EPA 600/3-82-004

PB82-265489

Sediment Suspension and Resuspension from Small-Craft Induced Turbulence

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Prepared for

Environmental Protection Agency
Annapolis, MD

Sep 82

U.S. Department of Commerce
National Technical Information Service
NTIS

EPA 600/3-82-084
September 1982

PB82-265489

SEDIMENT SUSPENSION AND RESUSPENSION FROM SMALL-CRAFT INDUCED TURBULENCE

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EPA-78-D-X0426

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CHESAPEAKE BAY PROGRAM
OFFICE OF RESEARCH AND DEVELOPMENT
AND
MIDDLE ATLANTIC REGION III
U.S. ENVIRONMENTAL PROTECTION AGENCY

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1 REPORT NO EPA 600/3-82-084	2	3 RECIPIENT'S ACCESSION NO. PB82 265489
4 TITLE AND SUBTITLE Sediment Suspension & Resuspension from Small Craft Induced Turbulence		5. REPORT DATE September 1982 6 PERFORMING ORGANIZATION CODE
7 AUTHOR(S) Hermann Gucinski		8 PERFORMING ORGANIZATION REPORT NO. CBP-TR-006S
9 PERFORMING ORGANIZATION NAME AND ADDRESS Anne Arundel Community College Environmental Center Arnold, Maryland 21012		10 PROGRAM ELEMENT NO. 11 CONTRACT/GRANT NO. EPA-78-D-X0426
12 SPONSORING AGENCY NAME AND ADDRESS EPA, Chesapeake Bay Program 2083 West Street Annapolis, Md. 21401		13. TYPE OF REPORT AND PERIOD COVERED Project Report 14. SPONSORING AGENCY CODE

15 SUPPLEMENTARY NOTES

16 ABSTRACT

The objective of this study was to determine if small vessels, operating in shallow waters, have any measurable effects in producing increased turbidities by the resuspension of fine sediments which may affect submerged aquatic vegetation (SAV).
A two-phase approach was used, consisting of field tests in a suitable sub-estuary of the Chesapeake Bay, and laboratory measurements of propeller effects. During field trials, two different vessel types were used to make passes at set speeds over known water depths. Before and after measurements of light extinction, transmission, and gravimetric suspended sediment determinations were used to identify effects. Laboratory experiments were conducted to delineate propeller contribution to possible resuspension; this was done using laser-doppler anemometry to map the turbulence field produced by propeller action.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
	Chesapeake Bay SAV	

18 DISTRIBUTION STATEMENT Unrestricted distribution	19 SECURITY CLASS (This Report) Unclassified	21. NO. OF PAGES 73
	20 SECURITY CLASS (This page) Unclassified	22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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PREFACE

The significant decline of submerged aquatic vegetation (SAV) in the waters of the Chesapeake Bay has led to a multidisciplinary approach in attempting to understand the underlying causes. Many variables needed to be understood, and possible interaction of several variables made it necessary to examine factors that, taken alone, might well be of minor or no significance. The resuspension of sediment by boat wakes and propeller action is thought to be a minor factor; it is addressed in this study because prior information is largely qualitative or stems from studies in geographic regions that cannot be readily extrapolated to waters of the Chesapeake Bay.

Many people contributed to this study in numerous ways, and they deserve thanks. I would like to add unequivocally, that any errors, misconceptions, or insufficiencies that may have crept into the work or this report are solely my own. Dr. Thomas Reif designed and conducted the laboratory experiments. L. Chris Athanas, Westtech consultant, wrote a report, appended to this document, assessing impacts of sediments on the submerged aquatic vegetation (SAV). Technical assistants, students, and volunteers drafted on short notice to help in the field included Debbie Blades, Gus Coccolan, Tristina Dietz, Heidi and Sally Gucinski, Michael Mallonee, Joey Phillips. Illustrating and printing help was provided by Edward Sparks and William Reem. The manuscript was typed by Paige Blick and Sandy Atwell. Valuable comments and criticisms at various stages of the work were provided by Bert Brun, Robert Cory, John Geremia, Blair Kinsman, Walter Valentine, Jerome Williams, and Don Wilson.

predict maximum depths to which effects may be noted. Using this data, together with experimentally determined effects on photosynthetic rates for SAV by other investigators, reduction in carbon fixation can be estimated; however, the ecological significance of changes in this range remains to be established.

This report was submitted in fulfillment of Grant No. EPA-78-D-X0426 by Anne Arundel Community College and the U.S. Naval Academy under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period of March 1, 1979 to March 1, 1980, and the work was completed as of February 5, 1980.

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LIST OF SYMBOLS

α	Light transmission coefficient, defined by $\alpha = -\frac{1}{L} \ln \left(\frac{I}{I_o}\right)$
D	Propeller diameter
Δ	Average increase in suspended sediment concentration
δ	Boundary layer thickness in test flume
$\frac{\delta}{\delta y}$	Partial differential with respect to y
f	Sediment particle drag coefficient
H	Fixed vertical distance between reference plane and water free surface
I	Light intensity at depth of interest
I_o	Reference light intensity of transmissometer
I_{ref}	Light intensity just below the surface, the reference level
J	Advance ratio $= \frac{V_\infty}{\pi DN}$
k	Light extinction coefficient, defined by $k = -\frac{1}{L} \ln \frac{I}{I_{ref}}$
LWL	Vessel's waterline length
ΔL	Depth change for successive photometer measurements
N	Propeller revolutions per minute
n	Sample size
R	Vertical distance from lab experiment fixed reference plane
ρ	Density, kg m^{-3}
$\overline{SS}$	Averaged suspended sediment concentration in mg l^{-1}
$(\overline{SS})_\alpha$	Suspended sediment concentration inferred from transmissometer data
$(\overline{SS})_k$	Suspended sediment concentration inferred from photometer data
τ	Reynold's stress, defined by $\tau_{xy} = -\rho\overline{u'v'} + \mu\left(\frac{\partial \bar{u}}{\partial y} + \frac{\partial \bar{v}}{\partial x}\right)$
UAVG	Velocity of water particle in lab experiment by integrating vertically all measurements a fixed horizontal distance from propeller
UINF	Velocity of water particle remote from propeller in lab experiment
u_m	Orbital velocity of a fluid particle due to wave activity
$\bar{u}$	Normalized mean horizontal velocity of a fluid particle
u'	Instantaneous horizontal velocity of a fluid particle
V	Vessel velocity in m sec^{-1}
V_∞	Fluid velocity in flume away from propeller incluence
v'	Instantaneous vertical velocity of a fluid particle
Y	Vertical distance above reference plane, an experimental variable

SECTION 1

INTRODUCTION

When a boat or ship moves along the surface of the sea, a disturbance is created in the water, part of which moves outward and downward, carrying with it a considerable fraction of the total energy expended to propel the vessel. If the vessel is moving in shallow water, or if the outward travelling disturbance reaches shallow water, some of the available energy may allow bottom interaction of sufficient magnitude to force sediments into motion and cause particle resuspension. The time required for the sediment to settle out of the water column will depend on the particle size, and the presence of background turbulence and motion that may retard the settling rate and produce significant lateral transport of the resuspended sediment.

The disturbance may have an effect on rooted aquatic vegetation if the erosive forces are of sufficient magnitude to displace organic detritus and inorganic silts and muds normally stabilized by the rooted plants; damage may result by subsequent direct attack on root structures. If the resuspended particles are small and hence have long settling times, they will contribute to increased light extinction in the water column, with possible impact on the photosynthetic rate of aquatic plants. Moreover, the settling itself may not reduce the problem immediately, for settling could take place onto leaf structures when appropriate conditions exist, contributing to the problem in another way.

The widespread disappearance of submerged aquatic vegetation (SAV) in the Chesapeake Bay, beginning in the early seventies, has been of intense concern to ecologists and resource managers alike. Many mechanisms have been hypothesized to explain negative or destructive effects on the vegatation. Among them are increased sediment loads caused by hurricane-produced runoff, the increasing reliance placed on herbicides in farm operations, nonpoint source pollution resulting from heavy development pressures in the coastal zone, as well as increased turbidities from increased utilization of Bay waters and tributaries by recreational watercraft (Stevenson and Confer, 1978). While it appears highly likely no single mechanism or process may be the one causative factor that has lead to the type of stresses causing reduction in SAV growth, each of the modes of action must be investigated and quantified, if possible, to

allow the isolation of the most significant, major impacts, or to allow an understanding of the possible synergistic effects of several interacting processes.

This study attempts to determine if small vessels, operating in shallow waters, have any measurable effects in producing increased turbidities by the resuspension of sediments, particularly the finer types of sediments. These have a tendency to remain waterborne for relatively long periods and therefore are capable of producing impacts away from the vessel's operating area if mechanisms for lateral sediment transport are present. The study furthermore seeks to describe limiting conditions under which impacts can be seen, so that some conclusions can be drawn that allow these impacts to be put into perspective with respect to impacts from other possible mechanisms. During field trials, two different vessel types were used to make passes at set speeds over known water depths. Before and after measurements of light extinction, transmission, and gravimetric suspended sediment determinations were used to identify vessel effects. Laboratory experiments were conducted to understand and delineate propeller contribution to possible resuspension. This was done using laser-doppler anemometry to map the turbulence field produced by the propeller's action.

Systematic theoretical study of waves produced by a disturbance in the water, such as a ship, began with Lord Kelvin (1887). It was continued by Taylor (1920) and many others when it became clear that wave-making resistance is the dominant form of resistance for a displacement type surface vessel. Ship design considerations to minimize wave-making resistance are now standard chapters in naval architecture texts (see for example, Comstock 1967). Because our understanding is far from complete, much work is continuing. For example, Peregrine (1971) examines the interaction of the transverse waves astern of a vessel with the bow and stern waves that move outward at an angle of nearly 20° of a vessel's centerline (see Tricker 1964, for an introductory discussion of ships' wakes, especially in shallow water).

Water motion by propellers has been difficult to characterize and understand well. Early theories envisioned propeller action to be like that of a screw advancing in a solid medium, and it was not until advances in aerodynamics were applied to propeller effects that a theory was developed that could account for the most important forces and motions developed by a rotating propeller in a fluid medium (see Comstock 1967 or Gilmer 1967) for basic principles). In essence, the rotating propeller blade acts like an airfoil, with lift generated by a pressure drop across the convex, forward facing surface, which is oriented to have an optimum angle of attack. The thrust developed by the sum of the forces on all blades is transmitted via the shaft to the entire vessel, while water is accelerated astern in a manner that, some distance astern, resembles a jet-like flow. Propeller

rotation imparts vorticity to the water, and the dissipation of vorticity, the jet-like flow, and other eddy effects lead to quasi-turbulent motion in the propeller wake.

While this disturbance does not propagate outward as does the ship-generated surface wave system, locally high-particle velocities can produce shear forces capable of considerable sediment stirring if propeller action occurs in water sufficiently shallow. Understandably, however, research in wave-making resistance and propeller effects has focused on attaining greater hull form and propulsion efficiency, with relatively little attention given to environmental effects. Addressing ships' wakes in particular, Sorensen (1973) notes that while wave formation is relatively well understood for major hull forms and speeds, data on the decrease of wave height with distance from a ship's line of travel is needed for specific situations, while knowledge concerning the effects of some hull forms is lacking. He does not explicitly state this, but his analysis suggests this is particularly true for small craft.

The bulk of the literature reporting wave and turbulent water motion effects comes from studies of coastal processes, such as sediment transport by littoral drift. Nakato et al. (1977), citing the lack of satisfactory theoretical models and the useful insights from laboratory studies, report that resuspension from regular wave trains is proportional to wave amplitude, with mean sediment displacement greatest nearest ripple crests -- when rippled sediment beds are found, a situation likely in beach zones, but unlikely in estuarine tributaries -- and that sediment resuspension affects water motion in the boundary layer. The exclusive use of quartz sands of fairly uniform particle size, median about 140 μ, may make applications to the typical sediment regimes found in the Chesapeake Bay difficult. Komar (1977) also states that no satisfactory relationship between littoral sand transport set into motion by breakers, but allows that the stress τ which leads to resuspension of sandy sediments will depend on the density, a particle drag coefficient f, and a term u_m^2 that is a function of water depth and wave energy as inferred from orbital particle motion.

A further complication is known when considering the nature of sediments more typically associated for the problem under investigation, namely clays and silts, which are cohesive sediments, i.e. sediments that can form highly cohesive aggregates under some conditions. Gust and Walger (1976), making measurements in tidal channels of the North Sea coastline and using metalclad hot wire velocity sensors, found that the normally assumed relationship for finding the friction velocity at the sediment interface does not hold. Instead, suspended cohesive sediments may have a turbulent drag reduction effect, inhibiting erosive stresses to some degree. Finally, Suhayda et al. (1976) add a last dimension of uncertainty by implying that measurement

of pressure fluctuations at the sediment interface suggest that the interface itself is accelerated in response to wave-induced oscillations, making the correct applications of the critical velocity concept even more tenuous.

Studies that combine the analysis of ship induced water motions with possible environmental effects, such as are investigated by coastal engineers, that have come to the attention to this author are relatively few in number. It also comes as no surprise that the majority take a strictly empirical approach. The preponderance of studies have the rationale to determine the effects of ship and barge traffic on channel bank erosion, such as Johnson (1975) and Liou and Herbich (1976). The latter study appeared most useful to contributing information applicable to small craft, as it was aimed at deriving a formula of sediment motion induced by propeller effects. Several shortcomings of the study limit its applicability. One is the use of the disc theory of propeller action; a theory that assumes one may replace the propeller by a disc which simply imparts momentum to the water across its cross-section. From this and typical vessel power and propeller data, a velocity distribution is derived without recourse to velocity measurements. It might be noted that it was the shortcomings of the disc theory that led to the presently used aerodynamic theory of propeller action. The distribution of velocity some distance downstream from the propeller is then analyzed using the theory of orifices, again without recourse to field or laboratory studies. Finally, the sediment interaction assumes noncohesive sediments, limiting interpretations to sediments that have no significant clay fractions.

Of the studies that include effects of small vessels, that of Collins and Noda (1971) addresses only erosive effects. Their overall conclusions suggest that small craft effects will necessarily be minor compared to other factors such as wind-wave damage. The authors assert, without inclusion of good evidence, that wind-induced circulation will be a substantial factor in the lateral transport of resuspended sediments. By assuming erosion rates proportional to the rate of energy dissipation, a step made necessary by time and budgetary contraints, effects of different particle-size distributions, and properties of cohesive sediments are neglected. Thus the estimates of erosive effects may differ from those including field measurements supplemented by attempts to characterize the nature of the boat-induced water motions. However, the approaches Collins and Noda take to arrive at a ranking of boat-wake effects compared to effects by other processes appear fruitful. They are done by looking at boat traffic density statistics, modifying them for distributions of differing hull types, and summarizing them in terms of energy dissipated per foot of shoreline per year. While the choice of units may not be the best possible, especially in terms of comparative analysis, an assessment of this nature is the input required by the resource manager.

Only one series of studies specifically addresses sediment resuspension by small craft. Anderson (1974, 1975), also taking an empirical approach, succeeded in partially plumbing a tidal flat with numerous water intakes, both close to the sediment interface and some distance off the bottom. This resultant sampling network allows sufficient data acquisition to make comparisons of suspended sediment changes with other environmental variables possible, something the author of the present report found difficult to implement. Anderson shows the dramatic impact of attendant environmental factors, particularly the state of the tide, that affect measured boat-induced resuspension of sediments. He concluded that horizontal bottom velocities as low as 0.15 m sec^{-1} are sufficient for resuspension to take place. Since the sediment particle size distribution includes cohesive sediments, this measured value is likely to have applicability to the problem of the study undertaken here. Anderson found the average increase in suspended sediment, produced by the action of two vessel passes during flood tide, to be 4 mg/l. He suggested that differences in sampling results with the state of the tide, even when sampled at identical tide stages (i.e., depths) may have in part been due to exchange of water masses from shallower areas, complicating the interpretation of boat-induced sediment resuspension.

As Anderson's work focused on wave effects, with the vessel pass away from the sampling intake structures, no results for either propeller effects alone or due to combined effects were reported. His analysis of resuspension for differing boat types deserves further discussion because of correspondence of some results seen in this study. Low amplitude waves, as produced by a small, low-powered boat had the effect of lowering the suspended sediment concentration near the bottom, which Anderson attributes to dilution by vertical mixing. Variability between sampling runs may result from lateral, downslope transport by tidal currents. Higher waves, such as 0.10 m waves produced by a 4.2 m (14 ft.) speedboat, produced an increase of suspended sediments of greater than 4 mg/l, but followed by insignificant increases on the second run. This suggests that dynamics of sediment resuspension, sediment settling, and sediment transport were not resolvable with the sampling scheme employed, as individual effects could only rarely be factored out.

Contradictory fluctuations in suspended sediments remained even when higher powered vessels, all planing types, were used. Only when high-powered (300 Hp), large (10 m), displacement vessels were used, or when waves exceeded 0.16 m was the observation of resuspended sediments unequivocal.

Anderson's general conclusions are that resuspension from planing power boats is minor, with resuspension greatest when operated at maximum wave-making speeds, i.e., at nonplaning speeds. Greatest resuspension takes place for displacement-type

vessels. His findings, that even at slow speeds (ca. 5 kn) the effects are significant, are not surprising, for naval architects generally concede that wave-making is greatest at hull-speeds defined as approximately equal to the square root of the waterline length multiplied by 1.4. (Here units must be feet and knots; see Herreshoff (1966) for discussion.) For the 10 m lobsterboat this is approximately 7.5, assuming a waterline length of 9 m (30 feet).

Finally, the work of Yousef (1974) addresses the effect of power boat operation on a number of water quality variables, including the resuspension of sediments. Qualitative evidence was gathered photographically, and showed that a 50 hp motor will stir up sediments in water 1.2 to 2.4 m in depth. It is not clear whether the motor was operated in a stationary mode, at planing speeds, or in the displacement mode. These differences are important because resuspension results from propeller turbulence and wave effects both. The wave effects will differ for different speeds and boat types, while propeller effects will also vary depending on the speed at which boat is moving.

Yousef reports that quantitative changes in turbidity (reported in Jackson Turbidity Units) took place when a boat's horsepower was increased from 28 to 50 and 115, in waters 1.2 to 3.3 m deep, but does not cite information on how boat speeds, propeller immersion, and resulting wakes differed. As will be discussed below, propeller immersion may be an important variable that dictates the distribution of water-particle velocities sufficient to resuspend sediments. Yousef obtains an empirical relationship between effective mixing depth, which he defines as lake depth where turbity changes are of such magnitude as to produce measurable changes in surface readings, and motor horsepower. It appears that because the number of variables that affect the changes of turbidity is quite large and the effect of single variables is not understood or unreported, extrapolation must be done with great care.

It is the lack of understanding of the contribution of individual variables that led us to undertake a laboratory study of a single aspect of the resuspension problem, namely propeller-generated, quasi-turbulent water motion. While combining the results from the laboratory study with the empirical field study may not give a full understanding, it is hoped to contribute information toward assessing a few major variables--such as the depth to which effects can be felt, the relative magnitude of the suspension, and possible impact of biological nature.

SECTION 2

CONCLUSIONS

While the data trends for the laboratory and field measurements show reasonably good agreement, the differences in predicted maximum water depth affected make synthesis of the two sets of observation difficult. Measurements for at least one more set of J values, including observation at a greater distance downstream, might clarify the findings.

Nevertheless, the observations can be summarized as follows:

1. The resuspension of sediments in the path of a small craft is influenced by these variables:

- o water depth.
- o depth of immersion and size of propeller.
- o the advance ratio J, defined as $J = \frac{V\infty}{\pi DN}$
- o wave-making tendency of the vessel.

2. The depth to which stirring is sufficient appears to be quite limited. For example, a small displacement craft that will produce significant stirring in waters 2.0 m deep will have barely measurable effects when water depth increases to 2.3 m.

3. Applying the results of the laboratory tests to a sizeable yacht, 12 to 15 m in length, with a propeller 0.6 m in diameter and immersed to a depth of 1 m, and assuming the worst case for the determination of J, may result in $v \approx 5$ m sec^{-1} at N = 800 rpm. J will become 3.3×10^{-3}, and the maximum depth of stirring is 2.7 m based on propeller effects alone. Because the empirical field tests suggest resuspension from all variables is likely at 1.5 times the depth predicted from laboratory results, sediment resuspension to perhaps nearly 4 m can be expected.

4. The tugboat induced sediment resuspension up to 2.7 mg l^{-1} along its line of travel in waters 2.0 m deep. The amounts were reduced to 1.6 mg l^{-1} when the vessel's path crossed waters 2.3 m deep. Expressed in terms of reduction of light levels at an arbitrary depth, say 1.0 m, this means the percentage of available light at the depth changes from 18 percent to 13 percent at a single vessel pass in waters 2 m deep. The corres-

ponding reduction is from 23 percent to 21 percent in waters 2.3 m deep.

5. Applying the results expressed in (4) to the problem of biological impact requires knowledge of quantitative relationships between suspended sediment effects, or reduction of available light on such factors as plant productivity or other indicators of healthy states for biota. Mr. C. Athanas (1979, see appendix) reported that workers had applied Michaelis-Menton kinetics to measure effects of light reduction on primary productivity. Bayley (1970) determined values for SAV productivity in the Rhode River. Using her approach, the reduction in productivity was calculated from 0.71 mg C h^{-1} to 0.62 mg C h^{-1} for a single vessel pass in 2 m of water, a drop of slightly over 12 percent for the duration of 1 hour.

Similarly, for a tugboat pass at the greater depth, the change of the 1 m level is from 0.77 to 0.76 mg C h^{-1}, only about a 1 percent reduction.

Similar techniques can be employed for the effects of accretion of suspended sediment on leaf structures, a process that may take place when water motion slows and particles are allowed to settle (Athanas 1979).

6. Is it possible to decide if the effects outlined in (5) above are of sufficient magnitude to be a factor in SAV growth? Is the postulated mechanism even valid? Frankly, we don't know. It can only be hoped that some of the other studies of the SAV program allow better deductions concerning such effects to be made. Williams (1980) shows that other effects, such as suspended sediment increases during high runoff periods, changes due to tidal scour, etc. appear to outweigh effects due to boating traffic.

These thoughts are offered on the problem:

a. The depths to which boating effects allow sediment resuspension coincide to depths to which SAV growth is limited in Bay waters.

b. No knowledge is available if multiple passes add linearly to the resuspended load (the work of Anderson 1974, suggests they do not, but the evidence is not conclusive), but it is not startling to envision that effects in areas of heavy boating traffic can easily magnify single vessel effects by an order of magnitude. The study conducted by Roy Mann Associates (1976) pinpoints areas of boating congestion. Comparison to SAV maps (R. Anderson 1979) for upper Bay waters suggests that areas of least SAV distribution, and slowest recovery during the survey period, are also areas of greatest

boating congestion. The same area suffers stresses from other human activity, so that correlation here in no way proves causation.

c. Knowledge of the sediment size distributions surrounding SAV beds would allow resource managers to decide that some areas may merit protection due to the presence of fine sediments which have long settling times (>1 hour), the capacity to allow accumulation on leaf structure due to their cohesiveness, as well as by maintaining higher light extinction in the water column. Our attemps to make an analysis of a limited area using data gathered by the Maryland Geological Survey proved premature, as many of their recently surveyed sites await analysis (Halka, personal communication). Furthermore, their present objectives and limited resources have not allowed extensive sampling in the tributaries, but are confined to Bay waters proper.

7. The problem of sediment resuspension by the action of the outward travelling wake of a vessel could not be adequately addressed given the resources of this study. It must be pointed out that this is a problem of considerable experimental difficulty. The wake of a vessel consists of a set of transverse waves that extend astern and move in the direction of the vessel itself. In deep water, the transverse waves are limited to a line extending outward and astern of the vessel, making an angle of nearly 20° with the line of movement. Here constructive and destructive interference reshapes the direction of the waves. Measurements can readily give wave height and amplitude for a given vessel at a fixed speed. Orbital velocity calculations then yield initial velocity for sediment resuspension. However, when the wave begins to act as an intermediate water depth wave upon interaction with the bottom, its speed, direction, and orbital particle velocities change in a complicated way, making predictions for a given site difficult. This is amplified when a multitude of boats, travelling at widely varying speeds, are to be considered. Our general conclusions, that a fast moving, planing boat creates the lesser effect, do hold in this case. Wake wavelengths are long, orbital velocity reduced, bottom interaction commences at greater depth, and energy dissipation (including that due to resuspension) is spread over a greater area than would be the case for a set of shorter, steeper waves for the same vessel travelling at its maximum wave-making speed. A recent study by Byrne (1980) points out that this "worst" speed is only a knot or two above the common 6 mph limit posted in many state waters.

This raises the question if wake effects must be included in the resorting of sediments in near shore waters of heavily impacted areas. In a reconnaissance survey, Kerhin (1977) finds sandy sediments predominant close to shore, in waters less than

about 2.5 m deep, at the mouth of the Severn River, while fine clay-like silts and muds are ubiquitous in deeper waters there.

Such distributions may have a protective effect for SAV beds in high wave/wake energy environments, if only from the view point of reduced fine suspended sediments.

8. We would cautiously advance these final statements:

Sediment resuspension can be initiated by boat traffic. It appears effects will be measurable in shallow areas of less than 3 m for the most part, and are most likely minor until depths are 2.2 m or less. The concept of the advance ratio allows prediction of the maximum depth affected for known vessel speeds, propeller diameters, and revolutions. Planing craft and other vessels of low propeller immersion will have the least impact, unless water depths become less than about 1.8 - 2.0 m. Effects are increased for vessels moving slowly under a heavy load at high engine rpms. Measured increases in light extinction for specific, but not unusual, craft are statistically significant and suggest decreases in photosynthetic rate for SAV may be possible.

It is tentatively recommended that ecologically sensitive areas be investigated for the presence of fine sediments (<60μ), in which case such areas be protected from excessive traffic, particularly deep-draft, high-powered craft. Can the feasibility of a suspended sediment increase criterion be investigated? Such criterion, if proven realistic from the point of biological impact, would allow some deductions about optimum and maximum traffic for a given vessel type. Its greater benefit may well be in allowing comparison of impacts from many sources, among which vessel wakes may well be minor.

SECTION 3

METHODS AND MATERIALS

FIELD OBSERVATIONS

Site Selection

The objective of the field studies was to determine if there were any measurable effects from sediment resuspension for the methods chosen, to test the effects of different boat/motor types, and to understand the effects for deeper waters and for differing sediments.

Field trials were made at three sites, with the greatest number of measurements at the site having the least depth and a small median particle size for the sediment.

Figure 1 shows the sampling areas, with the Fox Creek area chosen as the prime site because it best met the following criteria:

a. reasonably uniform water depths
b. minimum variation of bottom sediments with a high percentage small-sediment particles (less than 60μ)
c. availability of prior data on natural changes in suspended sediments
d. availability of support facilities, i.e., docks and electrical power.

Site surveys at Fox Creek disclosed a mean water depth of nearly 2 m, with variation across the site of less than 0.3 m. The site is bordered on the east by the locally steep bluffs of Big Island, on the west by the low shores of the Contees Wharf area. Pipette analysis (Carver 1971) showed median particle size to be less than 30μ, while Pierce (1973) reports the clay fraction to be 78 percent by weight, with a dry organic content between 0.3 and 0.48 percent. Significant sand fractions exist in a narrow strip along the beach area nearest the survey site, on Big Island, and here strips of rooted aquatic vegetation also abound.

Pierce (1973) reports similar clay fractions, ranging from 72 to 77 percent by weight for the Sellman Creek site, chosen for its similar sediment characteristic while averaging slightly greater water depths, from 2.0 to 2.4 m.

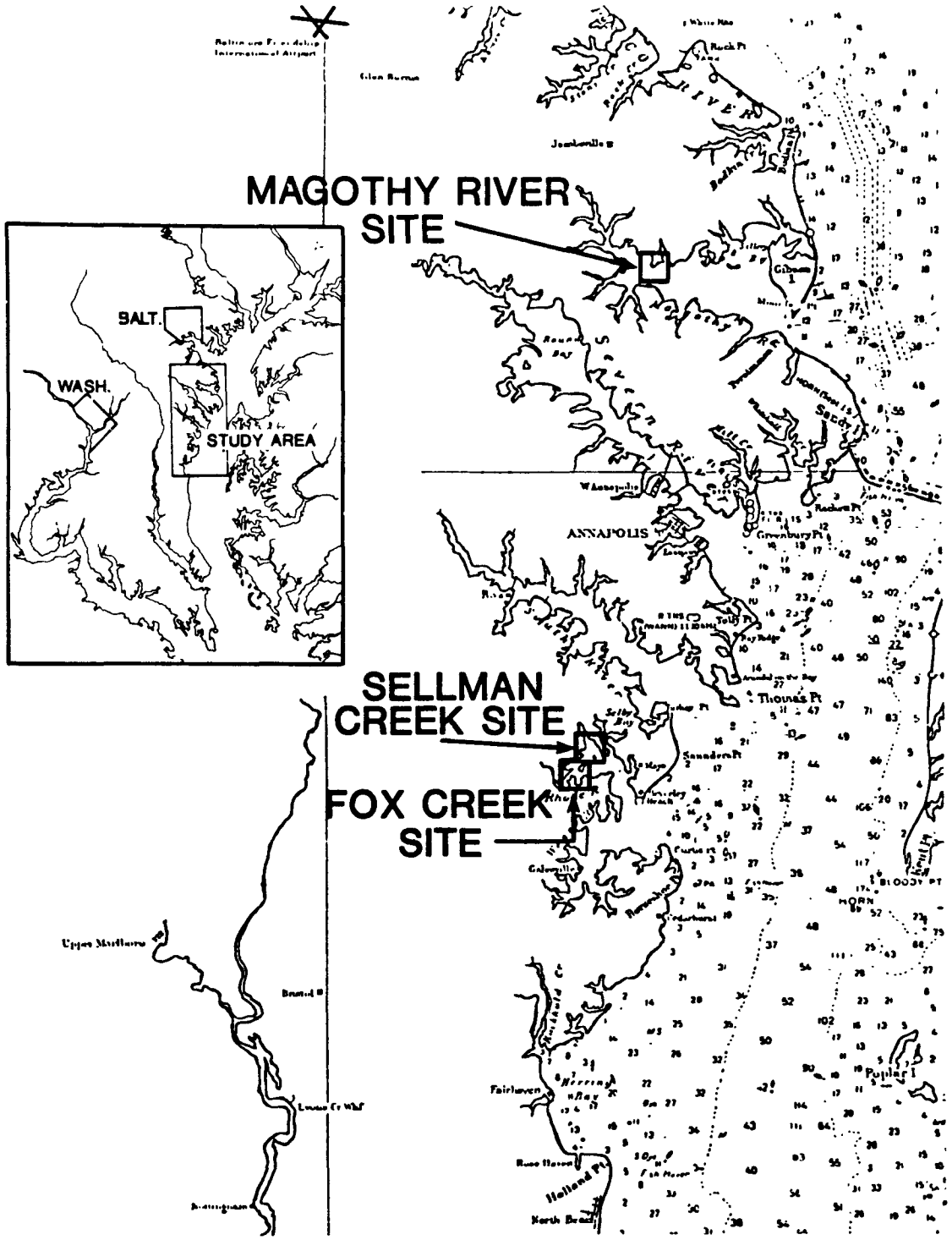

Figure 1. Sampling Sites

The Chest Neck site on the Magothy River was chosen because of the predominantly sandy bottom. It also had depths averaging 2.4 m, but these were minimum depths extending along the sampling line that followed an extended but rather narrow ridge, with water depths dropping off to 5 m on either side. Only a single test was conducted at this latter site; the run served to verify the expectation that no measurable result from the vessel pass would be seen.

Measurements

Each site was marked with a series of buoys, from three to six in number and spaced 25 m apart to mark a track for the test boat to follow as well as to serve as sampling points. Prior to the passage of the vessel a rowboat was used under oars as the sampling vessel. Position during sampling was maintained by tying the vessel to the buoys and avoiding any bottom stirring, such as might occur with the use of anchors. During initial trials, measurements of light extinction and light transmission were supplemented by measurements of conductivity, dissolved oxygen, and temperature using a multisensor Hydrolab Surveyor unit.

At each buoy light extinction and light transmission was determined at 0.5 m intervals initially, later increased to 0.25 m intervals. A set of 2 water samples were taken at the 1.0 m water depth. This was done in sequence for all buoys before and after the vessel path.

Light extinction was measured using a Beckman Enviroeye photometer. While the instrument may lack the sophistication of instruments such as the commonly used model manufactured by GM Corp., careful comparison of the two units showed the latter to have higher sensitivity, but the same degree of precision. As the work was conducted in waters allowing light penetration nearly to the bottom, maximum sensitivity was not deemed of primary importance, and the smaller size and versatility of the Beckman unit dictated its selection.

Light extinction (photometer) data was reduced by making the assumption that extinction followed an exponential curve, as given by Beer-Lambert's Law. Values obtained at a single buoy were plotted on semi-log paper and a leasts-square fit was used to obtain the straight-line segments whose slope represent extinction coefficients. When analyzing for significant before and after vessel pass differences, extinction coefficients obtained from repeated tests were averaged arithmetically.

Light transmission was measured using a Beckman Envirotrans transmissometer, having a folded light path of 0.1 m, but sampling a real space of 0.05 m. Again it was the compact size of the instrument that lead to its choice, and during initial

trials, when attempts were made to see if any changes in the water column could be detected, it proved adequate. However, for future studies the use of a transmissometer having a variable path length would be advisable. It is our belief that it is not any inherent instrument characteristics that affect the readings, but the volume sampled by the instrument. The pattern of measurements allowed somewhat greater consistency in results for readings that represent an average for sampling paths approaching 1 m, rather than measurements where paths were of the order of 0.1 m.

Calibrations

Field calibration of the transmissometer were made by setting the instrument of 82% value in air, all surfaces dry before each sampling sequence at any buoy. The 82% value in air corresponds to at 100% transmission in particle-free water.

During initial runs, readings were taken at the surface and at 0.5 m intervals to a depth about 0.3 m short of the bottom to avoid inadvertant stirring. With increasing experience, the measurement frequency was increased to 0.25 m depth intervals. Because possible detection of sunlight made surface readings with the Beckman transmissometer suspect, readings were not made at depths less than 0.5 m.

Because the relationship between suspended matter and light scattering or extinction is not completely known, water samples were taken for gravimetric determination of suspended sediments, following the method of Strickland and Parsons (1972). The method had to be modified in regard to the desiccation of the Millipore membrane filters, which curled and became brittle under the standard heating process. Comparison showed that filters desiccated for 24 hr. at room temperature had similar weight variability as those heated to 101°C, while weight changes of previously desiccated filters did not exceed 0.1 mg after heating.

Samples for gravimetric determination of suspended sediments were taken with a Martek 1 liter sampling bottle, with sampling held at a constant 1.0 m depth. The sample was decanted into appropriately labelled polyethylene bottles, and a replicate sample was taken for approximately one-third of the samples. Samples were taken to the lab the same day, generally within 1 hour of the conclusion of the vessel tests, and filtered through 0.45 μ Millipore filters under approximately 180 mPa of vacuum. As filter clogging leads to inordinately long filtration times for even 0.5 l samples, 0.2 l or 0.25 l aliquots were filtered. Care was taken to shake the sample bottle vigorously before decanting the sample into the filtration funnel, and the funnel walls were rinsed with de-ionized water during the last few minutes of the filtration cycle.

Replicate filters were prepared when the data variability proved extremely high, thus of the total of 134 gravimetric determinations of suspended sediments, all samples beginning with sample #59 have replicates, as do a number of prior samples. It should be noted that the sampling bottle, which measures about 0.25 m in height exclusive of the triggering mechanisms and is perhaps 0.08 m in diameter, also samples a relatively small volume of water. If microscale distribution of resuspended sediment, whether it is done by boat activity or natural mechanisms, produces large variation on a spacial scale of 0.1 m, then the gravimetric samples suffer from the same problem as the transmissometer measurements.

A sample blank determination was made for each day's sample batch to be analyzed. Filters for blanks were treated as filters for samples, they were desiccated, weighed, mounted on filtration apparatus, removed, oven dried, and reweighed. Only the actual sample filtration was omitted for blanks.

Completion of sampling prior to the vessel pass typically took from a maximum of 60 min. during the early trials to as little as 15 min. during later work, when the number of stations sampled was reduced from 6 to 3. The temporal framework can hence be called quasi-synoptic at best; however, since each buoy location was sampled before and after the vessel pass, each location has its own control, and temporal effects should at least in theory be separable from spacial effects.

Vessel passes were made at set speeds, selected to be the most likely speed for maximum wave making or maximum propeller effect. In the case of the tugboat shown in Figure 2, the R/V Bottlenose, a 9 m 5500 kg displacement-type vessel, powered by an 85 hp diesel engine, this speed proved to be nearly 3.6 m sec^{-1} (7 kn) at an engine rpm of 2000. The vessel swings a 19 x 22 three-bladed propeller, with its hub immersed at approximately 0.7 m. Only a single pass was made for each sampling test, as it was desired to keep variables to a minimum. Two or more vessel passes could conceivably increase complexity because effects may not be linearly additive. If the time interval between passes is sufficient, limited settling and lateral transport my take place, requiring a closely spaced, dense sampling grid for complete evaluation.

Low-speed passes with the tugboat were made at 1500 rpm, which corresponded to a speed of approximately 2.5 m sec^{-1} (4.8 kn). Wave making was slight, and propeller effects reduced in proportion to the reduction in rpm.

Tests involving a planing speedboat were conducted with the R/V Osprey, shown in Figure 3, a 6.7 m (22 ft.) runabout powered by a 135 hp outboard engine. Its propeller dimensions were

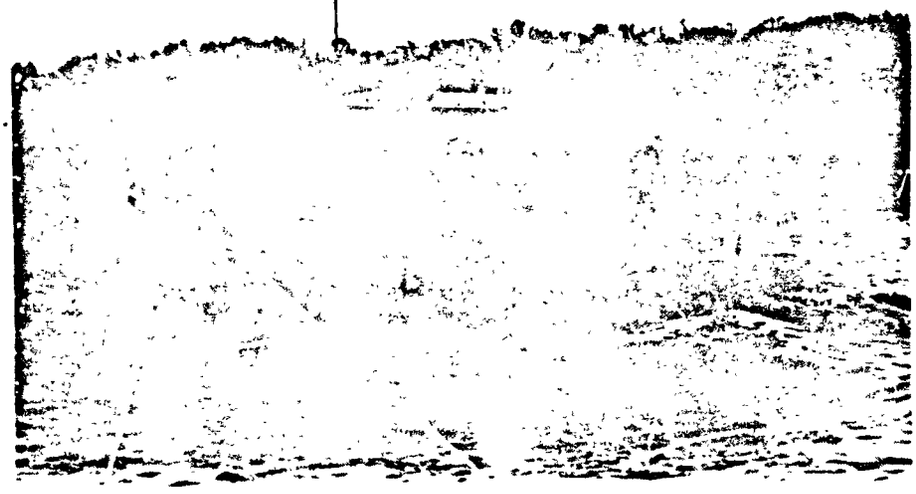

Figure 2. Research Vessel Bottlenose

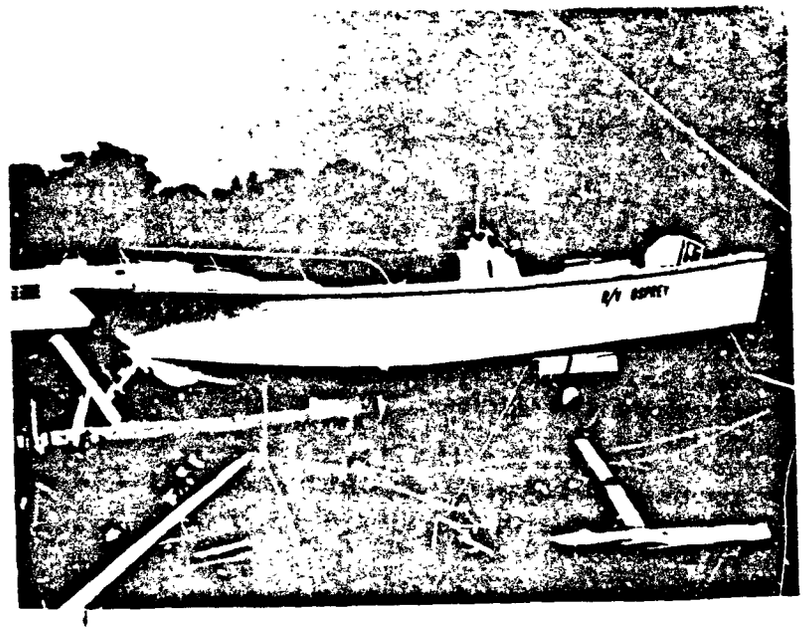

Figure 3. Research Vessel Osprey

16x19 and the depth of immersion of the hub was ca. 0.4 m. The vessel's gross weight is estimated to be 800 kg. Tests were conducted at near maximum planing speed, at 4000 rpm, when the vessel's speed was nearly 13 m sec^{-1} (25 kn). Low-speed runs were chosen as speeds when the boat was off the planing mode, travelling at hull speed, i.e., maximum wave-making speed, in this case 2000 rpm, estimated to be 2.8 m sec^{-1} (5.5 kn).

A few wave recordings of the tugboat at maximum wave-making speed were made, using a Interstate Electronics Model 438-2000 wave staff attached to a Hewlett-Pachard Model 7071B strip chart recorder. The wave staff operates via a conducting wire to measure the changes in immersion during the passage of the waves. Unfortunately, similar recordings were not available for passes of the planing runabout.

LABORATORY EXPERIMENTS

To determine the changes in water particle motion due to the effect of a boat propeller, measurements were made under laboratory conditions, which, by the use of appropriate scaling laws, can be applied to field situations to predict the distribution of stress sufficient for sediment resuspension.

An Armfield, Model 9097, open channel, rectangular flume was used to circulate water at such speeds as to allow a stationary propeller to simulate a moving boat. The appropriate scaling factor was the ratio of propeller advance velocity (i.e., vessel speed) to propeller tip velocity, called the advance ratio J. Measurements of velocity and turbulence intensity were made using a DISA Type 55L Laser Doppler Anemometer, electronically controlled to allow signal averaging appropriate for the turbulence intensities present, typically 150 sec. Details of the flume and the laser doppler anemometer have been published elsewhere (Reif, Metrakos and Hoyt, 1978). After initial experiments showed that appropriate resolution was obtained, each run for a given propeller rpm involved readings of velocity and turbulence intensity at 0.0125 m depth intervals over the entire height of the water column, approximately 0.21 m. Three such sets were measured, at distances of 0.00, 0.135, and 0.270 m dowstream of the propeller hub Complete experiments as described were conducted for 1200, 840, and 570 rpm of the model propeller. The propeller rpm and its corresponding vessel speed were modelled to represent the tugboat used under two different field conditions.

The geometry of the test configuration is shown in Figure 4, while the laser anemometer and the analyzer are shown in Figures 5 and 6, respectively.

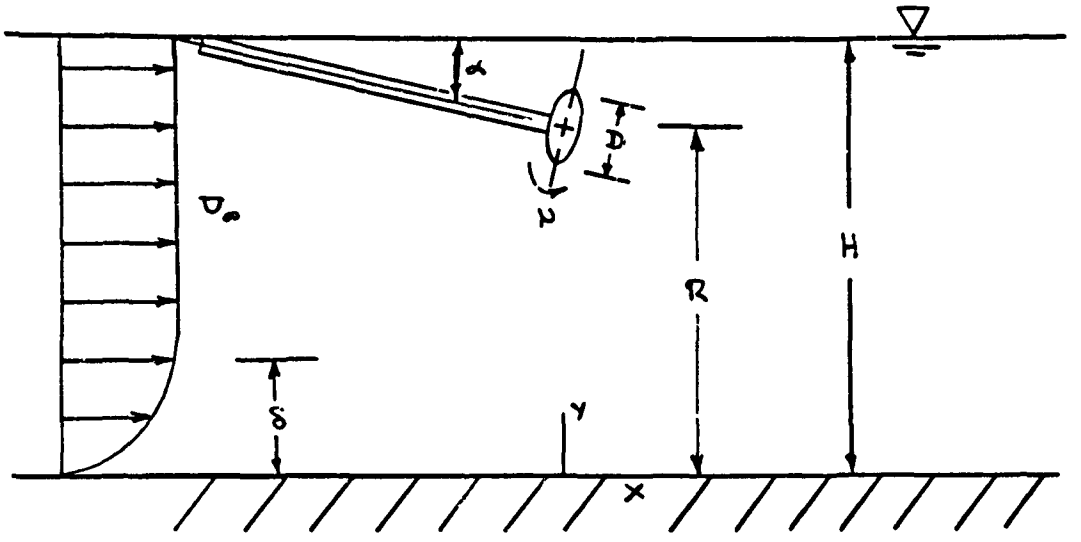

Figure 4. Laboratory Test Geometry

Figure 5. DISA Laser Doppler Anemometer and Test Flume

Methods

The advance ratio J is defined by the following equation

$$J = \frac{V_\infty}{\pi DN} \qquad (1)$$

where V_∞ is the propeller advance velocity, or, in the laboratory test, the velocity of the water in the flume at a location distant from the propeller. D is the propeller diameter, N is the propeller rpm.

For a given advance ratio, model results may be translated into dimensions of interest for full-scale application as follows: Changes along R, the distance from a reference plane to the location of the propeller hub, can be measured in terms of D, the propeller diameter which is the principal linear dimension.

Since the laboratory experiments were designed to simulate the tugboat test at Fox Creek, R was chosen to correspond to the propeller-Creek bottom distance. The ratio D/R was uniform for all experiments as was D/H where H is the water depth.

The unitless ratio Y/R used in the resultant graphs can be converted to represent any depth units if D and D/H are known. In the tests D/H = 0.264 and since D for the tugboat was 0.48 m H, the depth is D/0.264 = 1.82 m. Similarly, a unit along the Y/R scale represents Y/R = 1.17 m for this test. For other cases, but similar J values, the vertical dimension will vary in direct proportion to the propeller diameter.

To ensure that boundary layer effects at the flume bottom were small enough to be remote from the propeller vicinity, the boundary layer thickness was calculated from the experimental conditions, i.e., flume dimensions and velocity.

For a flow rate of 0.46 m^3 min^{-1}, and a water level of 0.22 m, giving a velocity of a 0.40 m sec^{-1}, the boundary layer thickness proved to be 0.04 m; small compared to the distance R of 0.14 m for these experiments. Test runs were conducted for values of J x 10^{-3} of 1.6, 2.4, and 3.5.

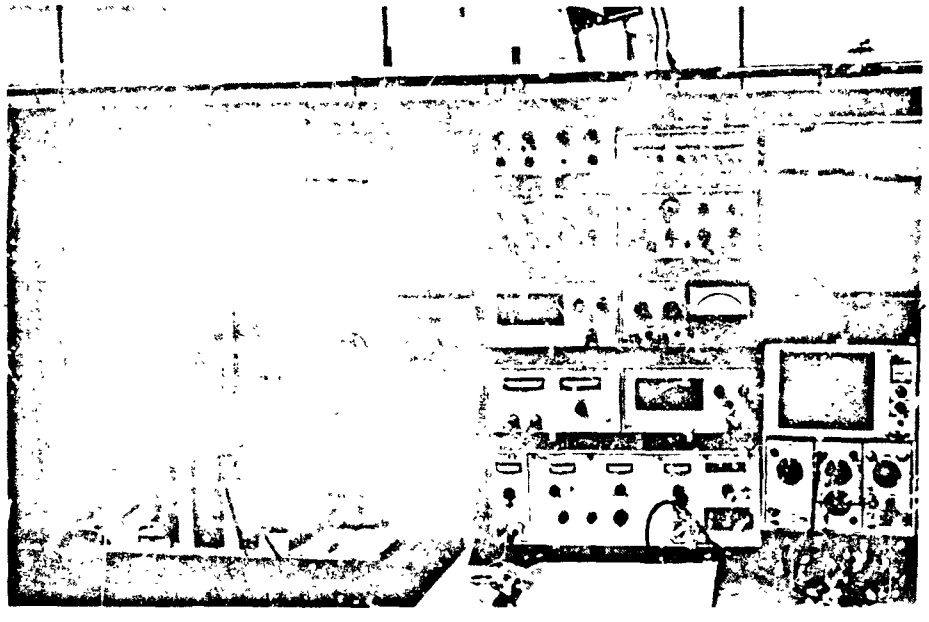

Figure 6. Propeller Turbulence Measurement Set-Up

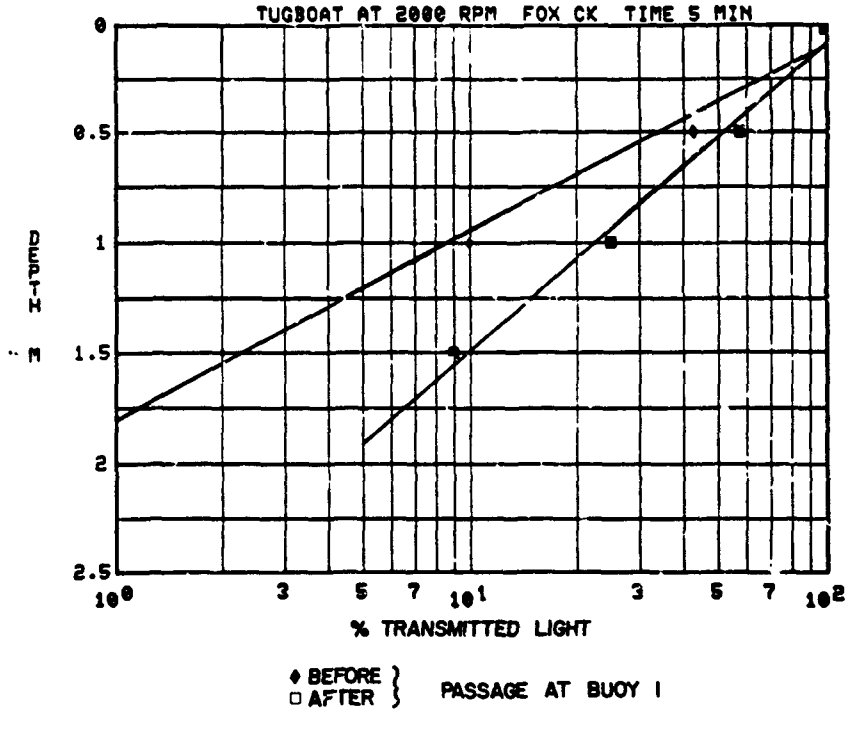

Figure 7. Photometer readings from a single test (before and 5 min. after single tug pass at buoy 1).

SECTION 4

RESULTS

LIGHT EXTINCTION MEASUREMENTS

Light extinction measurements using the photometer gave the most statistically reliable as well as most consistent results. Moreover, the measurements show a reasonable correspondence to the laboratory results, allowing the formulation of at least a tentative hypothesis concerning the most significant variables that affect sediment resuspension.

Figure 7 shows measurement results for a single pass of the tugboat Bottlenose at Fox Creek in a water depth of 1.8 m. The diagram may be taken as representative for test runs when observed light extinction increases were at a maximum. Figures 8, 9, and 10 show that with the passage of time some recovery to prior levels takes place.

The data were averaged for analysis of statistical significance, and grouped into three time intervals, 2-9 min, 15-34 min, and 35-36 min after the passage of the tugboat. Figure 11 is the semilog plot constructed from the extinction coefficient, k, obtained by averaging the extinction coefficients for each sample run, measured at three or six buoys. The result represents 18 samples (for a total of 320 separate measurements). The standard deviation for the 18 samples is shown. Student's t-test for small samples shows the difference of before and after vessel pass results to be significant at the 0.995 level.

Because tidal rise and fall varied the depths at the sampling site by approximately 0.2 m, samples taken when the depth was 1.8 m, the minimum depth at which tests were conducted, were analyzed separately. While the difference in extinction coefficient is small over that for all tugboat tests done at the Fox Creek site, 2.11 versus 2.01 m^{-1} compared to a control value of 1.68, the statistical significance in the former case is yet greater, being at the 0.9995 level.

Analysis of the influence of length of time after the vessel pass does not yield unequivocal results statistically. Results appear anomalous for the samples taken between 35 and 65 min after the vessel pass, as can be seen in Figure 12. Student's t-test is significant only at the 0.75 level for samples

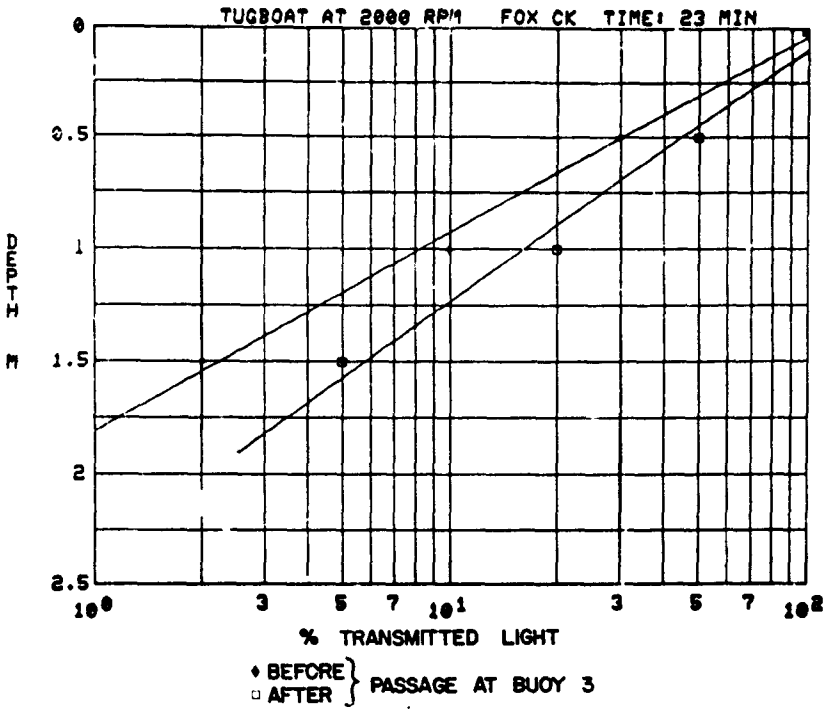

Figure 8. Photometer readings from a single test (before and 23 min. after single tug pass at buoy 3).

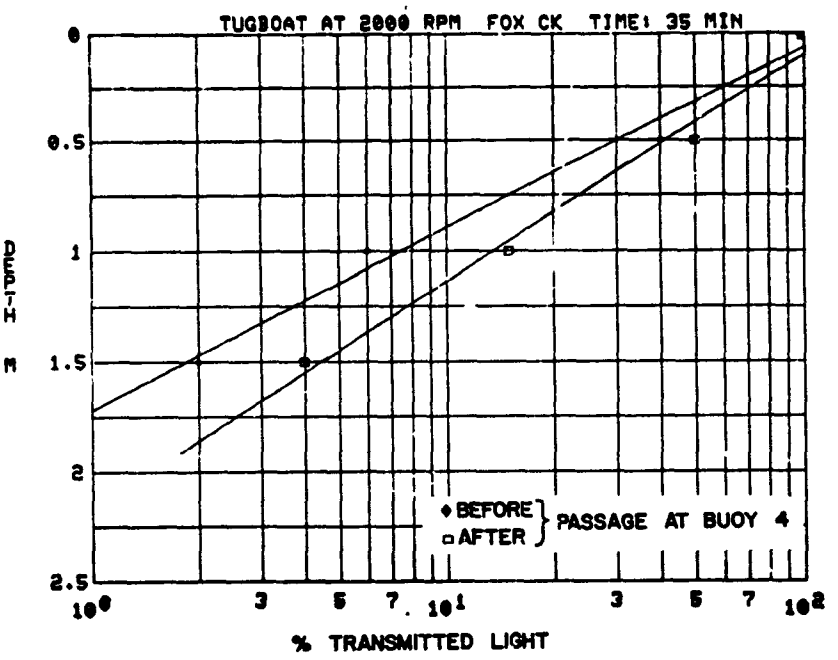

Figure 9. Photometer readings from a single test (before and 35 min. after single tug pass at buoy 4).

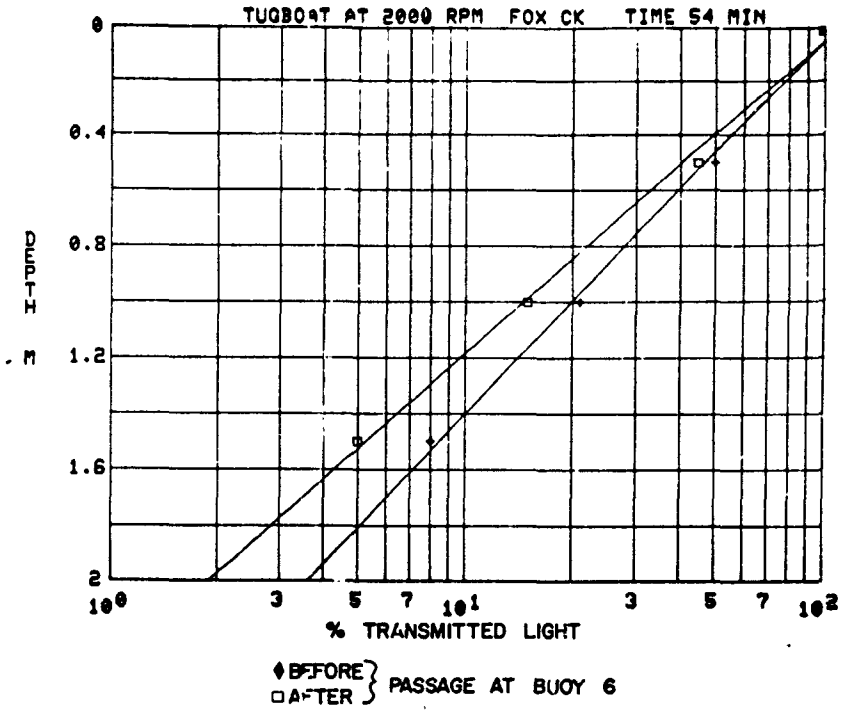

Figure 10. Photometer readings from a single test (before and 53 min. after single tug pass at buoy 6).

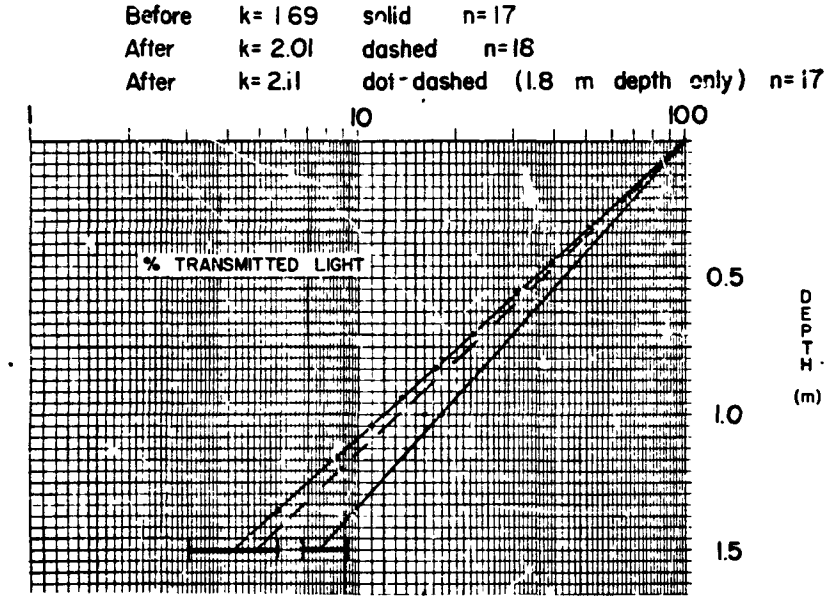

Figure 11. Plot of the arithmetic mean of extinction coefficients for tugboat runs (2000 rpm) at Fox Creek (1.8-2.0 m depths).

collected between 2 and 9 min after the vessel pass, but increases to significance at the 0.9, and 0.995 level for the 12-34 and 35-65 min intervals.

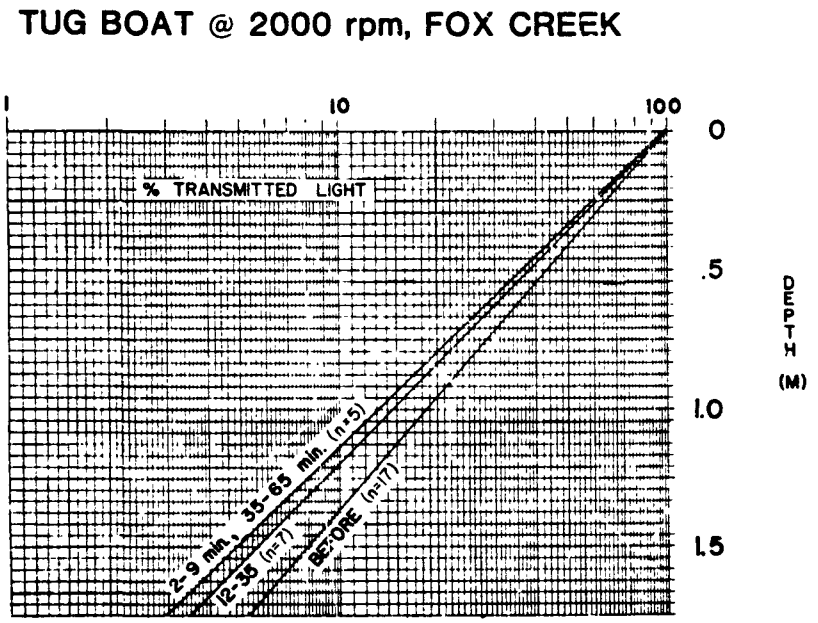

Figure 12. The effect of time after vessel passage on light extinction.

The displacement of the resuspended sediment due to currents may be a factor here, though care was taken to have the majority of observations taken within 1½ hour of slack tide. The nearest current measurement station, located at Fox Point, a creek area having a cross-section approximately :237 of the creek section used in these tests, recorded currents averaging less than .05 m sec^{-1} for time periods equally close to slack water (Correll, D., personal communication). As buoys were spaced in line with the creek's longitudinal axis, transport could be expected to have small lateral components. Maximum drift may have been 8-13 m during the first 9 min, the first interval tested, and as much as 50-90 m during the maximum interval allowed between vessel passage and sampling. Generally, the drift would have been less, and as the buoy line was 150 m in length, and the vessel tract generally extended beyond the buoy line at least 50 m to avoid effects of vessel turns, little impact is believed to result from currents.

Tugboat runs were repeated in slightly deeper water, at the Sellman Creek site, where water depths average 2.2 to 2.3 m, and sediment particle size distributions remain similar. The

increases in light extinction were much less than those seen at the Fox Creek site, and were only marginally significant when analyzed statistically. The extinction coefficient prior to vessel passes averaged 1.50 m^{-1}, and increased to 1.56 m^{-1} after vessel passes, as is shown in Figure 13.

Finally a single pass by the tugboat was made at the Chest Neck site in the Magothy River, where the water depth was slightly deeper than Sellman Creek, about 2.3 to 2.5 m, but the sediment was primarily sand. As expected, no detectable impact from the turbulent stirring of the boat pass was seen. It should be added, however that this site, unlike the previous two, had the typically weak tidal currents found in these waters running across the buoyed sampling track. It is conceivable that a stirred plume, if it persisted long enough to be detectable within the time frame of the test, might be swept out of the sampling zone. Figure 14 shows the result of the deep water, coarse substrate experiment.

Repeat tests were made at the Fox Creek site, where the variables changed were the boat and engine type. In these sets of vessel passes, the research vessel Osprey, an outboard powered, planing runabout was used. In terms of the resulting water motion dynamics, changing both boat and motor types represent a fairly large number of modifications, some of which are offsetting, others additive. The reduced displacement, the planing attitude of the vessel at the speeds used, as well as the reduced immersion of the propeller and its smaller diameter would tend to create a reduced volume of water set into quasi-turbulent motion. The larger power output, increased by over 60 percent over that of the tugboat, and the higher engine and consequent propeller rpm, and possibly the higher operating speed of the vessel would tend to produce increased water motions, and hence a greater likelihood of sediment resuspension.

Figure 15 shows a run by the R/V Osprey at 4000 rpm along the identical track used by the tugboat at the Fox Creek site. In this case observed effects were maximum, while Figure 16 shows the results more typical of the majority of the runs. Figure 17 is a graph constructed from the arithmetically averaged extinction coefficients. The net increase for a total of 13 samples, and about 90 measurements, show the extinction coefficient to go from 2.21 m^{-1} to 2.30 m^{-1}, statistically significant at the 0.75 level when tested using student's t. These findings are summarized in Table 1 for comparison with transmissometer and suspended sediment results.

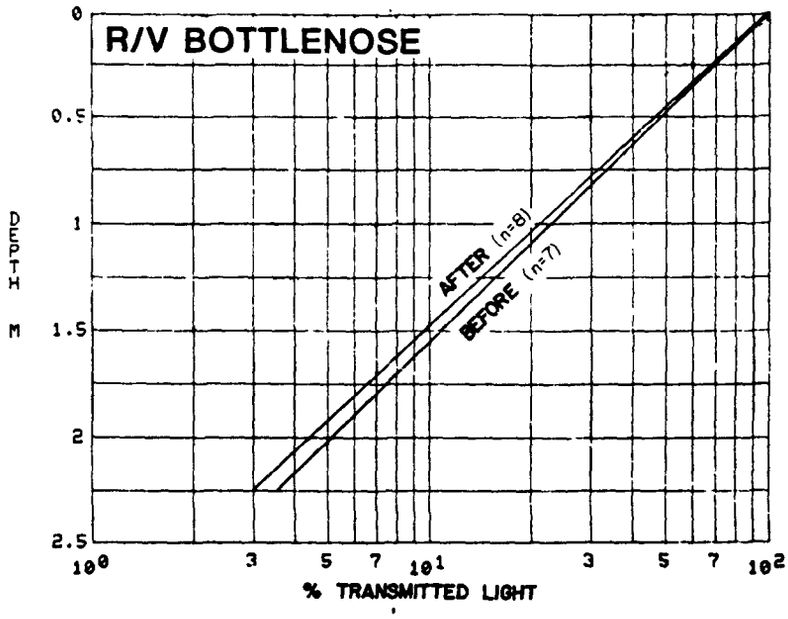

Figure 13. Plot of the arithmetic mean of extinction coefficients for tugboat runs (2000 rpm) at Sellman Creek (2.3-2.5 m depths).

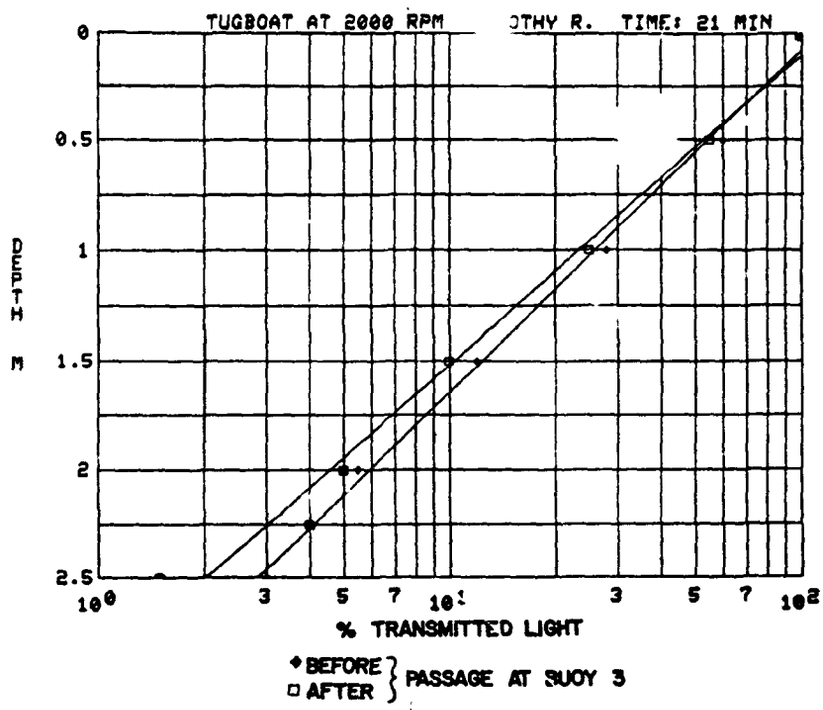

Figure 14. Photometer readings from a single test (before and 21 min. after single tug pass at buoy 3).

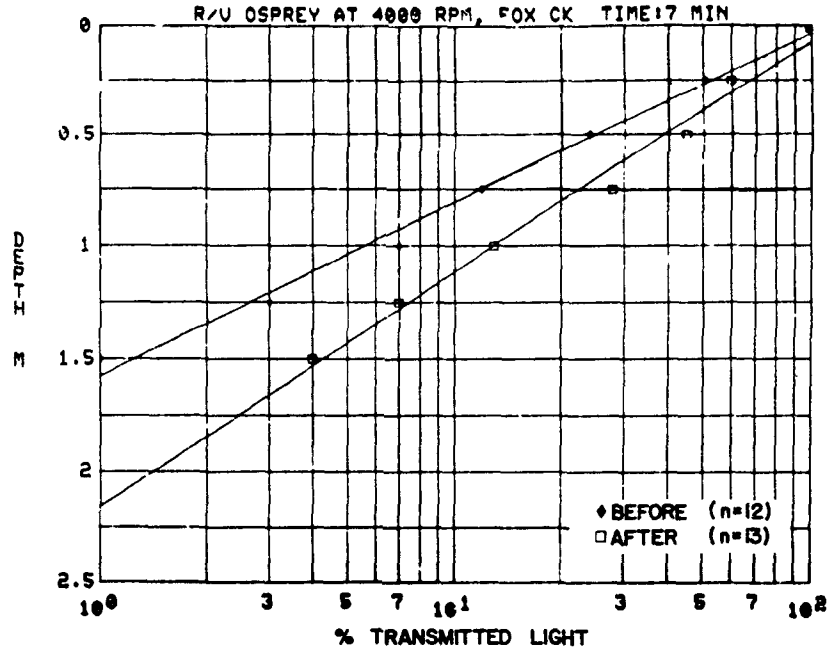

Figure 15. Photometer readings from a single test (before and 7 min. after single pass of the planing craft R/V Osprey at Fox Creek).

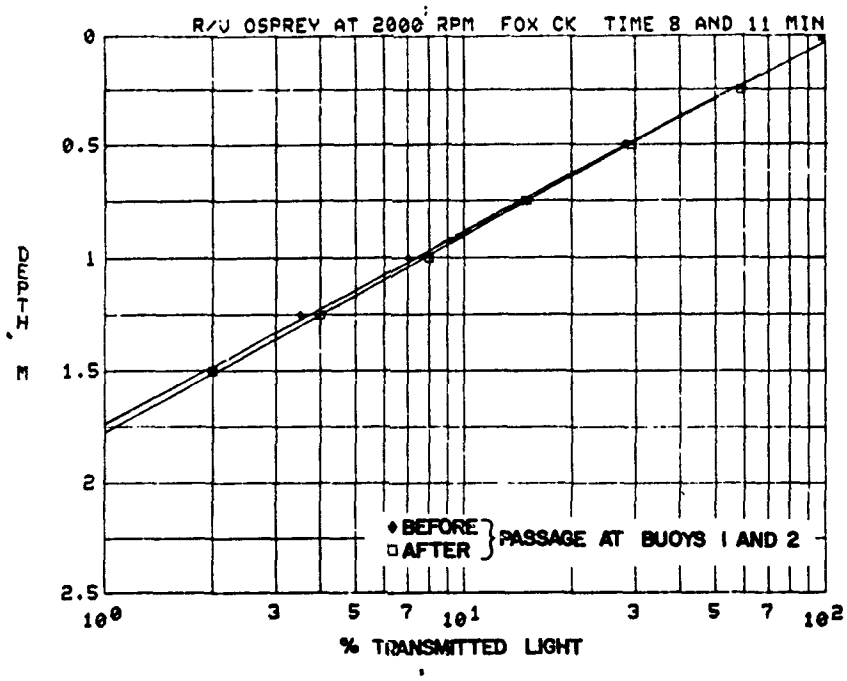

Figure 16. Typical photometer readings for a single test at 2 buoys (before 8 and 11 min. after pass of planing craft R/V Osprey at 2000 rpm, vessel off plane).

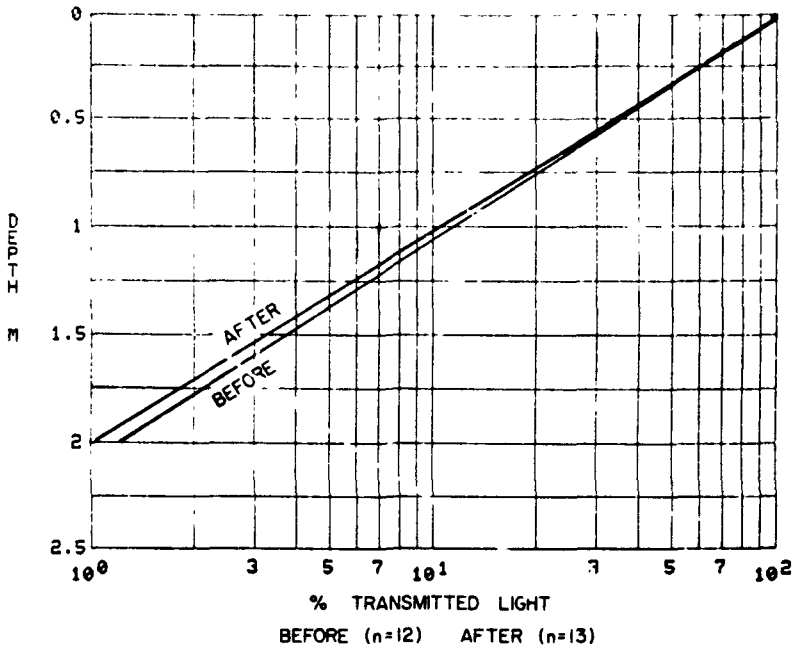

Figure 17. Plot of the arithmetic mean of extinction coefficients of the planing craft R/V Osprey (4000 rpm) at Fox Creek.

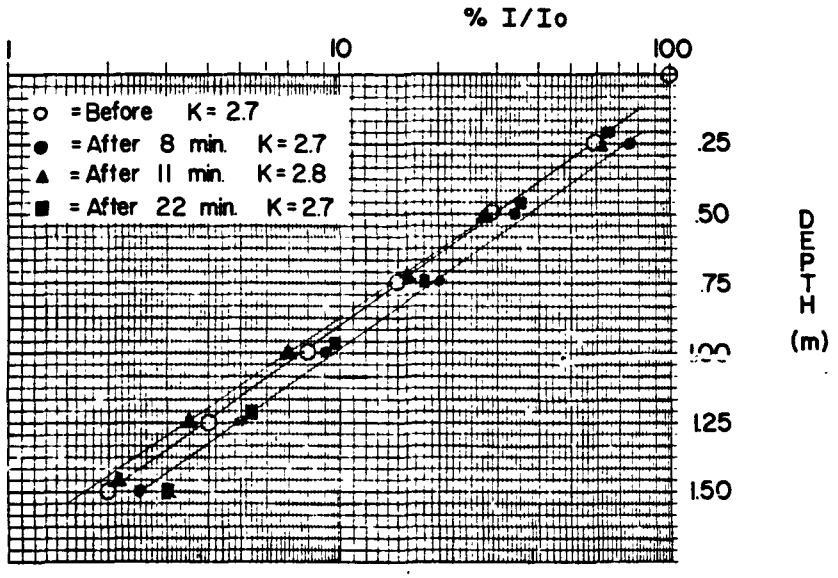

Figure 18. Plot of the arithmetic mean of extinction coefficients for the planing craft R/V Osprey (2000 rpm) at Fox Creek.

TABLE 1. SUMMARY OF PHOTOMETER EFFECTS

		Before			After			
Location	Vessel	n	k	std. dev.	n	k	std. dev.	Significance t-test
Fox Creek	Tugboat	17	1.69	0.2	17	2.11	0.44	0.995
Fox Creek	Outboard	12	2.21	0.33	13	2.30	0.30	0.75
Sellman Creek	Tugboat	7	1.50	0.16	8	1.56	0.13	0.75
Magothy River	Tugboat	3	1.43	0.06	3	1.47	0.06	——

No field tests were conducted that could reliably and demonstrably separate effects from propeller-induced motion to wake effects, one of the reasons that lead to the laboratory experiments. However, the result of a test of the R/V Osprey at slower speed was instructive. In this case, summarized in Figure 18, the vessel's engine rpm was held to 2000, exactly half of that used in high speed, planing runs. At the lower engine rpm the vessel did not plane, but moved through the water at the maximum wave-making speed. This speed is taken to be the speed when the stern wave actually begins to show its maximum amplitude astern of the ship. The speed is empirically given for nonplaning craft as

$$v\ (\mathrm{m\ sec^{-1}}) = 1.31\ \sqrt{LWL} \qquad (2)$$

where LWL is the waterline length of the craft in m. Visually, it appeared that confused wake and high stern waves should easily produce greater effects that at the high planing speeds, however the observations of extinction coefficients do not bear this out.

TRANSMISSOMETER MEASUREMENTS

For the majority of photometer measurements made, a transmissometer reading was taken concurrently. As was anticipated, the variability of the transmissometer data was far greater than the light extinction measurement, the general trend of the measurement follows and perhaps thereby corroborates measurements of light extinction coefficients. Figure 19 gives representative results for particular runs using the planing runabout and the R/V Osprey. Figure 20 shows the results summarizing all tests

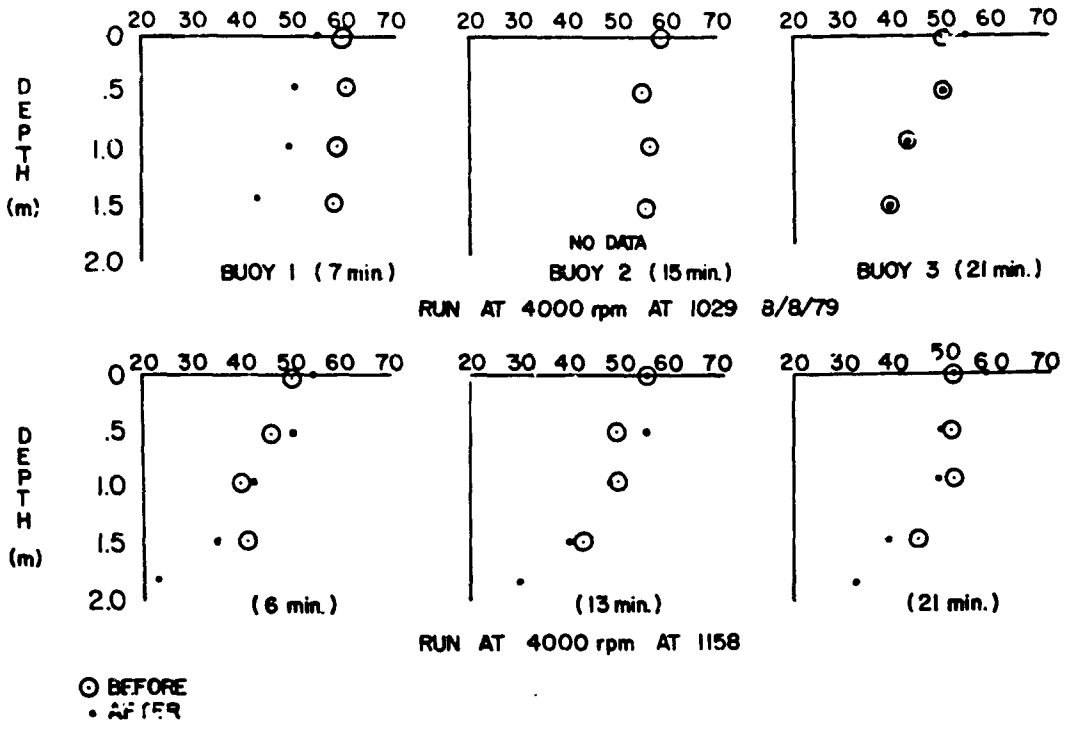

Figure 19. Representative transmissometer results for a single test of the planing craft R/V Osprey at Fox Creek.

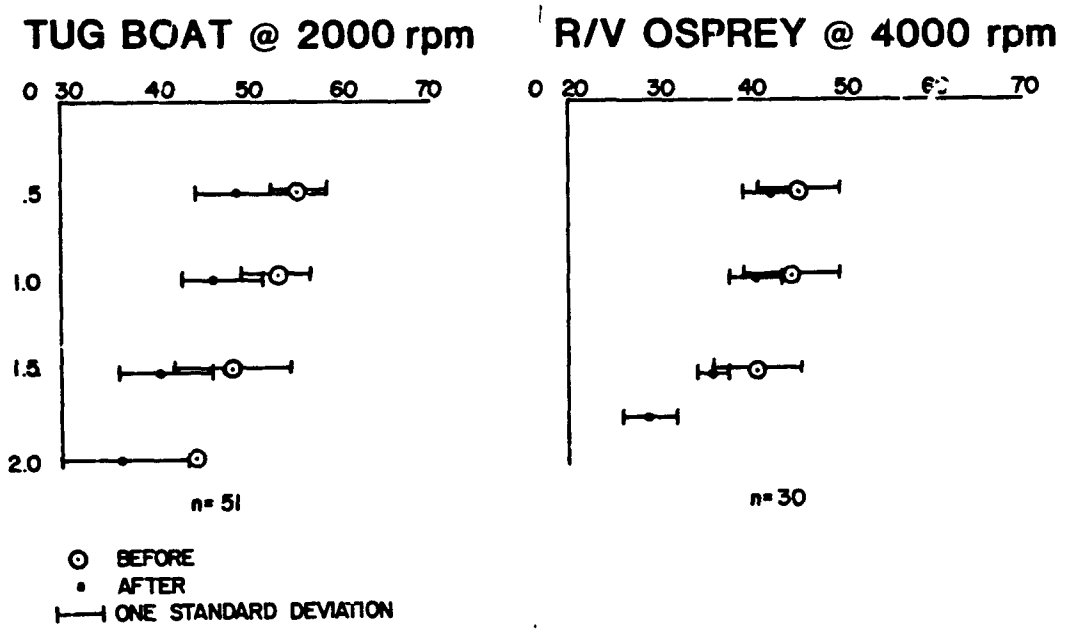

Figure 20. Average change in light transmission for all runs at Fox Creek (depths 1.8-2.0 m).

conducted with the tugboat, the R/V Bottlenose, at Fox Creek, as well as the tests with the R/V Osprey at the same location. The trend, and the relatively lesser effects of the boat having the least propeller immersion is apparent, and born out by statistical comparison, as shown in Table 2. The resulting alpha coefficients from the sample runs are summarized in Table 3. No transmissometer measurements were made at the Magothy River, deep water site.

TABLE 2. SUMMARY OF TRANSMISSOMETER EFFECTS

		Before			After			
Location	Vessel	sample size n	ave. % trans.	std. dev.	sample size	ave. % trans.	std. dev.	Significant level (t test)
Fox Creek	Tugboat	51	50.65	6.80	38	43.33	11.23	0.9995
Fox Creek	Outboard	30	43.5	9.3	30	39.9	6.58	0.995
Sellman Creek	Tugboat	6	67.3	7.6	9	67.6	5.9	none

TABLE 3. AVERAGED ALPHA COEFFICIENTS FROM TRANSMISSOMETER MEASUREMENT

		Before	After
Location	Vessel	Alpha	Alpha
Fox Creek	Tugboat	6.80	8.36
Fox Creek	Outboard	8.32	9.10
Sellman Creek	Tugboat	3.96	3.92

SUSPENDED SEDIMENTS

Carefully analyzed, the suspended sediment measurements must be judged a cautiously qualified failure. Their analyses were easily the most time-consuming part of all analytical procedures employed, yet returned the least information per unit effort. For initial measurements, there appeared to be a significant trend corroborating the findings from photometric and transmissometer measurements. When subsequent results began to show unaccountable fluctuations, replicates were prepared for each sample taken. Blank runs were made for each day of field work.

Thus, of a total of close to 150 gravimetric determinations of suspended sediments, 62 samples have replicates for assessment of confidence levels, while 14 blank determinations were made during the course of sampling. The average difference in suspended sediments, expressed in mg l^{-1}, for the replicates proved to be 5.2, with a standard deviation of 4.3 mg l^{-1}. Similarly, the 14 blank determination had a mean change in weight resulting from identical treatment as the actual samples, excepting the actual filtration, of 2.4 mg, with a standard deviation of 2.6 mg.

The results were nevertheless tabulated, using the averaged replicate pairs as individual results, and averaging these for statistical comparison. Surprisingly, even these dubious results follow the pattern established by the photometer results. Table 4 summarizes the data obtained from gravimetric determination of suspended sediments.

TABLE 4. SUMMARY OF SUSPENDED SEDIMENT ANALYSIS

			Before		After			
Location	Vessel	engine rpm	$\overline{SS}$* (mg/l)	std. dev.	$\overline{SS}$ (mg/l)	std. dev.	sig. level	n**
Fox Creek	Tugboat	2000	22.4	11.7	25.4	9.7	0.900	25
Fox Creek	Outboard	4000	19.9	9.44	21.6	7.1	0.750	32
Sellman Creek	Tugboat	2000	9.5	4.3	13.0	5.4	0.975	16
Magothy	Tugboat	2000	10.1	7.8	5.3	3.3	none	8
Fox Creek	Tugboat	1500	18.0	6.7	16.1	2.8	none	4
Fox Creek	Outboard	2000	26.8	6.0	23.5	3.7	none	1

*SS = averaged suspended sediment concentration
**n = sample size

The correspondence of results for the three measurement techniques employed forces the question whether there is a definite relationship between the alpha coefficient determined by transmissometer and the suspended sediments determined gravimetrically. Theoretically derived relations often involve assumptions about particle sphericity that may not hold for the predominant sediments found suspended in Bay waters (Jerlov 1968). Schubel (1968) reports an empirically derived relationship specifically for suspended sediments found in the upper Chesapeake Bay

$$\alpha = 0.42\ \overline{SS} \qquad (3)$$

where α is the transmission coefficient defined to be

$$\alpha = -\frac{1}{L}\ \ln\left(\frac{I}{I_o}\right) \qquad (4)$$

and $\overline{SS}$ is the suspended sediment concentration in mg l^{-1}. I/I_o is the fraction of light received at the detector after passing through length L of the water column. Shannon (1975) reports a relationship between α and k, the extinction coefficient as follows:

$$k = 0.2\ \alpha + 0.4. \qquad (5)$$

The coefficient k is calculated using the relationship shown in equation (4), with the understanding that L represents the depth at which the measurement is taken, still a path length in a sense. The physical significance of the measurement, of course, differs. The equations are readily manipulated and combined to allow an expression for $\overline{SS}$ both from α and k, the latter used as follows:

$$\overline{SS} = 11.9\ k - 4.76. \qquad (6)$$

Using these relationships, we have calculated the averaged results, as shown in the previous sections, and compared them to the measured suspended sediments. Table 5 shows that in a surprising number of instances, the agreement is rather good.

TABLE 5. COMPARISON OF SUSPENDED SEDIMENT DATA FOR THREE MEASUREMENT TECHNIQUES

Location	Vessel	Engine rpm	Before			After		
			$(\overline{SS})_k$*	$(\overline{SS})_\alpha$**	$\overline{SS}$†	$(\overline{SS})_k$	$(\overline{SS})_\alpha$	$\overline{SS}$
Fox Creek	Tugboat	2000	17.9	16.2	27.4	19.2	19.9	25.4
Fox Creek	Outboard	4000	21.5	19.8	19.9	22.6	21.7	21.6
Sellman Creek	Tugboat	2000	13.1	9.4	9.5	13.8	9.3	13.0
Magothy	Tugboat	2000	12.3		10.1	12.6		5.3
Fox Creek	Tugboat	1500	13.9	12.9	18.0	12.6	15.7	16.1
Fox Creek	Outboard	2000	27.4	24.3	26.8	27.6	24.2	23.5

*$(\overline{SS})_k$ = average suspended sediment concentration from k, the extinction coefficient.

**$(\overline{SS})_\alpha$ = suspended sediment concentration from α, the transmission coefficient.

†$\overline{SS}$ = average suspended sediment concentration determined gravimetrically.

Finally, the results of the three measurement approaches have been averaged to arrive at a net increase in suspended sediment due to the passage of a boat having characteristics similar to the ones used in these tests, and operating in waters of the same depths indicated. These results are shown in Table 6.

TABLE 6. SUMMARY OF SUSPENDED SEDIMENT BASED ON ALL MEASUREMENTS

Location	Vessel	Engine rpm	Depth (m)	Before $\overline{SS}$	After $\overline{SS}$	Δ
Fox Creek	Tugboat	2000	2.0	18.8	21.5	2.7
Fox Creek	Outboard	4000	2.0	20.4	22.0	1.6
Sellman Creek	Tugboat	2000	2.3	10.7	12.0	1.3
Magothy	Tugboat	2000	2.5	11.2	8.9	2.3*
Fox Creek	Tugboat	1500	2.0	14.9	14.8	0.1*
Fox Creek	Outboard	2000	2.0	26.2	25.1	-1.1*

Δ = average increase in suspended sediment.

* = these increases statistically insignificant.

As can be seen, decreases in sediment load can be observed at times, but such decreases were not observable when data were averaged over many sets of observations. In the case of the tugboat at 1500 rpm, and the outboard at 2000 rpm, only the results of a single vessel pass are available, as for the pass conducted in the Magothy River, hence the information in the last three rows has very low reliability, and the interpretations cited in the previous sections are believed more informative than the data in this table. On the other hand, the averaged results shown in the top three rows of the table represent our findings for many tests. These findings will be discussed in the light of the observations from the laboratory tests of propeller stirring.

LABORATORY EXPERIMENTS

The laboratory measurements were designed to yield information concerning the propeller effects alone. Using measured values for the averaged velocity imparted to the water by the propeller action, along with the turbulence intensity, it should be possible to map the distribution of critical stresses, i.e., stresses sufficient to cause resuspension of sediment. Experiments were done using three different advance ratios, J, to map a range of applicable conditions typical of small craft found in Bay waters. These J ratios were 1.61, 2.39, and 3.53 x 10^{-3} respectively. Table 7 gives the range of J values calculated for the conditions used in the field tests for comparison.

TABLE 7. REPRESENTATIVE J VALUES FOR FIELD TESTS CONDUCTED IN THIS STUDY

Vessel	V (m sec^{-1})	N (rpm)	D (m)	J x 10^{-3}
Tugboat	3.6	600	0.48	4.0
Tugboat	2.5	500	0.48	3.3
Outboard	13.0	2000	0.41	5.1
Outboard	3.1	1000	0.41	2.4

Note that N, the propeller rpm, is not the same number shown in the summary tables for the transmissometer, photometer, and suspended sediments data. In the latter cases the engine rpm was listed. Engine rpm and propeller rpm are directly proportional and a function of the reduction gear used with a particular engine. Thus, the tugboat has a 3:1 reduction gear, while the outboard uses a 2:1 reduction gear.

All velocities are expressed as ratios to the propeller advance velocity. In nearly all experiments the ratio of V_∞ to the average velocity obtained by integrating the instantaneous velocities over the height of the water column, shows small deviations from unity, i.e., UAVG/UINF < 1, which shows that the water surface is raised slightly abaft the propeller due to the forces it creates. These changes are not believed to affect the resulting turbulence measurements.

Figures 21 through 26 show the measurement results for increasing J values, paired so as to show the normalized mean velocity, $\bar{u}$, and the corresponding turbulence intensity, $-\rho\overline{u'v'}$, in each case. The relationship of $\bar{u}$ and $\rho\overline{u'v'}$ to shear stress is given by the Reynolds stress equation

$$\tau_{xy} = -\rho\overline{u'v'} + \mu\left(\frac{\partial\bar{u}}{\partial y} + \frac{\partial\bar{v}}{\partial x}\right) \qquad (7)$$

in its two dimensional form, in turn derived from the Navier-Stokes equation. It uses the concept of the Reynold's decomposition, which treats the velocity of a fluid particle as the sum of a mean velocity plus a fluctuating term. A rigorous application of the equation is not attempted here; the mathematical introduction is omitted. The reader is referred to standard texts such as Tennekes and Lumley (1972).

The figures show that the magnitude of propeller effects is greatest for low J values and decreases for increasing J values. This means that a vessel, moving through the water with

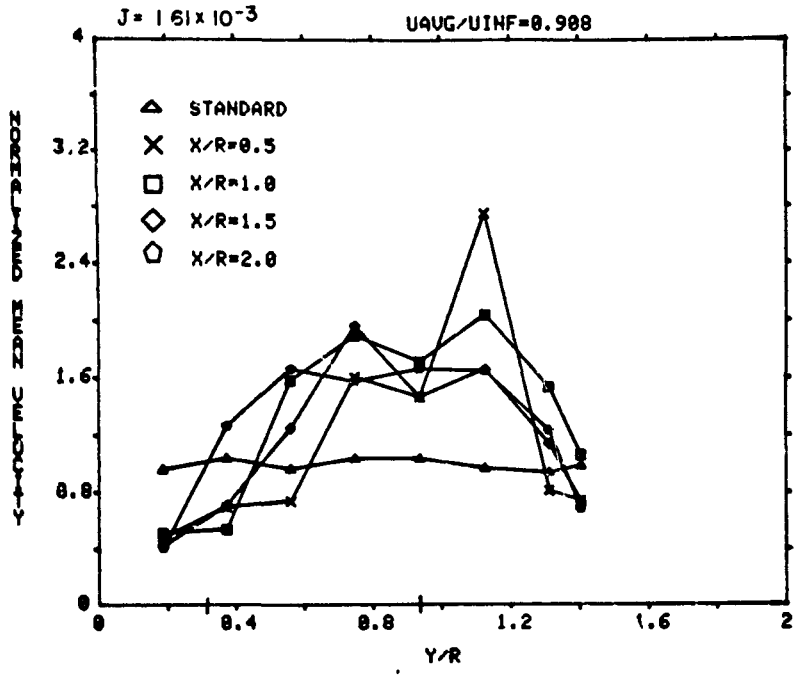

Figure 21. Average velocity distribution in propeller wake for low J value.

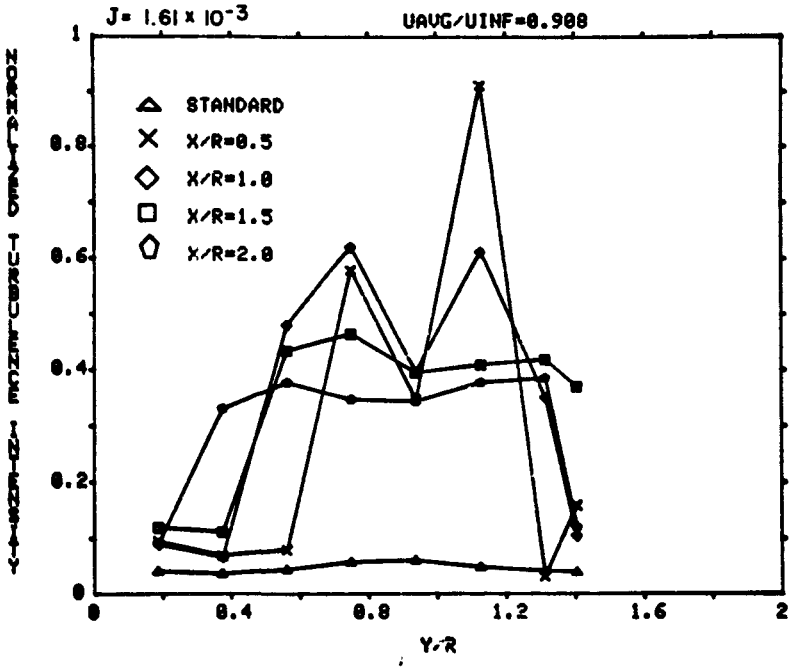

Figure 22. Turbulence intensity distribution for low J value.

high speed while the engine is turning at a moderate number of rpms, will have high J values and an effect that does not extend to great depth. Conversely, the same vessel under a load sufficient to slow its speed through the water at the same engine rpm will have propeller-induced water motion extend proportionately deeper into the water column.

Using the figures more quantitatively, and assuming that sediment stirring will take place when propeller effects exceed background motions observed under laboratory conditions, the following comparisons are estimated and shown in Table 8 for J values approximating those for the tugboat and outboard during high-speed field tests:

TABLE 8. ESTIMATED MAXIMUM DEPTH FOR PROPELLER EFFECTS SCALED FROM LABORATORY TESTS

Vessel	rpm	v(m sec^{-1})	J x 10^{-3}	Depth below prop. hub (m)	Max. water depth affected*
Tugboat	600	3.6	4.0	0.73	1.4
Outboard	2000	13.0	5.1	0.60	1.0

*This depth is found by adding the depth of propeller effects to the immersion depth of the propeller hub.

These results tend to agree with the field measurements that show greater measured sediment resuspension and greater light attenuation for the tugboat tests than for the outboard tests for water of the same depth. In the field tests the added effects from wake also play a role, of course, and cannot be neglected. These would tend to reinforce the pattern of findings, as the wave height of the planing outboard's wake was observed to be consistently lower than those produced by the tugboat travelling near its maximum wave-making speed.

A contradiction appears to arise when comparing propeller effects from the same vessel at different speeds. Both for the tugboat and the outboard, the J values increase when the vessel is slowed, implying that propeller effects extend more deeply into the water column. This increase was not observed for field measurements conducted under appropriate conditions, suggesting that other variables masked this effect. The effect does appear to make physical sense, and a single field test conducted with the tugboat stationary, anchored in Fox Creek, with the engine turning 1800 rpm, showed suspended sediment increases between 15 to 30 mg l^{-1}, and a degree of sediment stirring visible to the eye as never observed to during any test where the vessel remained in motion.

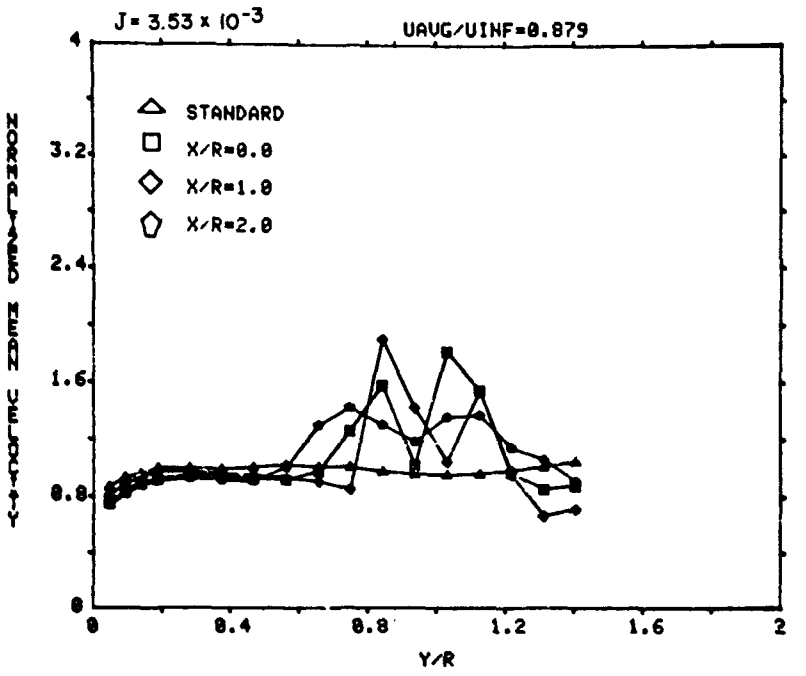

Figure 23. Average velocity distribution in propeller wake for high J value.

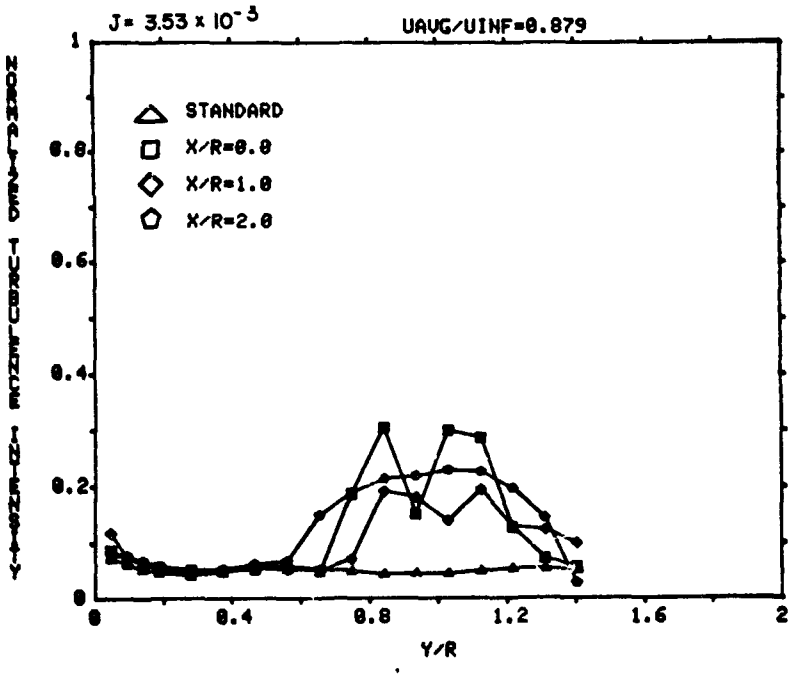

Figure 24. Turbulence intensity distribution for high J value.

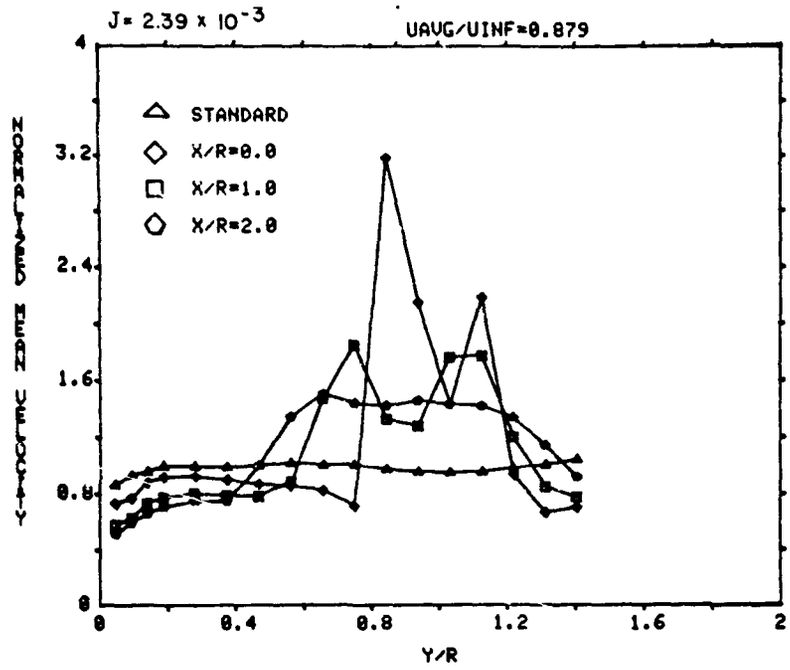

Figure 25. Average velocity distribution in propeller wake for intermediate J value.

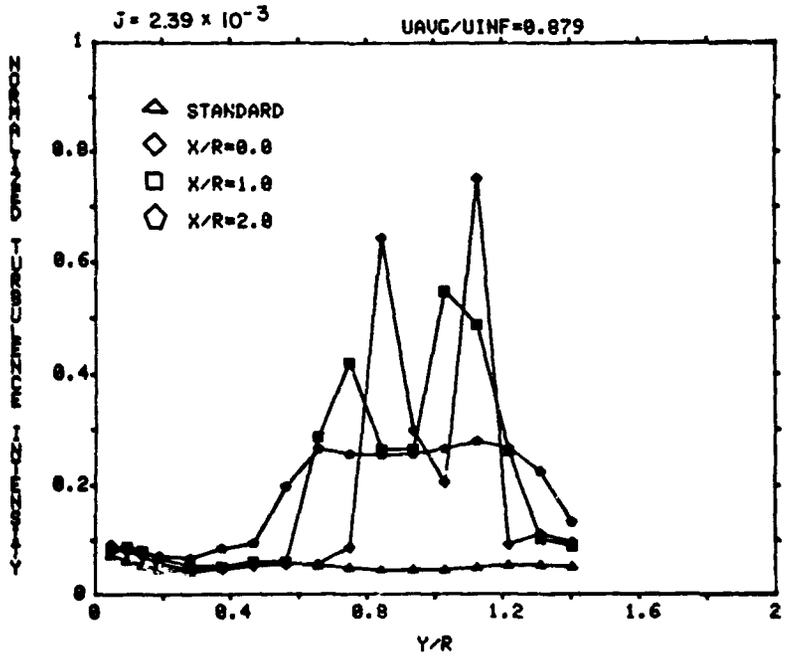

Figure 26. Turbulence intensity distribution for intermediate J value.

The laboratory measurements of average and fluctuating (turbulent) velocity have been examined in an attempt to relate them to a critical velocity sufficient to resuspend sediment. The critical velocity is taken from the literature. It was necessary to distinguish velocities measured above the water sediment boundary layer from the critical velocity at the sediment interface. Drag effects, a function of sediment particle size, cohesiveness, and sediment type, produce an exponential profile for velocity gradients in the boundary layer. Gust and Walger (1976) working with North Sea sediments of similar particle size as existed for this study, report critical velocities near 0.08 m sec^{-1}. They cite the work of Einstein and Krone, who report 0.07 m sec^{-1} for clay sediments (illite, montmorrilonite, and kaolinite) in San Francisco Bay. In a previous paper, Gust (1975) finds much higher critical velocities when such clay sediments, known to be cohesive, are compacted as might be found of areas of tidal scour. He reports critical velocities as high as 0.36 m sec^{-1}. Bagnold (1962) defines a critical stress θ_t for resuspension. However, his data, based on citation of Shields, is for particles of 60μ and up and must be extrapolated to the 30 to 60μ range of interest, for which values for θ_t of 0.12 to 0.13 can be estimated. Rossman, Seibel (1977) cite critical velocities of 0.14 m sec^{-1} for 63μ particles, the smallest size they report, but make no reference to effects when sediments are cohesive in particle ranges less than 60μ.

We therefore consider the range of critical velocities sufficient to resuspend sediments to be 0.08 to 0.14 m sec^{-1} as representative for particle distributions found in Fox and Sellman Creek. These are velocities measured at the bottom, but just above the boundary layer. If we examine the laboratory result for $J = 3.53 \times 10^{-3}$ we find that a normalized velocity unit, as shown in Figure 23, is determined as follows: $\bar{u}/V_\infty = 0.879$; the velocity of water in the tank was $V_\infty = 0.347$ m sec^{-1}, hence $\bar{u} = (0.347)(0.879) = 0.305$ m sec^{-1}.

Using Table 7, we can interpolate this speed to be 2.7 m sec^{-1} for the tugboat in field tests. Hence, if 1 normalized unit (at $J = 3.53 \times 10^{-3}$) corresponds to 2.7 m sec^{-1}, then the critical velocities of 0.14 m sec^{-1} and 0.08 m sec^{-1} correspond to 0.05 and 0.03 velocity units, respectively. By inspection of Figure 23, the difference of 0.05 above background occurs at Y/R = 0.48. Since D/H = .264 for the lab test (as defined in Figure 4) and D = 0.48 m for the tugboat, H = D/.264 = .48/.264 or H = 1.82. A unit Y/R represents 1.3 m. The distance below the propeller hub at which Y/R is such that the critical velocity is 0.05 m sec^{-1} above background is .52 Y/R units, or about 0.68 meters.

In the lab tests the propeller was held stationary while the water flowed at a known velocity. In the field, of course, the vessel is moving at a known velocity, and the water is considered

stationary. The "background" velocity must be taken as zero to allow comparison. It is conceivable that propeller effects actually extend to greater depths than our lab tests would indicate, but such effects are not measurable by the approach feasible to us in this study.

Velocity fluctuations, shown in Figure 24 as turbulence intensity, are root mean square values by which the normalized mean velocity could be exceeded. Turbulence intensities high enough to approach the critical velocity for resuspension, 0.14-0.08 m sec^{-1} correspond to 0.5 velocity units on the graph. Such fluctuations extend to a depth of 0.5 Y/R units, or about 0.65 m below the propeller hub.

Taken together, and assuming that background (identified as "standard" in figures) velocities represent zero velocities which must be exceeded by 0.08-0.14 m sec^{-1} to obtain sediment resuspension, we may conclude that the assumptions used to generate Table 8 are reasonable. In fact, the assumptions are necessarily conservative, as the background of flowing water may partially mask propeller induced motion, although the shape of the curves shown in Figures 22 through 26 suggest this to be a minor factor.

Using this approach, we have attempted extrapolation of the turbulence measurement data over wider J ranges, assuming an exponential relationship, with a maximum value of $J = 5 \times 10^{-3}$ deemed as one extreme. This allows the compilation of the maximum depths affected for J values from 1.6×10^{-3} to 5×10^{-3} (with depths in propeller diameters). With known diameters and depths of hub immersion, the actual water depths in m can be quickly estimated as shown in Table 9.

TABLE 9. MAXIMUM DEPTH OF PROPELLER EFFECTS AS A FUNCTION OF J IN TERMS OF PROPELLER DIAMETERS

	$J \times 10^{-3}$				
	1.6	2	3	4	5
Depth (Diameters)	3.0	2.9	2.1	1.5	1.4
Example for Tugboat (m)	2.1	2.1	1.7	1.4	1.4
Example for Outboard (m)	1.6	1.6	1.3	1.0	1.0

SECTION 5

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APPENDIX A

THE EFFECTS OF SUSPENDED SEDIMENTS, ACCUMULATED SEDIMENTS, AND WATER TURBULENCE ON THE GROWTH OF SUBMERGED AQUATIC VEGETATION

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INTRODUCTION

Most submerged aquatic vegetation (SAV) is substrate bound and is therefore limited, primarily by light, to coastal waters. Although the depth of SAV occurrence can be considerable in clear waters (Phillips 1974), SAV in the Chesapeake Bay and its tributaries is usually found in less than three meters of water (Stevenson and Confer 1977). Of the approximately 11 species of vascular SAV in Chesapeake Bay (Kerwin, Munro and Peterson 1975) only three, Zostera marina, Myriophyllum spicatum, and Ruppia maritima have received much research attention, and only a part of this has been directed toward light/productivity relationships. Due to its widespread occurrence (Harrison and Mann 1975) and ecosystem importance (Cottam and Munro 1954; Orth 1976) Zostera has been the object of most of this research. Myriophyllum and Ruppia have received less attention.

The productivity and abundance of submerged aquatic vegetation depends upon the intensity of light reaching the leaves (Sand-Jensen 1977; Backman and Barilotti 1976). This, in turn, depends upon the intensity of the light at the water surface, the light reflected at the air-water interface, and the attenuation of the light as it passes through the water column. The light intensity at the surface of the water depends primarily upon the latitude of the insolated site, the angle of incidence of the sun, and local atmospheric effects, such as cloud cover (Reifsnyder and Lull 1965). The turbulence of the water surface will affect the amount of light reflected from it (Jerlov 1968), while the attenuation of light as it travels through the water column is influenced by both the length of the water column and its turbidity. This report will discuss the effects, on SAV photosynthesis, of light attenuation by suspended sediments in the water column, and by sediments deposited on the leaves themselves. The mechanical effects of boat wakes on SAV will also be discussed. Methods will be presented to estimate the possible effects of these factors on SAV photosynthesis.

LITERATURE REVIEW AND CALCULATIONS

1. The effect of suspended sediments on SAV photosynthesis.

A number of papers have been published concerning the relationship between light and the standing crop and productivity of SAV. These have included studies on the distribution and abundance of SAV in relation to natural light intensities (Keller and Harris 1966; Peltier and Welch 1969; Orth 1977A), as well as those where natural light levels were decreased mechanically (Backman and Barilotti 1967; Congdon and McComb 1979). Rates of SAV production in relation to light intensity have been measured both in the laboratory (Sand-Jensen 1977) and in the field (Penhale 1977; McRoy 1974). In this section of the report the relationship between light and photosynthesis will be discussed, and a method will be presented to calculate changes in photosynthesis resulting from changes in light intensity.

Keller and Harris (1966) noted an optimum range, in relation to tidal depth, for the occurrence of Zostera marina at Humboldt Bay, California. Plant density declined toward the deeper portion of this range, probably because of decreasing light intensity. Peltier and Welch (1969), studying Potamogeton perfoliatus in Tennessee, noted a decrease in the net change of plant biomass when the available light decreased by 24 percent. The decrease occurred over a four week period. Orth (1977A) has suggested that Zostera marina may eliminate Ruppia maritima by shading. The two species seldom occur together except in shallower areas where Zostera growth is decreased.

Backman and Barilotti (1976), working in California, constructed submerged canopies that reduced the light reaching Zostera marina by about 63 percent. The experimental plants showed a remarkably rapid change to the decreased light, as the number of turions per area was reduced to an average of 27 percent of the control density over 18 days. This is a decrease of about 1.5 percent per day. After nine months the experimental plants had a density of 5 percent of the control plants. There were also indications that flowering was suppressed in the shaded plants, as well as vegetative regrowth in plants that had been shaded for nine months.

A report by Congdon and McComb (1979) further emphasized the long-term effects of shading on submerged aquatic vegetation. Working with Ruppia maritima in Australia, their results demonstrated a slower response to shading by Ruppia than Backman and Barilotti (1976) showed for Zostera. After two months at a 60 percent reduction in light Ruppia standing crop was about 66 percent of the control values. Ruppia however, showed a long-term response to shading similar to Zostera. By a series of harvests from 61 to 267 days after initiation of the experiment the authors demonstrated that higher light intensities were required to

maintain a standing crop 50 percent of the control value. For example, after 61 days the experimental standing crop equal to 50 percent of the control standing crop occurred at approximately 10 percent of the control light intensity, while at 164 days 50 percent of the experimental standing crop occurred at about 50 percent of the control light intensity. At 267 days the 50 percent level occurred at greater than 70 percent of the control light value. Table 1 shows experimental yields of Ruppia (as a percentage of control yields) at various levels of light (as a percentage of control light) as found by Congdon and McComb (1979).

TABLE 1. THE PERCENT YIELD OF RUPPIA MARITIMA AT SEVERAL LIGHT INTENSITIES. (after Congdon and McComb 1974)

Percent of Control Light	Percent of Control Yield
100	100
80	90
60	72
40	47
20	19

Although the preceding reports discussed standing crop, not productivity, a decrease in standing crop during the height of the growing season indicates decreases in productivity rates.

Sand-Jensen (1977), in a laboratory study, investigated the loss in photosynthetic rate in Zostera leaves due to epiphytic growth. He compared the photosynthetic rate of leaves with epiphytes and without epiphytes at increasing light intensities, up to saturation at about nine $mWcm^{-2}$. I have calculated a regression equation from his Figure 4, which shows the decrease in photosynthetic rate of a leaf without epiphytes, with decreasing light intensity. The calculated equation (for less than saturation light intensity) is:

$$Y=88.7-10.58X$$

where Y equals the percent reduction (from light saturated values) of photosynthesis and X is equal to light intensity, in $mWcm^{-2}$. A 50 percent reduction in the maximum photosynthetic rate occurs at about 37 percent of the saturating light intensity.

Two reports have been published which are important in constructing a general method of estimating SAV productivity. Penhale (1977), working in North Carolina and McRoy (1974), working in Alaska have done research on Zostera productivity using carbon-14 uptake. McRoy measured Zostera productivity in situ at four levels of irradiance; 100 percent of surface irradiance, 50, 25, and 10 percent of surface irradiance. Maximum photosynthesis occurred. Figure 1 shows the relationship between carbon uptake

and the percentage of surface light intensity as reported in McRoy's paper. Below saturated light levels a hyperbolic curve is generated; above saturation no further increase in photosynthesis occurs. In fact, above saturating light levels photosynthesis decreased.

McRoy (1977) described the curve below the 50 percent light level as fitting the following equation:

$$V = V_{MAX} \frac{S}{S+K_{LT}}$$

where V is equal to the carbon uptake rate in mg C per gram dry weight of plant per hour; V_{MAX} is equal to the maximum uptake rate; S is equal to the in situ light intensity (as a percentage of the surface intensity); and K_{LT} is equal to the percentage light intensity where the photosynthetic rate equals ½ of V_{MAX}.

This equation is of the Michaelis-Menton form. Other biological phenomena, such as phytoplankton nutrient uptake, have been described using this type of equation. Penhale (1977), working with Zostera, used it to calculate maximum photosynthetic rates from measured rates.

The above equation for estimating photosynthetic rates can be used to calculate the decrease in photosynthesis due to suspended sediments. The equation requires three values; a maximum rate of photosynthesis, a percentage of the surface irradiance at which the photosynthetic rate is ½ of the maximum photosynthetic rate, and a value for the in situ irradiance (as a percentage of the surface irradiance). The last value is site specific and therefore should be a field measurement. For the purposes of this report the first two are values taken from the literature. Sand-Jensen (1977) reported a V_{MAX} value of 1.25 mg $Cg^{-1}hr^{-1}$ in his lab experiments on Zostera. Penhale (1977) calculated V_{MAX} of 1.19 mg $Cg^{-1}hr^{-1}$ from photosynthetic measurements on Zostera, and McRoy (1974) reported a V_{MAX} of 1.18 mg $Cg^{-1}hr^{-1}$. An average of the three values, 1.21 mgC/ghr, is used in this report.

Values for K_{LT} are more difficult to find. McRoy (1974) reported a value for K_{LT} of 12.5 percent of the surface light, although this value might represent a physiological adaptation to far northern light patterns (Penhale 1977). Another value for K_{LT} is calculated from a figure from Sand-Jensen (1977) of 37 percent of saturating light intensity. Burkholder and Doheny (1968; cited by Phillips 1974), reported a 50 percent reduction in photosynthesis at less than 15 percent of surface light.

Perhaps the best way to use these values is to calculate a range of photosynthesis using the lowest and highest values. A sample calculation, using light penetration data from the Rhode River to estimate monthly changes in photosynthetic rates, is shown in appendix B.

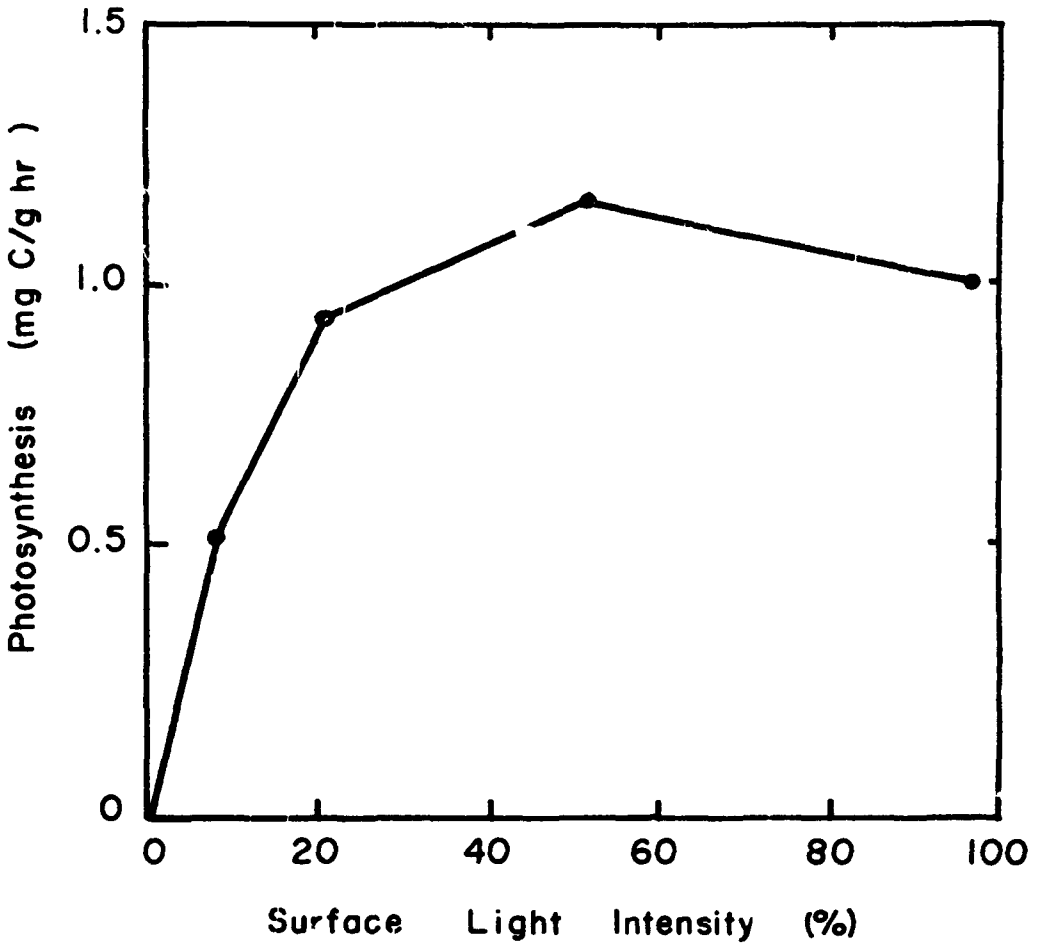

Figure I. The relationship between Carbon uptake and the % of surface light reaching the leaf. (After McRoy, 1974).

2. Sediment effects on SAV photosynthesis.

Sediment particles taken up into the water column can be released when water conditions change. These particles can accumulate on the leaves of SAV (Marsh 1973). Epiphytic growth on the leaves of certain SAV species commonly occurs (Marsh 1973; Sieburth and Thomas 1973; Sand-Jensen 1977; Penhale 1977). This epiphytic growth might produce light reduction effects similar to those produced by sediment deposition.

Although work has been done on the effects of sediment deposition on benthic invertebrates (Flemer et al. 1968; Pfitzenmeyer 1973), little information is available concerning sediment deposition and SAV growth. This section of the report will discuss the effects of sediment deposition on SAV photosynthesis. The reduction of photosynthesis by epiphytic growth will also be discussed. A method for estimating the reduction of SAV photosynthesis due to sediment accumulation will be presented.

Marsh (1973) noted a bed of Zostera so heavily laden with silt, epiphytes, and sessile organisms that the leaves were almost prostrate. He noted that this particular bed was growing near the lower limits of its light requirement. This accumulation might have occurred because of a diminished leaf turnover time resulting from reduced photosynthesis, since Sand-Jensen (1975) reported a new leaf produced every 15-20 days in healthy Zostera, and a leaf growth rate of from 2-8g $m^{-2}d^{-1}$. Bourn (1932) noted that a high sediment load could be detrimental to SAV. Odum (1963) reported that a SAV bed in Texas was killed by a 30 cm sediment deposition. Epiphytic growth on SAV, which might act in a somewhat similar fashion as sediment accumulation in terms of light attenuation, was shown by Sand-Jensen (1977) to reduce Zostera photosynthesis by 31-58 percent. These epiphytic accumulations can account for a significant proportion of combined leaf-epiphyte weight (Penhale 1977) and, by their heterogeneous surface, serve as a substrate for the accumulation of various biotic and abiotic particles (Sieburth and Thomas 1973). Zostera beds reduce currents and turbulence in the water flowing through them (Orth 1977B), thus decreasing the sediment carrying capacity of the water. This might cause Zostera to be susceptable to increased suspended sediments. The relatively wide leaves of Zostera probably facilitate the accumulation of material on them, while other fine-leaved species, such as Potamogeton pectinatus, apparently escape this problem (Stevenson and Confer 1977).

There is little in the literature that addresses the problem of sediment accumulation on SAV leaves. However, the equation for estimating the rate of photosynthesis (see appendix B) can be applied to calculate the percentage of light lost by sediment deposition. It can be done in the following manner.

1. McRoy (1974) reported a mean Zostera productivity of 4 gC $m^{-2}d^{-1}$. This mean biomass in his study for June, July, and August was 565 g m^{-2} (calculated here from his monthly data).

2. Using the previously assigned value of V_{MAX} (see appendix B) of 1.21 mgC per gram of plant tissue per hour, and the above biomass value, we calculate a V_{MAX} of 10 gc m^{-2} per 15 hour day.

3. The K_{LT} values will remain the same (12-15 percent).

4. The amount of suspended sediment settling out on a surface of known area, and the resulting light attenuation, are calculated (these calculations are beyond the scope of this report).

5. The photosynthetic equation is then applied using the above V_{MAX} and K_{LT} values, field-measured light readings, and the calculated light available after the losses from sediment accumulation.

A sample calculation is shown in appendix C.

3. Physical damage to SAV.

Damage to SAV can result from the physical impact of dredging (Taylor and Saloman 1968) or from contact with boat propellers (Zieman 1976). Damage resulting from less extreme effects, such as boat wakes, is not documented in the literature. The following discussion concerns known and possible effects of physical disturbance on SAV.

SAV beds can be damaged when plant leaves and rhizomes are injured or removed. Zieman (1976) reported long-term effects on beds of Thalassia testudinum in south Florida. Shallow channels, used frequently by boats, showed much of the damage. The damaged Thalassia rhizomes grew back very slowly. Dredging over SAV beds can also result in damage, since both leaves and rhizomes are physically removed from the site (Taylor and Saloman 1968).

Damage might also result from less extreme factors. Wood et al. (1969) noted that SAV beds (in this case Thalassia) require a reducing sediment for optimum growth. Zieman (1976) reported that both pH and the redox potential were changed in mechanically disturbed sediments. This sediment disturbance effect might occur if boat wake turbulence was sufficiently strong. Boat wake turbulence might also remove sediment from around SAV rhizomes. This could leave the plant more vulnerable to uprooting by storms, as well as exposing the rhizomes to grazing damage.

At the present time, no methods seem to be available to quantify these effects on SAV, and their importance remains unknown.

SUMMARY AND CONCLUSIONS

A survey of the pertinent literature showed that decreases in light intensity can result in a decrease in SAV productivity. These changes in growth rate can occur rapidly. Long-term decreases in light intensity can severely reduce SAV density. Light reaching the plants can be reduced either by an increase in water turbidity (suspended sediments), or by accumulation of sediment on the SAV leaves themselves.

Heavy sediment accumulation can destroy or severely damage SAV beds. The effects of lighter sediment accumulation on SAV leaves may increase the amount of sediment deposition on the leaves.

The photosynthetic response of SAV to light is hyperbolic up to saturation light levels. This hyperbolic curve can be described by the Michaelis-Menton kinetic equation. The equation can be used to estimate the changes in SAV photosynthetic rate due to suspended sediments in the water column. The equation can also be used to estimate the photosynthetic changes resulting from sediment accumulation on SAV leaves. In each case, the light intensity at the water surface, and the light intensity reaching the leaf, must be known.

SAV beds can be damaged by dredging and by boat propeller injury to leaves and rhizomes. The pH and the redox potential of the substrate can be changed by churning of the sediment. The water turbulence caused by boat wakes may also cause chemical changes in the sediment. Turbulence may also remove sediment from around the rhizomes, exposing them to predators and decreasing their ability to anchor the plant.

Submerged aquatic vegetation in the Chesapeake Bay is of great ecological importance. The recent decline of SAV in the Bay increases the importance of the remaining beds. The information presented in this report indicates that SAV is vulnerable to decreases in light intensity. Water turbulence might have an effect on SAV rhizomes. With the decreasing coverage of SAV in the Bay, and the increasing recreational and commercial boating use, localized effects on SAV assume greater importance. Several lines of investigation might prove useful in examining localized effects on SAV. A few examples are:

1. What is the light intensity and productivity of SAV beds in heavily utilized areas as compared to those in little used areas?

2. What are the chemical and physical changes in the sediments of SAV beds in heavily utilized areas?

3. What percentage of SAV beds are subjected to heavy boat traffic?

These questions, and others, should be asked if the importance of local disturbance to SAV is to be determined

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APPENDIX B

ESTIMATING SAV PHOTOSYNTHETIC RATES FROM LIGHT TRANSMITTANCE VALUES

Monthly values of light penetration on the Rhode River, Maryland in 1961 (from Bayley 1970) are used to calculate monthly rates of SAV photosynthesis, using the Michaelis-Menton equation.

	Percent of Solar Radiation Reaching a Depth of 3 Feet	Calculated Photosynthetic Rates (mgC/ghr)	Percent Change in Photosynthesis
March	19.0	0.72	0
April	8.5	0.49	32
May	6.0	0.39	20
June	4.0	0.29	26
July	14.0	0.64	55
August	9.0	0.42	34

Sample Calculation

$$V = V_{MAX} \frac{S}{S + K_{LT}}$$

$$= 1.21 \text{ mgC/g per hour} \quad \frac{0.19}{0.19 + 0.125}$$

$$= 0.72 \text{ mgC/g per hour}$$

V = Photosynthetic Rate = mgC/g Plant per Hour
V_{MAX} = Maximum Photosynthetic Rate = 1.21 mgC/g Plant per Hour
K_{LT} = Percent Solar Radiation at which the Photosynthetic Rate = $0.5V_{MAX}$ = 12.5%
S = Percent of Solar Radiation Reaching the Leaves

APPENDIX C

ESTIMATING THE DECREASE IN SAV PHOTOSYNTHESIS RESULTING FROM SEDIMENT DEPOSITION ON LEAVES

The percent light transmittance in the Rhode River in July, 1961 (from Bayley 1970) is used to calculate on SAV photosynthetic rate. The percent light transmittance is then reduced to simulate sediment accumulation on SAV leaves.

Sample Calculation

1. Without sediment accumulation

$$V = V_{MAX} \frac{S_1}{S_1 + K}$$

$$= 10 gC \text{ per } M^2 \text{ per day } \frac{0.14}{0.14 + 0.125}$$

$$= 5.3 \text{ gC per } M^2 \text{ per day}$$

2. With sediment accumulation

$$V = V_{MAX} \frac{S_2}{S_2 + K_{LT}}$$

$$= 10 \text{ gC per day } \frac{0.07}{0.07 + 0.125}$$

$$= 3.6 \text{ gC per } M^2 \text{ per day}$$

V = Photosynthetic Rate = mgC/g Plant per Hour
V_{MAX} = Maximum Photosynthetic Rate = 1.21 mgC/g Plant per Hour
K_{LT} = Percent Irradiance at which the Photosynthetic Rate = $0.5V_{MAX}$ = 12.5%
S_1 = Percent of Solar Radiation Reaching SAV Leaves (no sediment)
S_2 = Percent of Solar Radiation Reaching SAV Leaves (with sediment)

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ABSTRACT

The objective of this study was to determine if small vessels, operating in shallow waters, have any measurable effects in producing increased turbidities by the resuspension of fine sediments which may affect submerged aquatic vegetation (SAV).

A two-phase approach was used, consisting of field tests in a suitable sub-estuary of the Chesapeake Bay, and laboratory measurements of propeller effects. During field trials, two different vessel types were used to make passes at set speeds over known water depths. Before and after measurements of light extinction, transmission, and gravimetric suspended sediment determinations were used to identify effects. Laboratory experiments were conducted to delineate propeller contribution to possible resuspension; this was done using laser-doppler anemometry to map the turbulence field produced by propeller action.

Results of field tests show that a 9000 kg displacement vessel with a 19x22 propeller, travelling at hull speed of 3.6 m sec^{-1} in waters 2 m deep will produce statistically significant increase in light extinction and suspended sediment, averaging 2.7 mg/l when light data is converted to suspended sediment using empirical formulations for Chesapeake Bay waters. In slightly deeper waters (2.5 m), of similar sediment size distribution (median particle size 60μ), the same vessel produced increases averaging to 1.3 mg/l but only marginally significant statistically. A fast, planing outboard boat with a 16x19 propeller, produced significant increase in waters 2.0 m deep, but only when travelling at high speed. At lower speeds, deemed to be speeds inducing maximum wave making, no significant changes were detected.

Laboratory studies of propeller generated turbulence show that the relevant variables are the advance ratio J, i.e. the vessel velocity divided by the linear propeller tip velocity, and the propeller diameter. The lower the J value, i.e. the lower a vessels speed for a high propeller rpm, the greater the vertical extent of turbulence, and hence the depth to which consequent stirring can become possible. By modelling the propeller effects of the tugboat and outboard used in field tests, even when assuming that minimal turbulent stresses will resuspend sediment, the depths to which effects extend were generally less than those for which field tests showed impact. However, trends indicated by laboratory measurements corroborate field tests and allow limited extrapolation to cover a range of J values to