area because of the presence of an endangered species, the West Indian manatee.

Recommendations

87. Results from this study provide the following recommendations for controlling hydrilla in the Three Sisters Canal system:

a. Contact-type herbicides should be applied at low tide, during periods of isothermal water conditions, which usually occur in the fall and, possibly, the spring of the year.

b. Mechanical harvesters, rather than herbicides, should be used in the summer months, when stratified water conditions exist.

88. Although the basic water exchange patterns in the Three Sisters Canals have been determined, the following studies are suggested to improve the capability for predicting the optimum time for herbicide application:

a. Inject dye into the Three Sisters Springs in winter, summer, and fall to test the water circulation hypothesis developed in the initial study.

b. Determine the relationship between dye half-life and water temperature regimes. (This relationship would allow operational personnel to measure water temperature and predict the water exchange rates necessary for optimum herbicide efficacy.)

c. Evaluate selected herbicide application techniques in the springtime, to maximize the period of hydrilla control.

d. Evaluate various fluridone applications in the fall, with emphasis on prolonging fluridone persistence in the water (e.g., the use of controlled-release formulations).

e. Treat Canal D (which is influenced by internal springs) with dye in winter, to determine if the water exchange rate in this canal is significantly faster than in the other canals, as was the case in October 1987 (treatments B_2/D_2).

f. Conduct laboratory and field herbicide efficacy experiments in which the initial herbicide concentration is continuously reduced by dilution, over a range of half-lives.

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Table 1

Dye Treatment Dates and Comparisons Between Dye Treatments in the Three Sisters Canals, Matched with Study Objectives

Date	Treatment	Tide	Vegetation*	For Comparison	Objective**
			1987		
25 Aug	A_1	Spring	-	B_1, C_1, D_1	1
27 Aug	C_1	Spring	-	A_1, B_1, D_1	1
31 Aug	A_2	Neap	-	A_1	2
8 Sep	D_1	Spring	-	A_1, B_1, C_1	1
10 Sep	B_1	Spring	-	A_1, C_1, D_1	1
5 Oct	A_3	Spring	+	A_1	2
28 Oct	B_2	Neap	+	D_2	1,3
	D_2	Neap	+	B_2	1,3
10 Dec	A_4	Neap	-	C_2, A_2	2
	C_2	Neap	+	A_4, B_2	2
			1988		
24 Mar	A_5	Neap	+	C_2, B_3	2,3
	B_3	Neap	+	B_2, A_5	2,3
21 Apr	A_6	Neap	-	C_3, A_4	2
	C_3	Neap	+	A_6, C_2, A_5	2
31 May	A_7	Spring	-	C_4, A_6	2
	C_4	Spring	+	A_7, C_3, A_3	2
6 Oct	A_8	Neap	+	A_3, C_5, A_5	1,2,3
	C_5	Neap	+	A_8, C_3, C_2, A_5	1,2,3

* Symbols indicate the absence (-) or presence (+) of vegetation.

** Study objectives were to (1) characterize bulk water exchange in four of the Three Sisters Canals and determine whether these canals could be treated as experimental replicates; (2) compare the influence of tidal cycles, vegetation density, and time of year on bulk water exchange in the canals; and (3) evaluate the efficacy of herbicides applied to the canals under optimal conditions for controlling hydrilla, as predicted by water exchange patterns.

Table 2

Regression Equations for the Linear Model of Dye Dilutions from the Three Sisters Canals

Canal	$C_t = C_o - a(t)$	R^2 percent	Half-Life hr
A_1	y = 2.16 - 0.055t	98.9	12.6
B_1	y = 2.01 - 0.036t	93.8	19.2
C_1	y = 2.84 - 0.062t	99.3	11.2
D_1	y = 1.79 - 0.052t	99.1	13.2
A_2	y = 1.15 - 0.052t	87.9	13.3
A_3	y = 1.76 - 0.006t	81.3	119.9
B_2	y = 2.58 - 0.011t	97.3	60.0
D_2	y = 1.57 - 0.018t	98.5	37.7
A_4	y = 2.46 - 0.023t	97.9	29.5
C_2	y = 2.36 - 0.014t	96.3	50.6
A_5	y = 1.77 - 0.011t	98.2	62.1
B_3	y = 1.52 - 0.011t	98.3	64.9
A_6	y = 1.91 - 0.035t	99.3	19.7
C_3	y = 1.98 - 0.028t	99.2	24.5
A_7	y = 1.54 - 0.029t	94.6	23.8
C_4	y = 1.49 - 0.028t	86.4	24.7
A_8	y = 2.05 - 0.009t	97.6	76.7
C_5	y = 1.40 - 0.006t	95.3	116.9

Table 3

Percentages of Initial Dye Concentrations Remaining in the Dye Bags and Open Water Over Several Days Posttreatment

Time After Bags Filled, hr	Treatment: B_2 (Bag) (9.5)*	Treatment: B_2 (Open) (13.2)
0	100	100
19	108	83
45	103	51
Rain →		
195	112	14
Rain →		
329	93	3
	A_4 (Bag) (8.5)	A_4 (Open) (12.2)
0	100	100
11	102	89
36	100	73
61	102	26
87	100	11
Rain →		
138	95	5
186	90	1

* Initial concentration, in micrograms per liter.

Table 4

Mean Dye Concentrations from Depth Profiles Taken in Canals A, B, and C After the Treatment of Canals A and C, Indicating Cross-Contamination

Time After Treatment, hr	Dye Concentration μg/ℓ			Concentration in B as Percentage of Canals A and C*	
	A	C	B	A	C
		Transect 2			
29.8	3.97	3.19	0.09	3	3
54.6	2.03	2.51	0.13	6	5
103.5	0.73	1.02	0.08	11	8
127.6	0.36	0.64	0.05	14	8
152.7	0.18	0.48	0.04	22	8
		Transect 4			
29.8	6.28	6.62	0.06	1	1
54.6	3.27	4.62	0.08	2	2
103.5	1.32	2.30	0.10	8	4
127.6	0.41	1.15	0.05	12	4
152.7	0.18	0.58	0.03	17	5

* The concentrations in Canal B are expressed as percentages of the equivalent concentrations found in Canals A and C.

Table 5

Mean Concentrations of Dye at Transects 2 and 5, Calculated from All But the First Sampling Times

Treatment	Dye Concentration, μg/ℓ Transect 2	Transect 5	Concentration at Transect 5/ Concentration at Transect 2
		Summer	
A_1	0.39	3.53	9.05
A_2	0.05	1.54	30.80
A_6	0.56	1.75	3.12
A_7	0.41	2.18	5.32
B_1	0.57	4.25	7.46
C_1	0.59	2.16	3.66
C_3	0.78	3.00	3.85
C_4	0.46	2.47	5.37
D_1	0.40	2.06	5.15
		Winter	
A_4	1.08	2.03	1.88
B_2	1.50	2.63	1.75
C_2	1.84	3.77	2.05
D_2	0.21	1.10	5.24
		Fall	
A_3	1.68	6.46	3.84
A_8	1.07	3.32	3.10
C_5	0.56	4.37	7.80
		Spring	
A_5	0.97	3.00	3.09
B_3	0.51	4.00	7.84

Table 6

Half-Lives of Dye ($t_{1/2}$) and R^2 at Each Transect for the Treatments That Had Significant TRANSECT*TIME Interactions

Treatment	Parameter	Transect 1	2	3	4	5
A_4	R^2, %	60.6	93.8	99.6	97.8	96.5
	$t_{1/2}$, hr		35.1	29.1	25.3	26.6
C_2	R^2, %	36.0	51.4	97.9	98.0	99.2
	$t_{1/2}$, hr		89.8	44.2	44.6	42.3
B_2	R^2 , %		95.7	96.2	97.2	98.4
	$t_{1/2}$, hr		67.0	59.2	54.7	57.1
D_2	R^2, %		99.1	96.1	97.1	97.2
	$t_{1/2}$, hr		28.8	45.8	42.7	40.3

Table 7

Mean Concentrations of Dye at the Top and Bottom of the Water Column, Calculated from All but the First Sampling Times

Treatment	Dye Concentration, μg/ℓ Top	Dye Concentration, μg/ℓ Bottom	Top Concentration/ Bottom Concentration
		Summer	
A_1	3.37	0.72	4.68
A_2	0.62	0.11	5.63
A_6	1.22	0.71	1.72
A_7	1.04	0.60	1.73
B_1	2.29	1.02	2.24
C_1	1.89	0.74	2.55
C_3	2.12	1.06	2.00
C_4	1.52	0.37	4.11
D_1	1.47	0.44	3.34
		Winter	
A_4	1.25	1.75	0.71
B_2	1.82	2.32	0.78
C_2	2.70	3.62	0.75
D_2	0.53	0.74	0.72
		Fall	
A_3	2.93	5.92	0.49
A_8	1.48	2.83	0.52
C_5	1.26	2.28	0.55
		Spring	
A_5	2.08	1.75	1.19
B_3	1.36	2.02	0.67

Table 8

Total Changes in Water Level Summed Over Eight Tidal Cycles Following Each Set of Dye Treatments

Treatment	Rise, cm	Fall, cm
	Spring Tide	
A_1	+541	-535
A_3	+498	-495
A_7, C_4	+520	-512
B_1	+484	-469
C_1	+515	-507
D_1	+529	-525
Mean	+515	-507
	Neap Tide	
A_2	+404	-394
A_4, C_2	+421	-414
A_5, B_3	+386	-380
A_6, C_3	+386	-388
A_8, C_5	+401	-381
B_2, D_2	+396	-368
Mean	+399	-387

Table 9

Comparisons of Spring and Neap Tide Treatments When All Other Factors Were Constant

Spring Tide		Neap Tide		
Treatment	$t_{1/2}$*	Treatment	$t_{1/2}$	Significance of ANOVA Interaction TREAT*TIME
A1	12.6	A_2	13.3	Not significant
A_7	23.8	A_6	19.7	Not significant
C_4	24.7	C_3	24.5	Not significant
A_3	119.9	A_8	76.7	Not significant

NOTE: Regression equations are shown in Table 2.
* Dye half-life, hr.

Table 10

Comparisons of Simultaneous Canal Treatments* with Dense and Sparse Vegetation with All Other Factors Constant

Dense Vegetation			Sparse Vegetation			Significance of ANOVA Interaction
Treat	Veg	$t_{1/2}$	Treat	Veg	$t_{1/2}$	TREAT*TIME
			Summer			
C_3	>51	24.5	A_6	29	19.7	Not significant
C_4	>51	24.7	A_7	>29	23.8	Not significant
			Winter			
C_2	66	50.6	A_4	23	29.5	$P < 0.001$

NOTE: Regression equations are shown in Table 2.
* Treat = dye treatment; Veg = percentage of vegetation in longitudinal section along the canal center (%); $t_{1/2}$ = dye half-life, hr.

Table 11

Comparisons of Treatments Carried Out in Different Seasons, As Defined by Water Temperature Regimes,* with All Other Factors Constant

Comparison Between Seasons						Significance of ANOVA Interaction TREAT*TIME
Dye Treatment	Season	$t_{1/2}$	Dye Treatment	Season	$t_{1/2}$	
A2	Summer	13.3	A4	Winter	29.5	P < 0.001
A6	Summer	19.7	A_4	Winter	29.5	P < 0.001
C_3	Summer	24.5	C_2	Winter	50.6	P < 0.001
C_3	Summer	24.5	C_5	Fall	116.9	P < 0.002
C_4	Summer	24.7	A_3	Fall	119.9	P < 0.001
C_3	Summer	24.5	A_5	Spring	62.1	P < 0.001
C_5	Fall	116.9	C_2	Winter	50.6	P < 0.001
C_5	Fall	116.9	A_5	Spring	62.1	Not significant
A_8	Fall	76.7	A_5	Spring	62.1	Not significant
A_5	Spring	62.1	C_2	Winter	50.6	Not significant
B_3	Spring	64.9	B_2	Winter	60.0	Not significant

NOTE: Regression equations are shown in Table 3.

* See Figure 9.

Table 12

Dye Treatments with Their Half-Lives Sorted According to Season (As Defined by Water Temperature Regimes), Type of Tide, and Density of Vegetation

Vegetation	Dye Half-Lives (hr) by Treatment Summer	Fall	Spring	Winter
		Spring Tide		
Sparse	A_1 12.6			
	A_7 23.8			
	B_1 19.2			
	C_1 11.2			
	D_1 13.2			
Dense	C_4 24.7	A_3 119.9		
		Neap Tide		
Sparse	A_2 13.3			A_4 29.5
	A_6 19.7			
Dense	C_3 24.5	A_8 76.7	A_5 62.1	B_2 60.0
		C_5 116.9	B_3 64.9	C_2 50.6
				D_2 37.7

Table 13

Estimates of Vegetation Density Calculated from the Percentage of Vegetation in Longitudinal Fathometer Recording Along the Centers of the Canals (Percent)

Date of Recording		Canal A		Canal B		Canal C		Canal D
				1987				
10 Sep		44		22		11		21
14 Oct		97						
	E-->							
27 Oct		18		92				70
			E-->				E-->	
9 Nov		15		53				60
24 Nov		15		28				50
10 Dec		23		17		66		51
					E-->			
				1988				
17 Mar		67		99				
	E-->		E-->					
25 Apr		29		31				
			M-->		M-->			
8 Jun		49		50		51		
6 Oct		100		100		100		100
	E-->		E-->		F-->		F-->	
13 Oct		71		58		100		100
24 Oct		17		22		100		100
					M-->		M-->	
				1989				
11 Jan		48		65		75		76

NOTE: Herbicide applications (E = endothall, F = fluridone) or mechanical harvesting (M) that may have reduced the amount of vegetation immediately prior to the fathometer recordings are indicated.

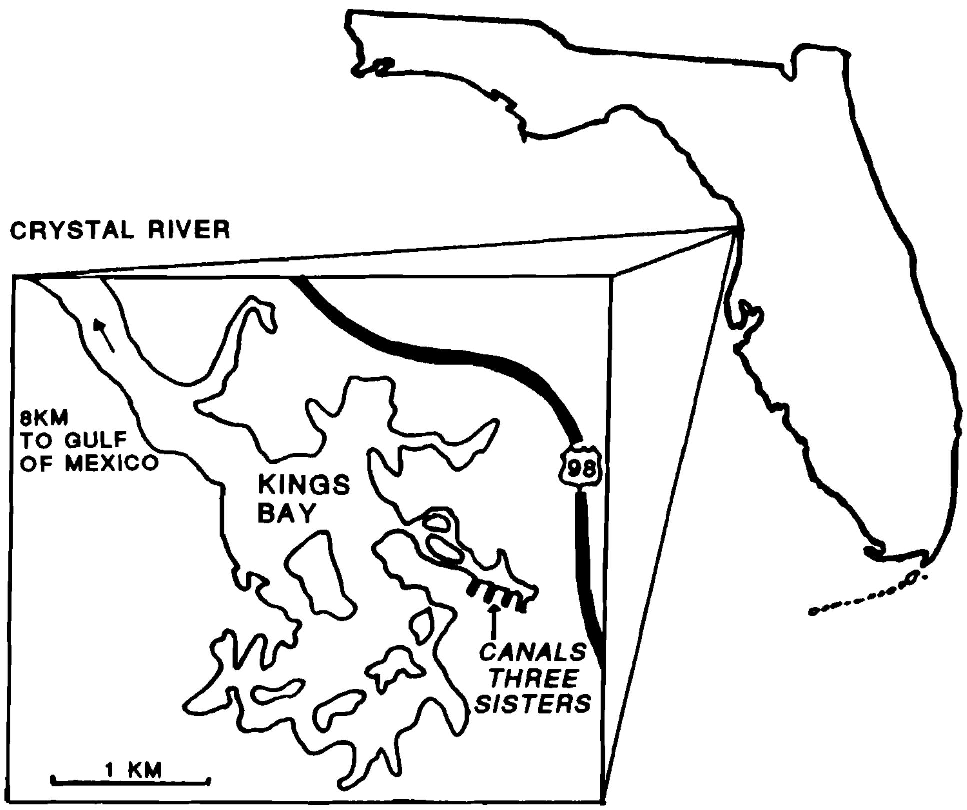


Figure 1. Location map of Three Sisters Canals,
Crystal River, Florida

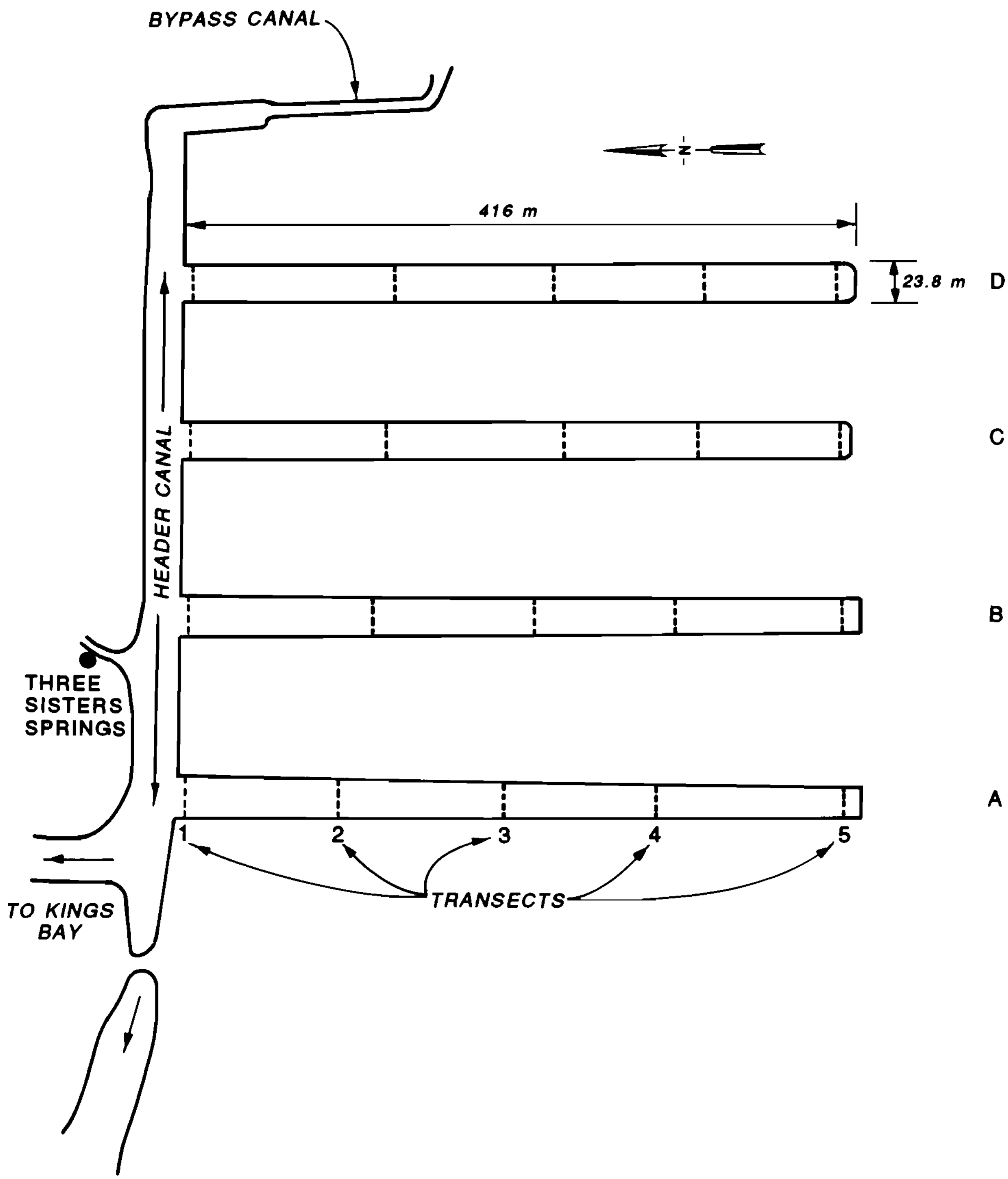


Figure 2. Scale plan of the Three Sisters Canals showing the sampling transects

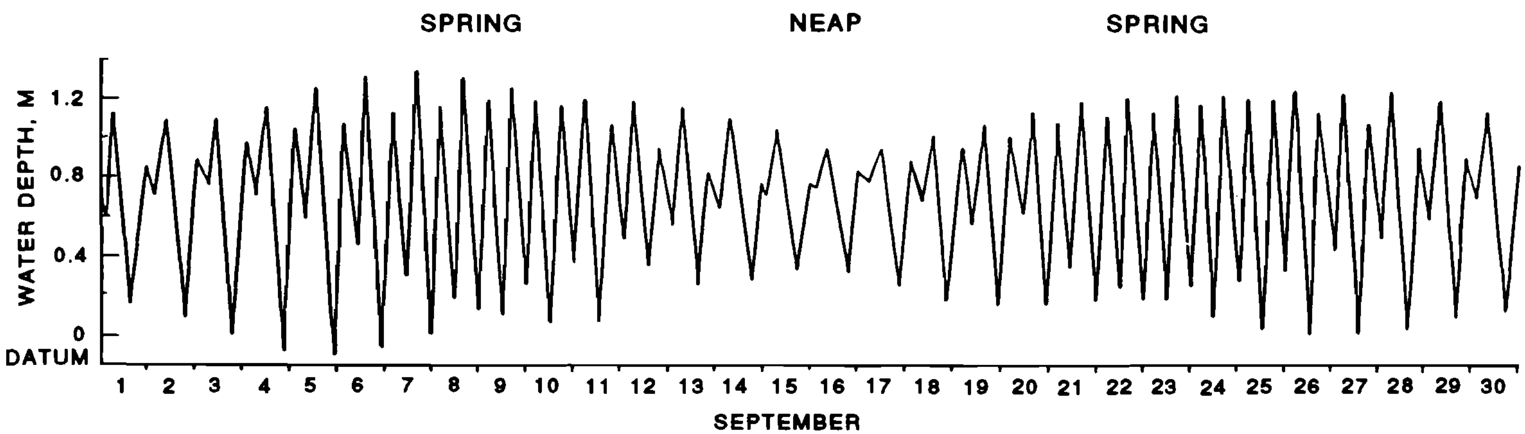


Figure 3. Predicted tidal cycles for Kings Bay, September 1987
(0 = datum = mean low water springs)

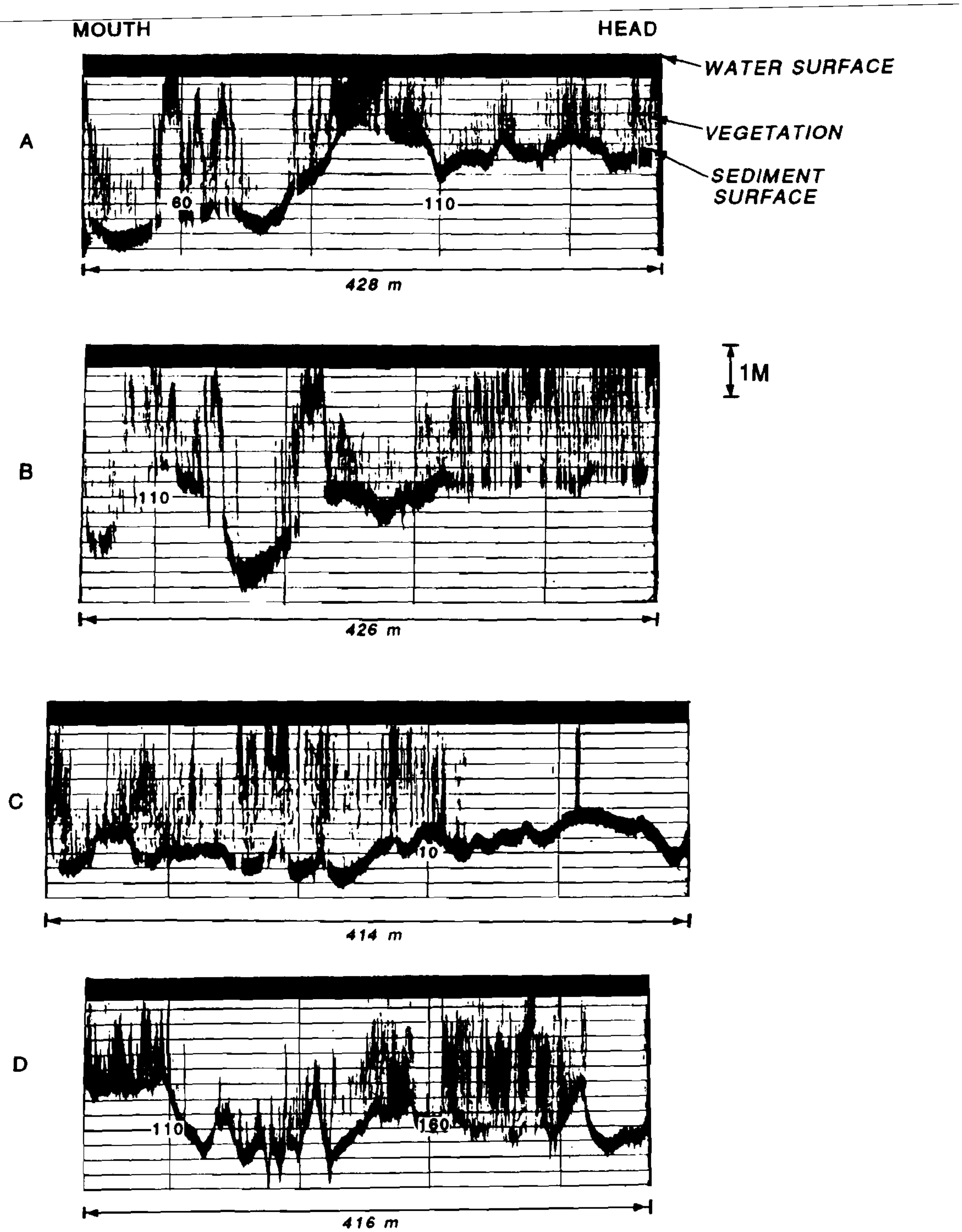
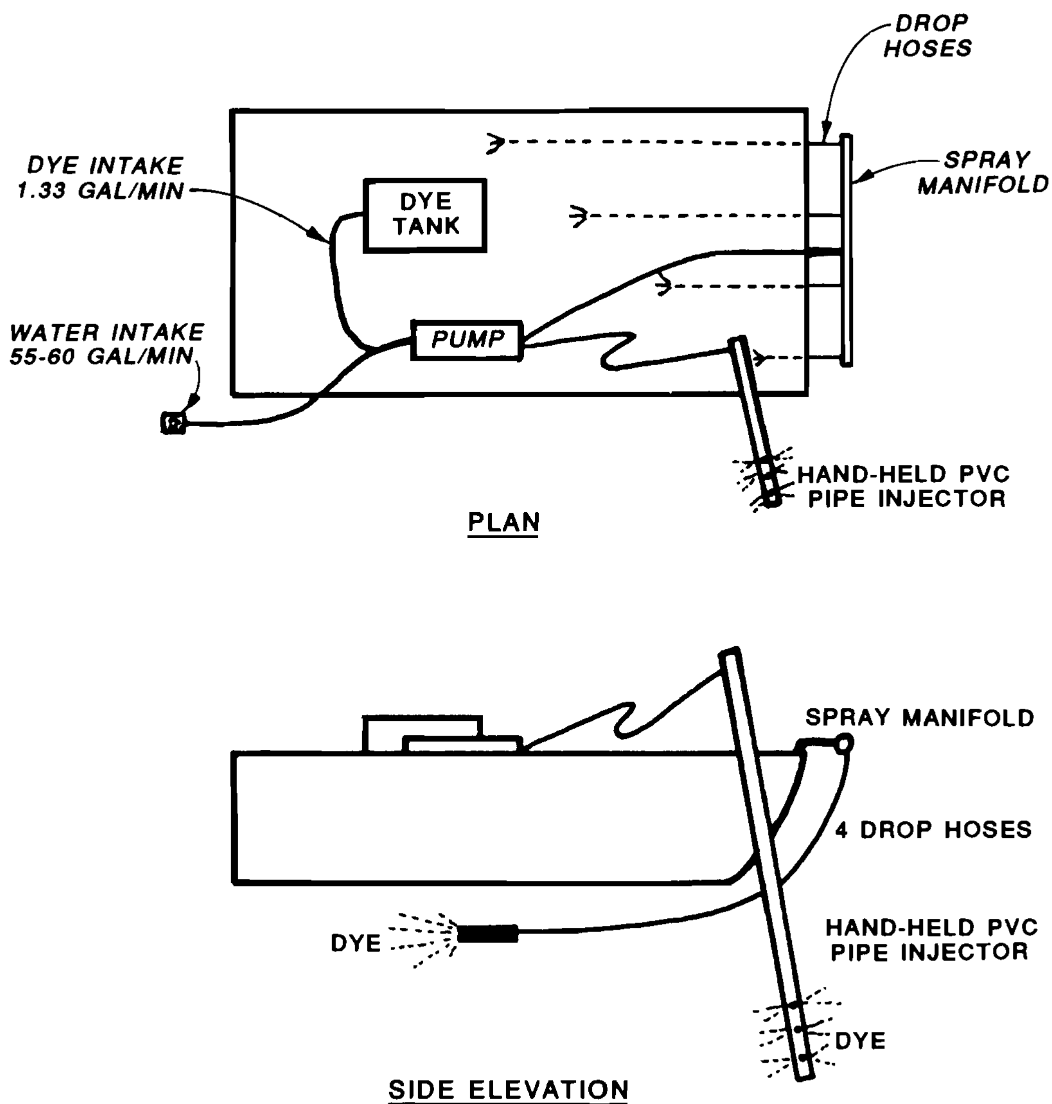


Figure 4. Longitudinal fathometer tracings along the center line of each canal



SPECIFICATIONS:

BOAT SPEED	1 MPH (1.6 KM/HR)
PUMP	227 ℓ/MIN CENTRIFUGAL
DYE TANK MIX	1/2 REQUIRED DYE IN 227ℓ WATER APPLIED AT RATE OF 5 ℓ/MIN
MAKE-UP WATER	208-227 ℓ/MIN

Figure 5. System used to apply dye to the Three Sisters Canals

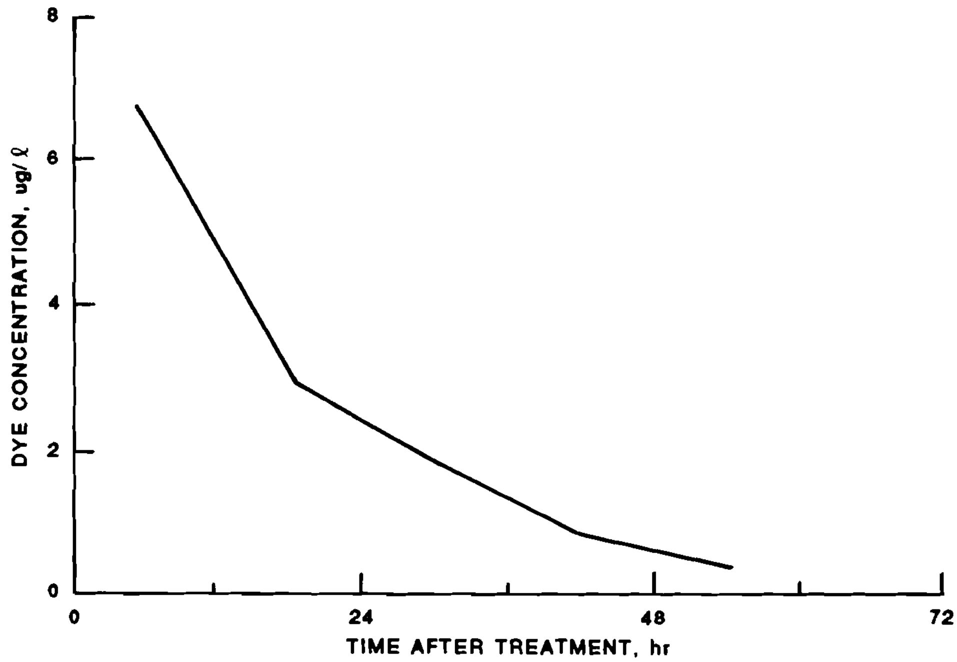


Figure 6. Dye concentrations in Canal A after treatment A_1 showing exponential dilution

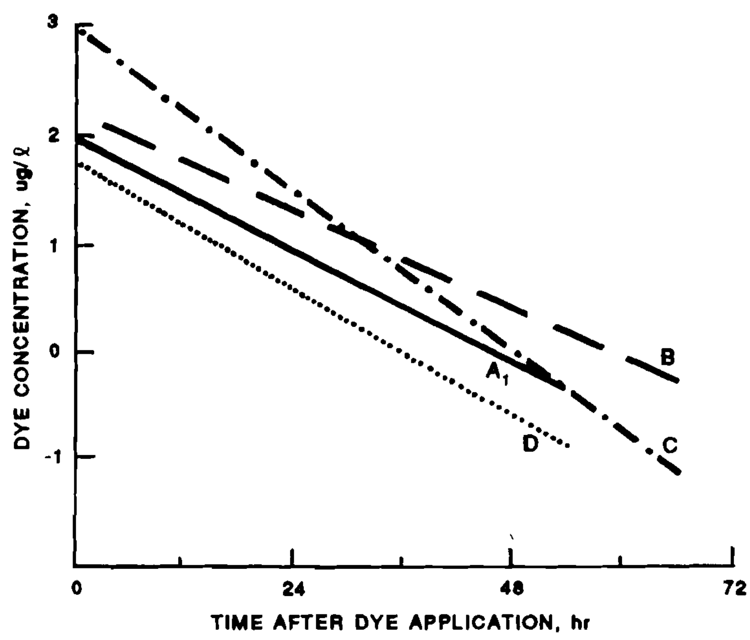


Figure 7. Linear regression lines for the dilution of dye from the four unvegetated canals on spring tides

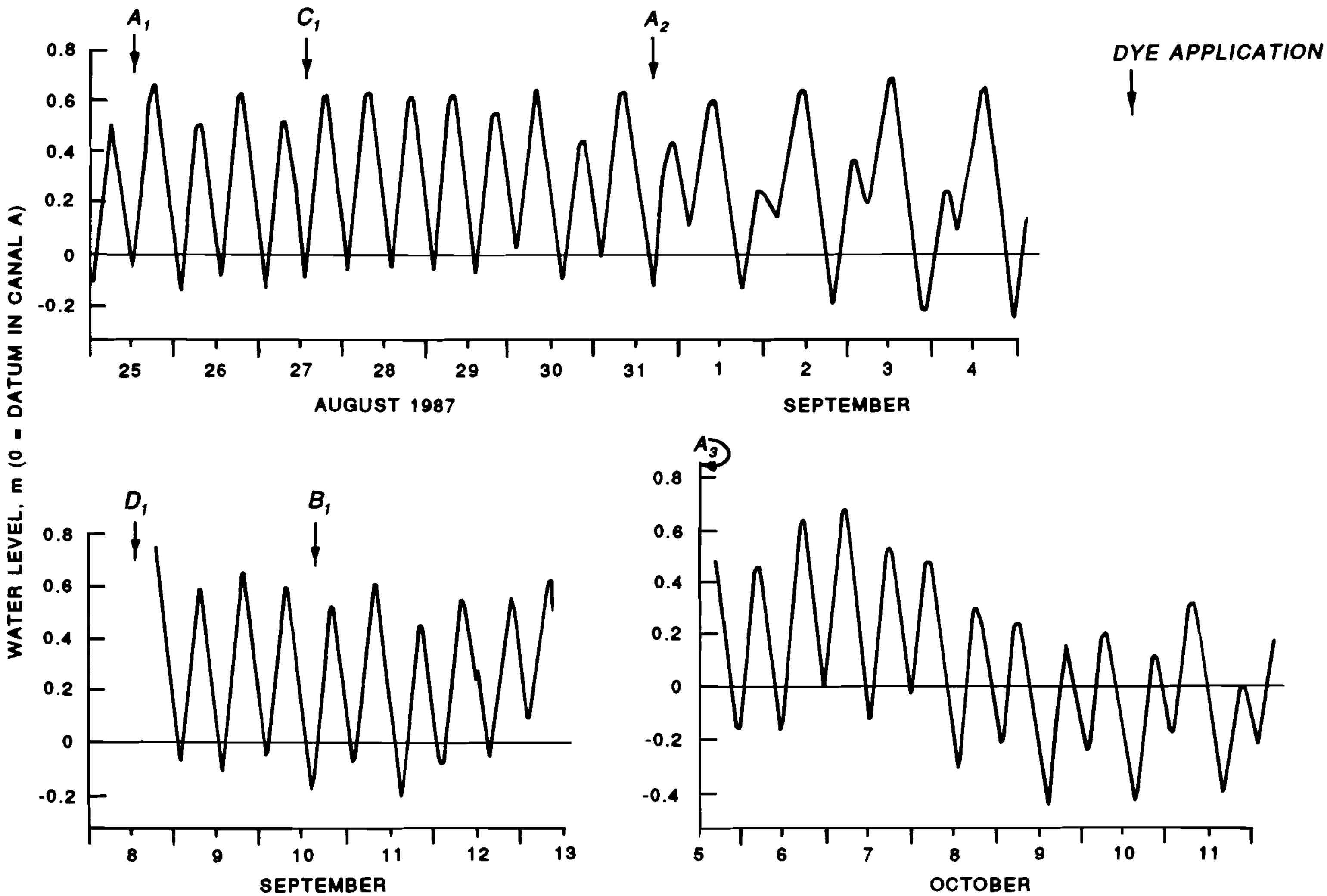


Figure 8. Water levels in the Three Sisters Canals after each dye application (Sheet 1 of 3)

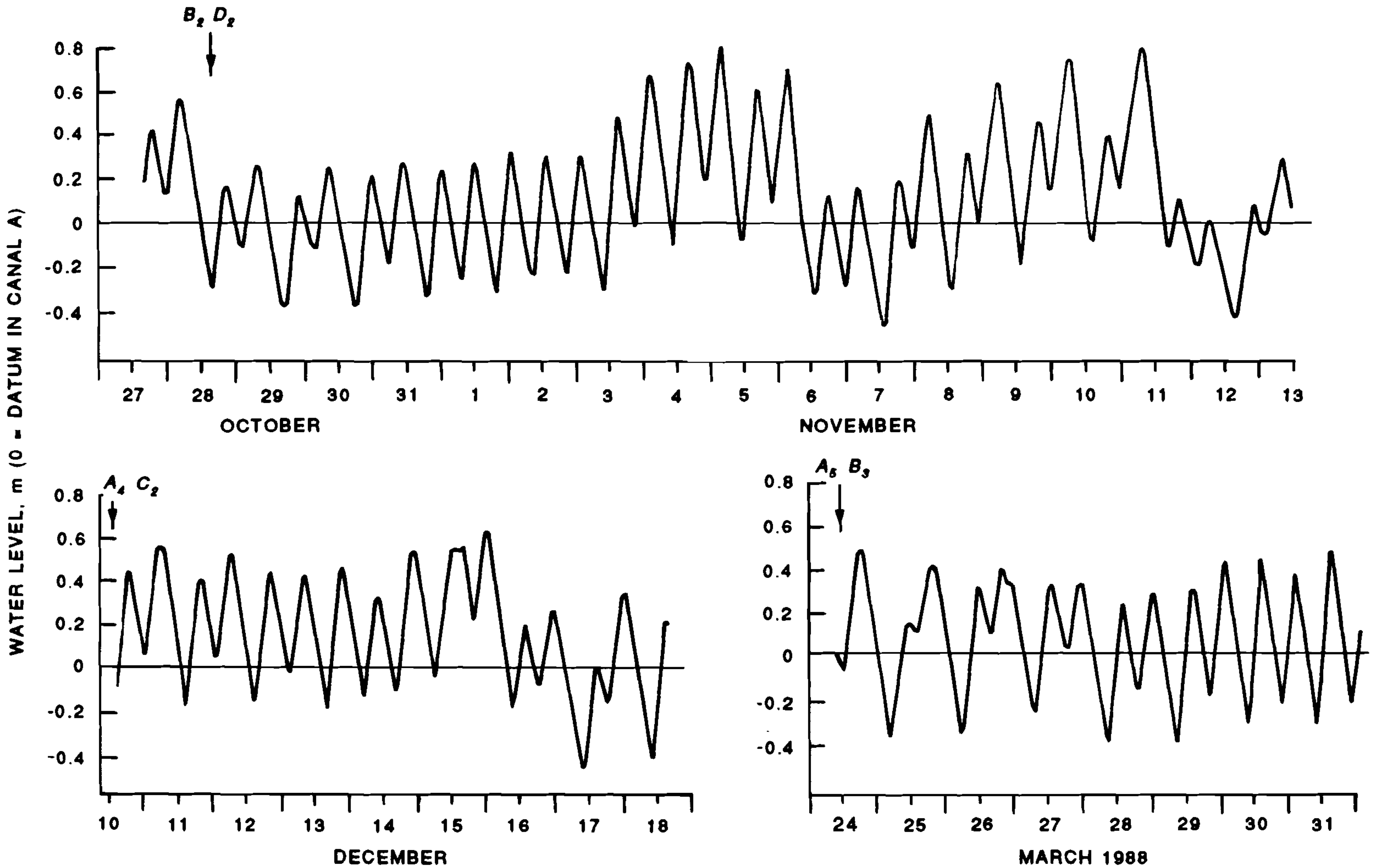


Figure 8. (Sheet 2 of 3)

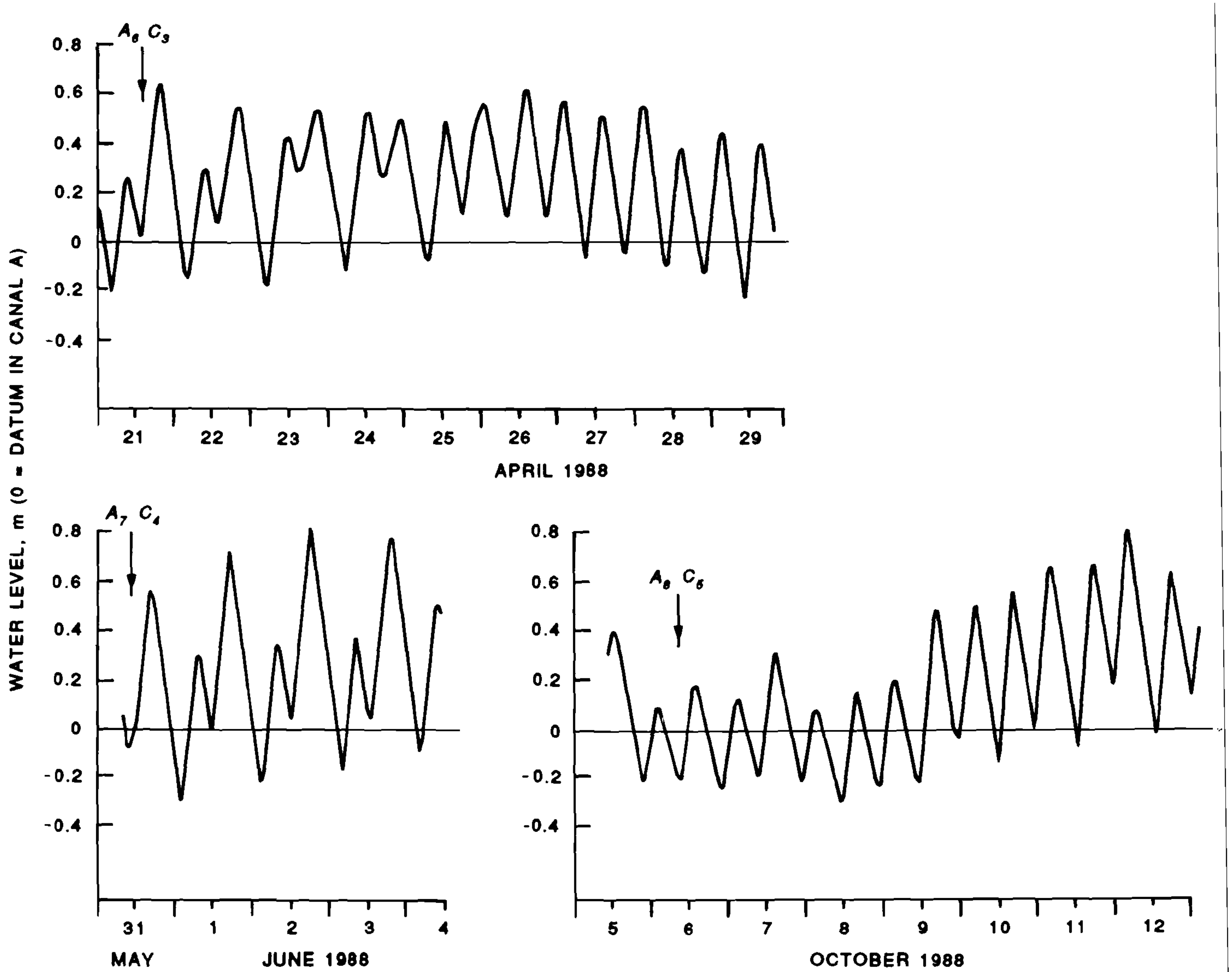


Figure 8. (Sheet 3 of 3)

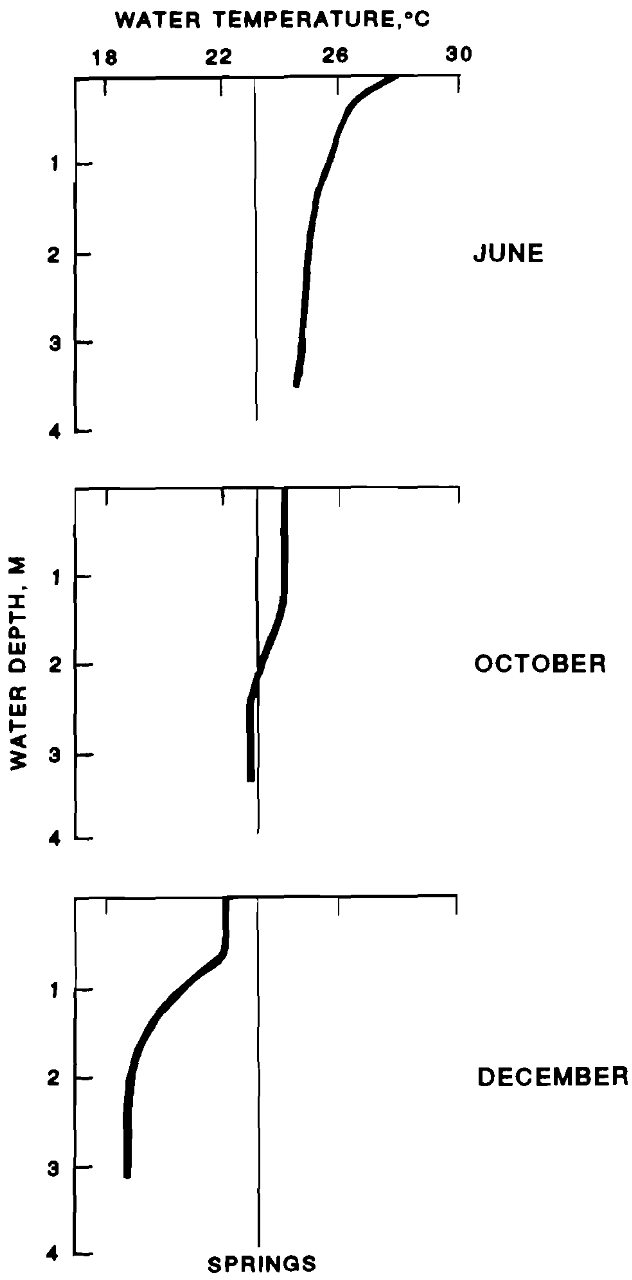


Figure 9. Vertical profiles of water temperatures in Canal A, transect 2, in relation to mean water temperature in Three Sisters Springs

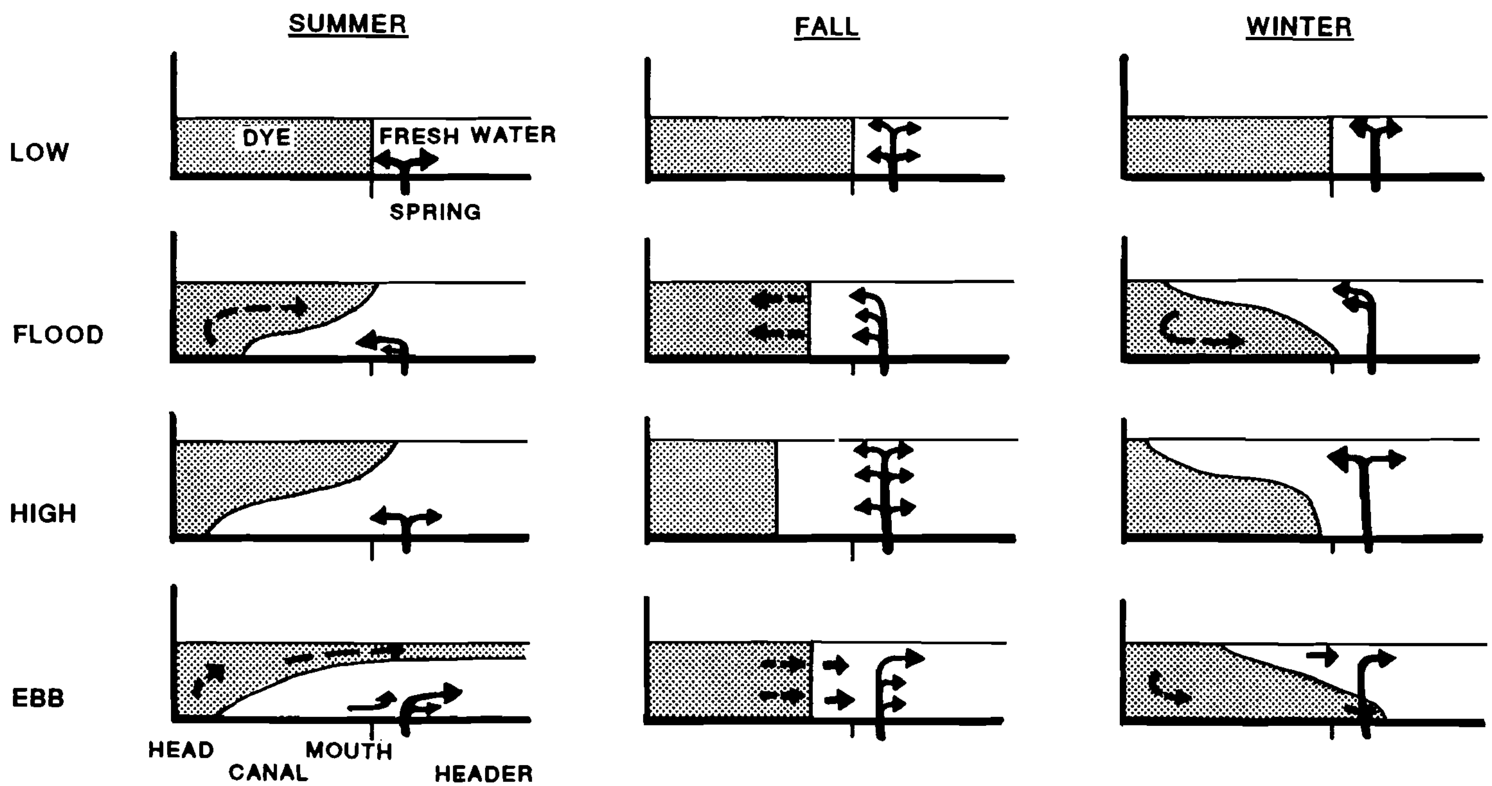


Figure 10. Simplified side elevation diagrams showing possible mechanisms of dye dilution over one tidal cycle after treatment

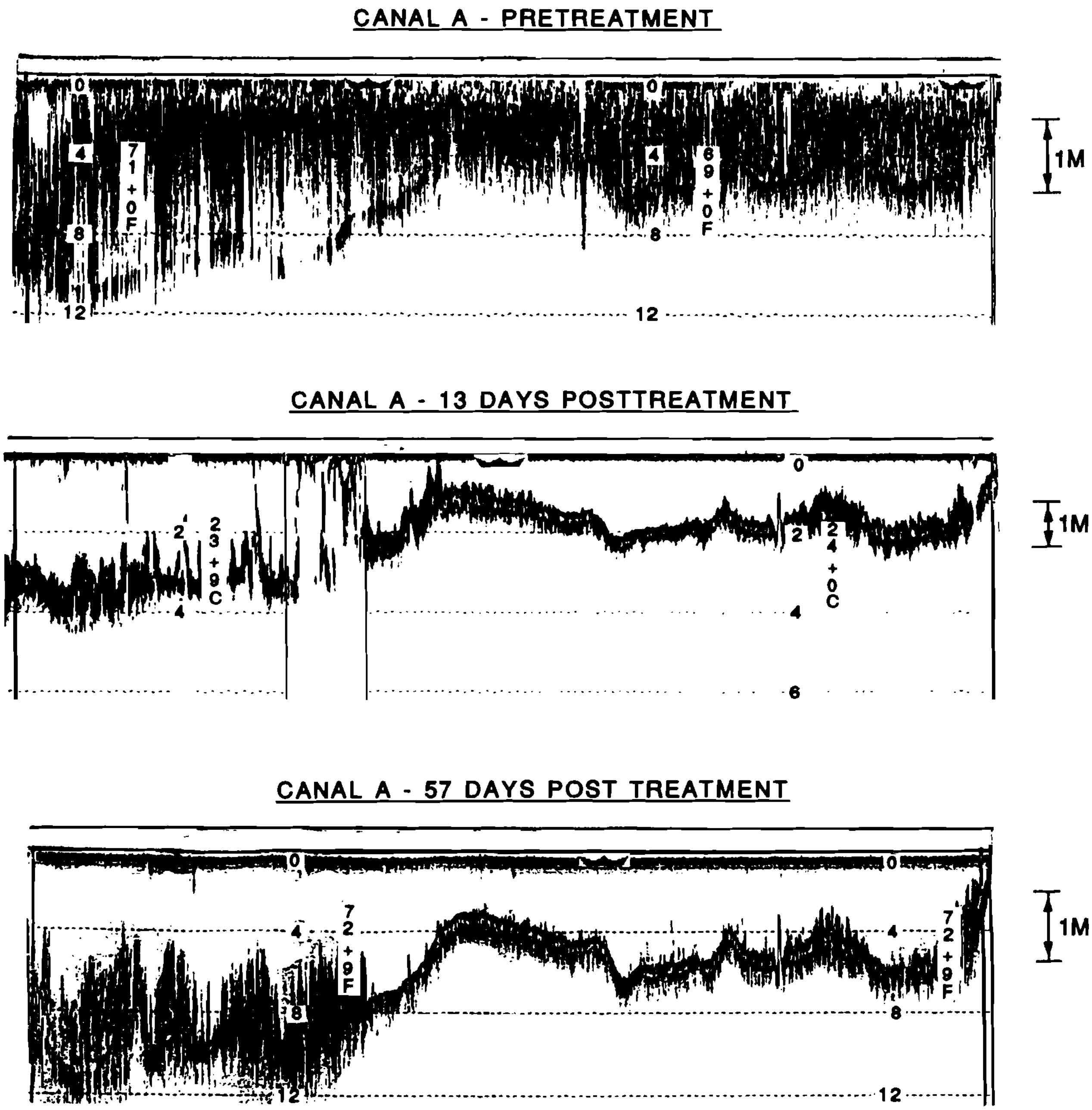


Figure 11. Longitudinal fathometer tracings from the center of Canal A before and after an endothall treatment on 14 October 1987