

Observations of tidal flux between a submersed aquatic plant stand and the adjacent channel in the Potomac River near Washington, D.C.

Nancy B. Rybicki, Harry L. Jenter, Virginia Carter, and Robert A. Baltzer

U.S. Geological Survey, 430 National Center, Reston, Virginia 22092

Michael Turtora

U.S. Geological Survey, 227 N. Bronough St., Tallahassee, Florida 32301

Abstract

Dye injection studies and direct velocity and water-level measurements were made in macrophyte stands and adjacent channels in order to observe the effects of the macrophyte stand on flow and mass exchange in the tidal Potomac River. During the summer, dense stands of submersed aquatic plants cover most shoals <2 m deep. Continuous summertime water-level records within a submersed aquatic plant stand and in the adjacent channel revealed time-varying gradients in water-surface elevation between the two areas. Water-level gradients are created by differing rates of tidal water-level change in vegetated and unvegetated areas. Results were consistent with the idea that on a rising tide the water was slower to enter a macrophyte stand, and on a falling tide it was slower to leave it. Differences in water elevation between the stand and the open channel generated components of velocity in the stand that were at right angles to the line of flow in the channel. Seasonal differences in flow speed and direction over the shoals indicate substantial differences in resistance to flow as a result of the vegetation.

Estuaries are often characterized by channels flanked by extensive shoals and shallow embayments (Kuo and Park 1995). Increasingly, goals are being set to improve water-quality conditions in estuaries in order to restore submersed macrophyte beds because of their habitat value and ability to stabilize sediments, reduce turbidity, and recycle nutrients (Batiuk et al. 1992; Greening and Eckenrod 1995). Estuarine models are being revised to include more detail on littoral zones and exchange between littoral zones and channels in an effort to make these models more accurate and to model living resources such as submersed aquatic vegetation (Cercio 1994; Kuo and Park 1995).

In the 1980s, the freshwater tidal Potomac River experienced a resurgence of submersed aquatic macrophytes (Carter and Rybicki 1986). By 1989, many shoals <2 m deep were covered with dense stands of *Hydrilla verticillata* Royle (hydrilla) mixed with lesser amounts of other species. The coverage in 1989 is shown in Fig. 1. It is well documented that submersed aquatic vegetation can increase temperature stratification, dissolved oxygen concentration, and pH of the surrounding water during photosynthesis (Carter et al. 1988, 1991; Frodge et al. 1990). Phytoplankton numbers and suspended-sediment concentration decrease inside aquatic plant stands improving water clarity compared with adjacent open water (Fonseca and Fisher 1986; Marshall and Westlake 1990). Further knowledge of the mass exchange process between a macrophyte stand and the open water is necessary, however, before models can be developed that quantify chemical exchanges between the two areas.

Acknowledgments

We appreciate the help of numerous volunteers from other USGS projects, other agencies working on the Potomac River, and citizen volunteers during the course of our experiments. We also thank the reviewers of this manuscript, Hugh Dawson, Lisa Roig, and two anonymous reviewers, whose comments were very beneficial.

Numerous studies have been conducted on the effects of submersed aquatic plants on flow conditions. In a number of studies, velocities were substantially reduced within a submersed aquatic plant stand versus open water (e.g. Madsen and Warncke 1983; Marshall and Westlake 1990; Pitlo and Dawson 1990). In streams with velocities ranging from 0.8 to 79 cm s⁻¹, macrophytes were found to lower velocities and obstruct flow near the bottom causing a simultaneous increase in velocities above the plants (Gregg and Rose 1982; Marshall and Westlake 1990). A flume study of flow through seagrasses showed plant-canopy friction was strongly correlated with percentage of water column occupied but was not correlated with stem density (Fonseca and Fisher 1986). The significance of the structure, stiffness, and biomass of a plant stand in contributing to variations in flow resistance has been well noted, and increases in plant biomass seasonally have been demonstrated to increase hydraulic roughness (Dawson and Robinson 1984; Kouwen 1988; Pitlo and Dawson 1990). None of these studies, however, reported velocity (both speed and direction) in tidal rivers where mass exchange between a macrophyte stand and the open water is driven by tidal action.

The life cycle and growth form of hydrilla and other macrophytes affect plant stand structure and biomass and must be considered in mass-exchange studies between macrophyte beds and open water. In temperate regions, hydrilla sprouts from underground tubers in May; it spreads by forming vine-like runners that also sprout numerous shoots. By July, the leaves and branches are concentrated near the water surface and form a plant canopy. In tidal areas, the plant-canopy density varies with the stage of the tide. Near Washington, D.C., the tidal range is ~1 m and, at low tide, foliage in the plant canopy is bent over and compacted into the uppermost several decimeters of the water column. At high tide, the canopy straightens up into the deeper water, plants are erect, and water may flow above the fully extended canopy. In late

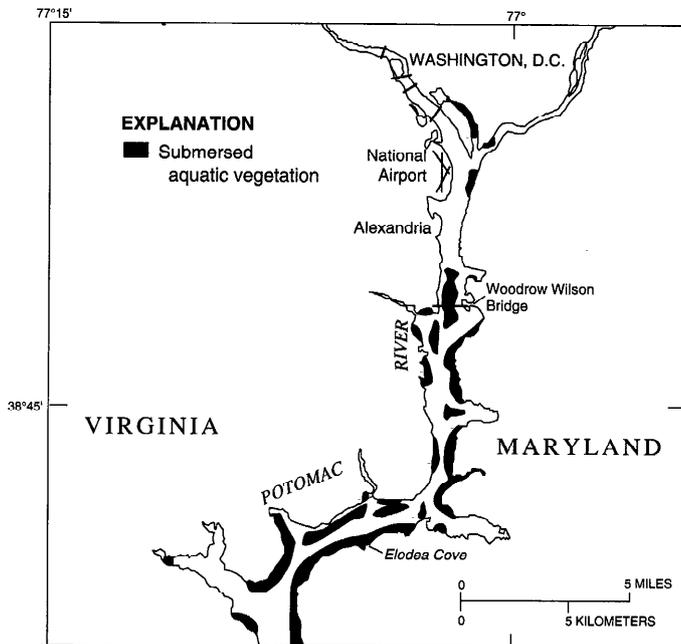


Fig. 1. Study area in the freshwater tidal Potomac River showing coverage of submersed aquatic vegetation in 1989.

fall, plants senesce, detach from the sediment, and float away.

This paper documents observations of how hydrilla stands can alter flow across shoals. Measurements of speed and direction of flow in a hydrilla stand and in the adjacent channel, water-level gradients between a hydrilla stand and the adjacent channel, and the effect of plant-density (biomass/unit volume) profiles on velocity profiles are reported.

Methods

Two field sites with dense stands of hydrilla were studied in the freshwater tidal Potomac River, one just north of Woodrow Wilson Bridge (WWB) and one at Elodea Cove, 9 km downstream from the WWB site, on the Maryland shoreline (Fig. 1). This reach of the river is well described by Callender et al. (1984). Channel depth (mean low water) at the WWB site is ~9 m on the western side and 6 m on the eastern side of the shoal. Water depth on the shoal at the WWB site ranges from ~0.5 m at low tide to 1.5 m at high tide. Water depth on the shoal at Elodea Cove ranges from ~1.4 m at low tide to 2.4 m at high tide, and water depth in the adjacent channel is ~7 m.

Dye transport, WWB—One dye study was made at ebbtide on 30 August 1989, and one at floodtide on 6 October 1989, at the WWB site only. The dye study started ~3 h before and 3 h after low tide so that the plant canopy reached the water surface, but water was not yet flowing above the plant canopy. In both studies, dye was injected in the hydrilla stand and dye concentration was measured over time at points in the hydrilla stand at known distances from the injection. Prior to injection, a water sample was collected for

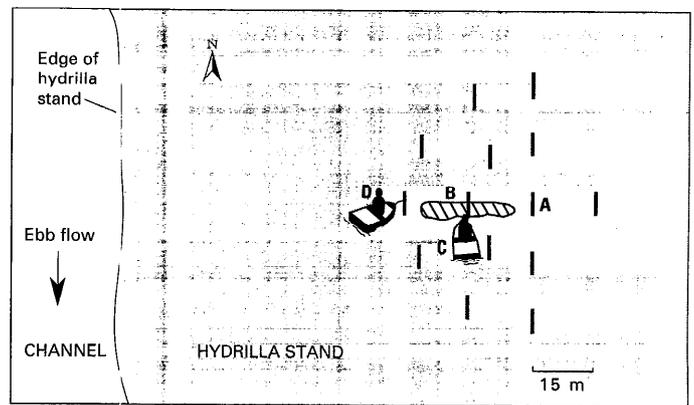


Fig. 2. Top view of the dye movement during the ebbtide dye study at the Woodrow Wilson Bridge site, 1989. A, the injection point; B, the dye; C, the roving boat with a flow-through fluorometer; D, an anchored boat collecting samples every 4 min.

background fluorescence. Dye concentration was measured with a Turner model 10 flowthrough fluorometer.

One hundred milliliters of the dye concentrate (rhodamine WT 20% solution) was diluted in a container with river water and rapidly injected (2 min) with a manual bilge pump into the water column in a small area cleared of plants (~0.3 m square). During the first half hour of each dye experiment, concentrations were measured in the field to establish the direction of flow and amount of dispersion. Dye concentration and water temperature were measured at an array of poles set up in a concentric pattern around the injection site (Fig. 2). Sampling boats were moved by pulling on rope tied between the poles to avoid disturbing the water or the plants.

After determining the direction of flow, one sampling site was chosen 30 m downstream from the injection site. At that site, water samples were pumped about every 4 min through flexible tubing. Samples were collected 0.5 m below the water surface and 0.2 m above the bottom sediment. Throughout the study, a roving boat continued to measure dye concentration at poles within and outside the path of the dye. Sampling was continued until the dye cloud had passed the fixed site and concentrations at the fixed site approximated background concentration (~1.5 h after injection). These samples were kept in the dark, analyzed in the laboratory with a Turner model 10 fluorometer, and used to determine flow speed.

The time required for the dye to reach the measurement site was determined for the leading edge, peak, trailing edge, and centroid of the dye cloud for each dye-study date and for each depth using techniques described by Hubbard et al. (1982) and Parker et al. (1983). The leading edge was defined as the time when the dye cloud concentration had increased to 5% of the peak concentration at the sampling point, peak as the time of maximum dye concentration at the sampling point, trailing edge as the time when the dye concentration had decreased to 5% of the peak concentration at the sampling point, and centroid as approximately the arrival time of the dye cloud's center of mass. Integrating the concentration curve with respect to time since injection provides centroid arrival time (T):

$$T = \frac{\sum_{i=1}^N T_i C_i dt}{\sum_{i=1}^N C_i dt} \quad (1)$$

where N is the number of measurements between the arrival time of the leading edge and the arrival time of the trailing edge. T_i is the i th minute since injection; C_i is the observed dye concentration at T_i , in $\mu\text{g liter}^{-1}$; and dt is the amount of time between successive measurements. Flow velocity can be estimated from the centroid arrival time for each study date and depth by the relation

$$V = d/T \quad (2)$$

where V is velocity, and d is distance between injection site and sampling station. The flow steadiness criterion, an assumption necessary to use Eq. 1 and 2, seemed to be met because the experiments were concluded before the tidal flow changed direction.

Water-level differences, WWB—Water levels were recorded at the WWB site at 5-min intervals between 17 August and 29 November 1990, with automatic digital recorders (ADRs) placed on free-standing platforms—one in the center of the hydrilla stand and a second on a dock at the western edge of the river channel 600 m away. The two ADRs were equidistant from the head of tide; therefore, we assumed that the water-level gradient between them would be zero at all tidal stages during the unvegetated season and zero at high tide during the vegetated season when the entire plant stand is submersed. Possible exceptions to this are rare times when strong, steady cross-stream winds could set up small cross-stream gradients in water level. Water-level gradients between the two sites (defined in Fig. 3) were measured by setting the gages to read the same water level at high tide on a windless day when the plants were completely submersed. The gage precision was ± 0.3 cm. Throughout the study, the mean difference between the gages at high tide was only 0.3 cm, with a standard deviation (SD) of 0.3 cm. The water-level differences between the hydrilla stand and the channel were calculated for every 5-min interval. The maximum difference during the ebb and flood tide for each 12.4-h tidal cycle (Fig. 3) was also calculated. In addition, the mean water level for each tidal cycle was determined by smoothing the data by a 12.4-h lowpass filter technique (Chambers et al. 1983).

Flow speed and direction, WWB and Elodea Cove—Water velocity was measured for one full tidal cycle in July and August 1990 at the WWB site and was measured during ebbtide only at the Elodea Cove site in September 1990 and at the WWB site in January 1991. At the WWB site, simultaneous measurements were made in the main channel (except in January) and at two sites within but on opposite sides of the hydrilla stand. The two sites were ~ 75 m inside the eastern and western edges of the hydrilla stand. At Elodea Cove, simultaneous measurements were made in the main channel and ~ 50 m inside the hydrilla stand at the center of the mouth of Elodea Cove (Fig. 1).

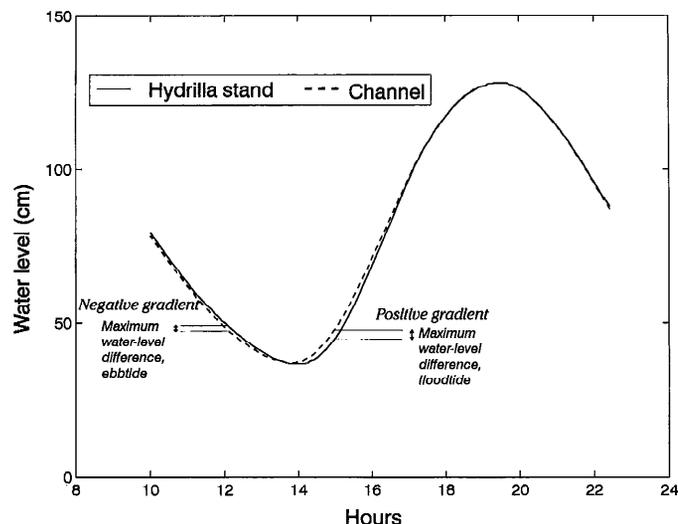


Fig. 3. A comparison of water-level records in the hydrilla stand and channel for a single tidal cycle showing the maximum water-level difference (water level in the channel minus water level in hydrilla stand) for ebb and floodtide on 18 September 1990 near the Woodrow Wilson Bridge in the tidal Potomac River. A positive gradient forms when water level is lower in the hydrilla stand (floodtide) and a negative gradient forms when water level is lower in the channel (ebbtide).

Flow velocities in the channel were measured at 10-min intervals at three depths in the water column. A Price AA current meter (Rantz et al. 1982) was used to determine the flow rate at 0.2, 0.6, and 0.8 of the total depth. Mean velocity in the water column was calculated by averaging the 0.2- and 0.8-depth observation and then averaging that result with the 0.6-depth observation (Rantz et al. 1982). Surface-flow direction was visually estimated by use of a hand-held compass aligned along the current meter's axis and assumed to be constant with depth.

Individual vertical-velocity (speed and direction) profiles of the entire water column at the sites within the hydrilla stands were made at 20-min time intervals using Neil Brown Instrument System acoustic current meters with internal flux-gate compasses. The current meters were suspended from fixed structures and were raised and lowered by a cable and pulley system operated from boats positioned 20 m from the measurement site in order to minimize flow disruption. Plants were removed from an area (0.3 m square) directly beneath the instrument to prevent interference as the meter was raised and lowered. Measurements were made at 0.15-m depth intervals from the bottom to the surface. Each recorded velocity was a 30- or 60-s average (depending on the steadiness of the reading) of a 2-Hz data sampling. The current meters have a rated speed accuracy of 0.25 cm s^{-1} in the range $0\text{--}250 \text{ cm s}^{-1}$ with a precision of 0.1 cm s^{-1} and a rated directional accuracy of ± 2 degrees with a precision of 0.1 degree; data were corrected for magnetic variation.

In addition to reporting the mean velocity for the entire water column in the hydrilla stand for each 20-min observation, we divided the tidal cycle into two half-tide periods, ebb and flood, and determined mean speed and direction for

Table 1. Mean and range for the maximum tidal cycle water-level differences between the channel and the hydrilla stand during the vegetated and unvegetated season at the Woodrow Wilson Bridge site, 1990. A negative value indicates water-level was lower and a positive value indicates water level was greater in the channel than in the hydrilla stand. Water-level differences in cm \pm SD.

	Tidal cycles	Maximum water-level differences			
		Mean ebb	Mean flood	Range ebb	Range flood
All tidal cycles					
Vegetated period	133	-14.0 \pm 0.702	2.7 \pm 0.158	-4.3 to 0.3	0.6-9.1
Unvegetated period	58	-1.2 \pm 0.466	1.3 \pm 0.139	-2.5 to 0	0-6.1
Tidal cycles when water level was >35 cm					
Vegetated period	92	-1.2 \pm 0.623	2.0 \pm 0.792	-4.3 to 0.3	0.6-4.3
Unvegetated period	33	-1.1 \pm 0.436	0.6 \pm 0.319	-2.1 to 0	0-1.6

each period. Ebb was defined as the time when water level was falling in the hydrilla stand, and flood was defined as the time when water level was rising. Velocity profiles were also averaged by vertical strata to investigate the effect of plant density (biomass/unit volume) on velocity. The water column was divided into three strata on the basis of biomass-profile measurements: below the plant canopy, within the plant canopy, and above the plant canopy. At Elodea Cove the strata within the plant canopy occupied a larger portion of the water column than at WWB because the plants were taller (plant height 1.85 m at Elodea Cove versus 1.10 m at WWB).

Biomass, WWB—Plant biomass and biomass profiles were measured at the WWB site. A diver collected 12 0.3-m-square plant-biomass samples (above- and belowground biomass combined) in July and again in August 1990. Vertical profiles of plant density also were measured by a diver, using a 1 \times 1 \times 2.5-m cubical framework marked at 0.25-m depth intervals. One plant-density profile was made at high and low tides in both July and August. Vegetation within the frame was clipped at 0.25-m depth intervals from the water surface down to the sediment surface. All plant material was oven-dried at 105°C for 12–24 h and weighed.

Results

Dye transport, WWB—Measurements of dye concentration recorded with a flow-through fluorometer showed that the dye moved in a direction nearly perpendicular to the edge of the plant stand at the surface and the bottom. During ebbtide, the dye cloud moved westward on the west side of the bed, toward the channel in a direction substantially different from flow within the channel (Fig. 2). During flood tide, the dye cloud moved from the injection site eastward toward the center of the bed. The estimated mean flow velocities during the ebb were 0.52 cm s⁻¹ on the surface and 0.58 cm s⁻¹ on the bottom and during the flood were 0.52 cm s⁻¹ on the surface and 0.50 cm s⁻¹ on the bottom. Over the 30-m distance, the estimated velocities for surface and bottom were very similar. Upstream and downstream dispersion of the dye cloud was minimal (<1 m) during the ebb and most of the flood. During the flood, when the dye intersected a depression where water flowed above the plant

canopy, some dye dispersed upstream and downstream several meters. No dye was detected at any pole except the pole between the injection site and the fixed sampling site (Fig. 2).

During the dye study, wind and temperature did not have an obvious effect on dye movement. During the ebbtide study, wind speed exceeded 16 km h⁻¹ in the direction opposite to the dye motion and, during the floodtide study, was \sim 8 km h⁻¹ in the direction perpendicular to that of the dye motion. Within the hydrilla stand, temperature differences between the surface and bottom were <1°C during the dye studies. Mass flux was nearly perpendicular to channel flow and this was apparently not a result of wind or thermal circulation.

Water-level differences, WWB—Water-level differences are affected by resistance caused by friction at the river bottom and drag from the hydrilla stand. During the unvegetated period, water-level differences consistently occurred when the low-tide water level was <35 cm and were infrequent when the low-tide water level was >35 cm, as measured at our gage on the shoal. In an effort to reduce the complication of friction dominated by river-bottom effects, trends were determined using only those tidal cycles when the low-tide water level over the shoal was >35 cm. This reduced water-level differences in the unvegetated season particularly on the flood (Table 1).

Figure 4 shows daily maximum water-level gradient between the channel and the shoal. Differences in water level were consistently >1 cm during the vegetated period (17 August–26 October) and generally <1 cm during the unvegetated period (27 October–29 November) (Fig. 4). The tidal-cycle maximum water-level difference during the vegetated period averaged 1.2 cm (SD = 0.623) for the ebb and 2.0 cm (SD = 0.792) for the flood, whereas the maxima for the unvegetated period averaged 1.1 cm (SD = 0.436) for the ebb and 0.6 cm (SD = 0.319) for the flood. A rank sum test (Wilcoxon 1945) showed differences during the vegetated season were significantly greater than during the unvegetated season during floodtide but were not significantly greater during ebbtide.

The wide range of differences in water level during the vegetated period is affected by daily mean water level in the river and maximum daily rate of water-level change. Figure

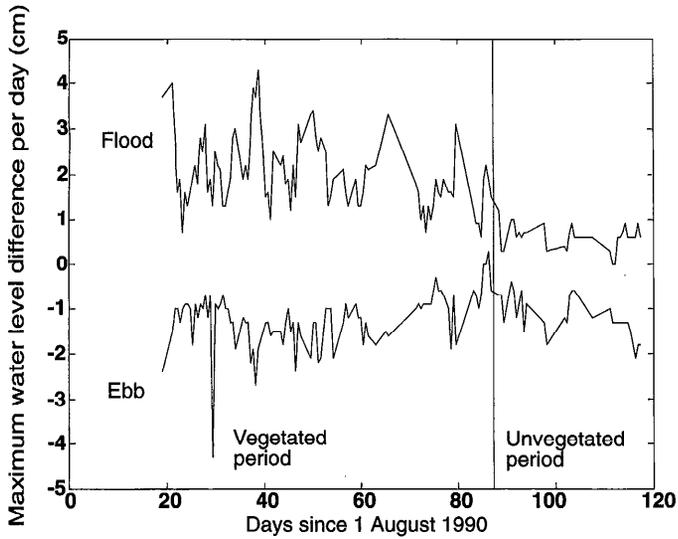


Fig. 4. Plot of the maximum floodtide and ebbtide water-level difference between the channel and the hydrilla stand versus days since 1 August 1990 at the Woodrow Wilson Bridge site. Days 17–87 are the vegetated period and days 88–119 are the unvegetated period. Differences in water level between the channel and hydrilla stand result in a positive gradient during floodtide and a negative gradient during ebbtide.

5A (the vegetated period) and B (the unvegetated period) are plots that relate the daily maximum water-level differences to the daily mean water level in the river during the flood (positive) and ebb (negative). There is a tendency for larger differences to occur during the vegetated period (Fig. 5A) than during the unvegetated period (Fig. 5B). During the vegetated period there is a considerable range of differences at any given water level. This variation can be explained by a second variable, the maximum daily rate of water-level change. Figure 5C and D depicts the maximum water-level difference as a function of the maximum daily rate of water-level change in the channel each day. During the vegetated period (Fig. 5C), there is a positive relationship between the rate of water-level change and maximum differences. This relationship is not evident for the unvegetated period (Fig. 5D). Water-level differences between the hydrilla stand and channel (Table 1) are greater during the flood than during the ebb because the rate of water-level change is greatest during the flood; a floodtide cycle requires ~5 h, whereas an ebbtide cycle requires ~7 h in this part of the Potomac River.

Flow speed, WWB—Figure 6 shows the mean speed and direction in the hydrilla stand and channel averaged over an entire ebb or floodtide. Velocities varied substantially from

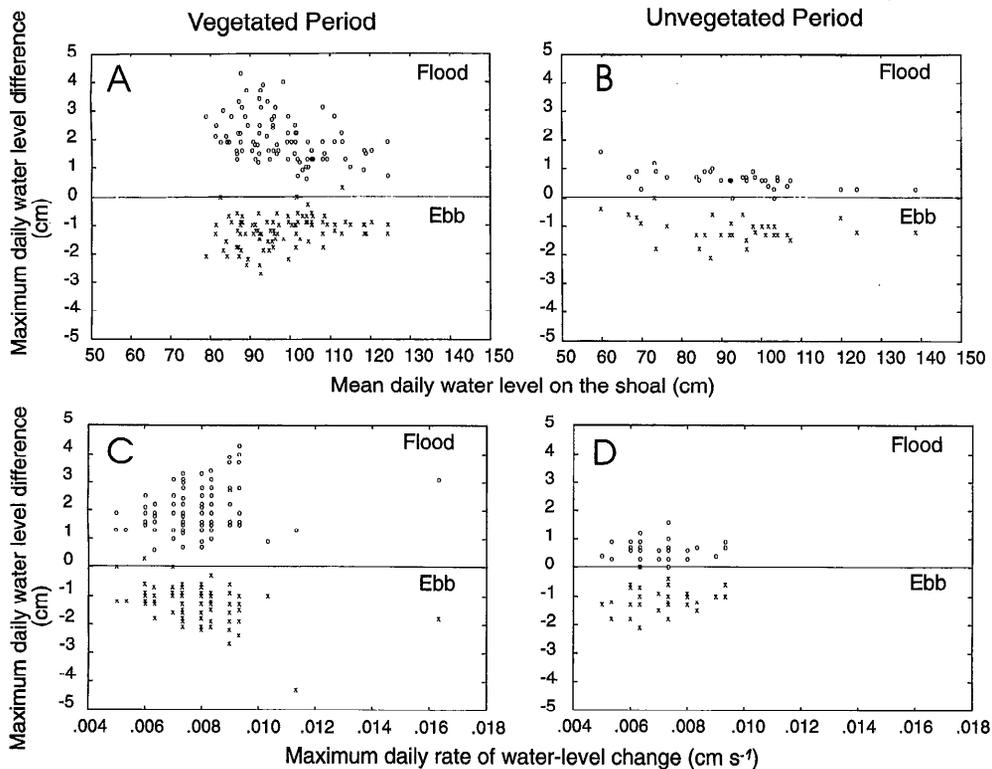


Fig. 5. A, B. Scatter diagrams of the maximum daily flood (o) and ebb (x) water-level difference vs. the mean daily water level on the shoal at the Woodrow Wilson Bridge site in the vegetated period and unvegetated period. C, D. Scatter diagrams of the maximum daily flood (o) and ebb (x) water-level difference versus the maximum daily rate of water-level change in the vegetated period and the unvegetated period. Differences in water level between the channel and hydrilla stand result in a positive gradient during the flood and a negative gradient during the ebb.

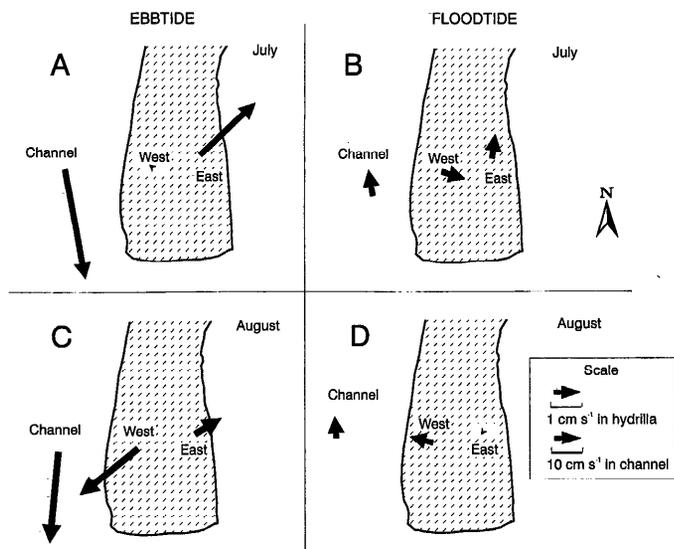


Fig. 6. Mean velocity in the hydrilla stand and channel averaged over an entire ebb or floodtide in July and August at the Woodrow Wilson Bridge. The velocity scale for the channel is 10 times that of the hydrilla stand (the shaded area is the hydrilla stand north of the Woodrow Wilson Bridge). In panels A and D the abbreviated arrows indicate velocities of 0.2 cm s^{-1} .

one side of the hydrilla bed to the other; velocities were fastest at the east site in July and at the west site in August. In general, velocities in the channel were >10 times faster than velocities in the hydrilla stand.

In July, the depth-averaged velocities ranged from 52.9 to 20.0 cm s^{-1} in the channel, 4.0 to 1.3 cm s^{-1} at the east site in the hydrilla stand, and 1.4 to 0.04 cm s^{-1} at the west site in the hydrilla stand. In August, the velocities ranged from

38.5 to 1.6 cm s^{-1} in the channel, 1.7 to 0.2 cm s^{-1} at the east site, and 2.9 to 0.8 cm s^{-1} at the west site. In January, velocities at the east site ranged from 18.7 to 2.1 cm s^{-1} , and at the west site, from 16.2 to 3.0 cm s^{-1} . In January, during the unvegetated period, maximum velocities on the shoal were ~ 4 times greater than those during the vegetated period.

Flow speed, Elodea Cove—At the Elodea Cove site the velocities in the channel were also ~ 10 times faster than in the hydrilla stand (Fig. 7A). The average velocity in the channel was 21.8 cm s^{-1} . In the hydrilla stand, velocities ranged between 2.9 and 1.4 cm s^{-1} .

Flow direction, WWB—As seen in the dye study, flow between the hydrilla stand on the shoal and the open water was expected to be roughly perpendicular to the edge of the hydrilla stand. Figures 8 and 9 show each 20-min, depth-averaged velocity during ebb and floodtide in the hydrilla stand during July and August. During the ebb in July and August at the east and west sites, flow direction in the hydrilla was variable (Fig. 8), yet mean flow had a substantial component perpendicular to the edge of the plant stand and to the direction of flow in the channel (Fig. 6A, C). During the flood, at the July west and August east site, mean flow direction was reversed, compared to ebbtide direction and was approximately perpendicular to the edge of the hydrilla stand (Fig. 6B, D); however, there was tremendous variability about the mean flow (Fig. 9). In contrast, in July at the east site, mean flow was in the same direction as that in the channel (Fig. 6B), although Fig. 9 (July East Flood) shows that not long after low tide water flowed west into the hydrilla stand for more than an hour. At the August west site the water did not flood in an easterly direction into the bed; water generally flowed out of the hydrilla stand toward the

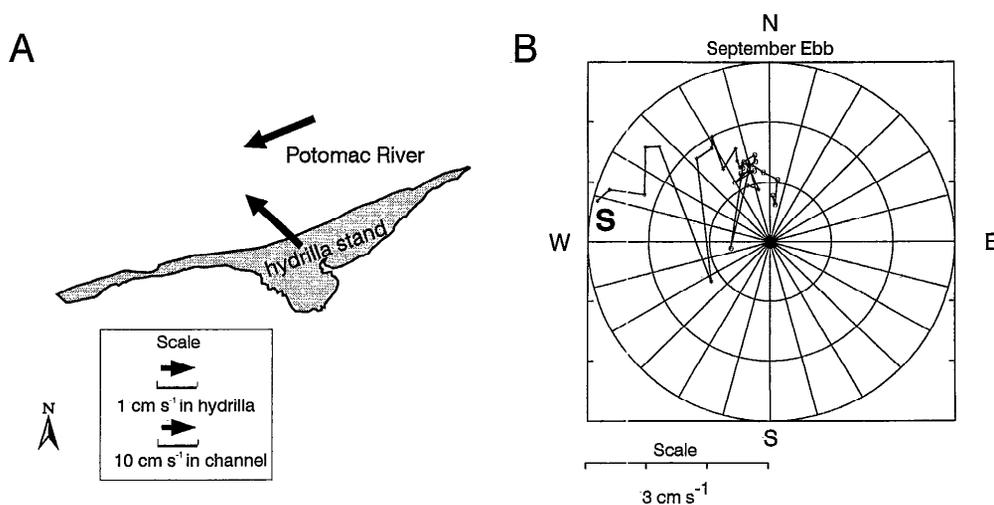


Fig. 7. A. Mean velocity in the hydrilla stand and channel averaged over an entire ebbtide in September at Elodea Cove. The velocity scale for the channel is 10 times that of the hydrilla stand (the shaded area is the hydrilla stand). B. Depth-averaged velocity in the hydrilla stand for ebbtide direction in September at Elodea Cove; measurements are 20 min apart. Velocity is shown here as the compass direction and speed an arrow would indicate if drawn from the center of the compass to each point on the line. An S indicates start of the sequence.

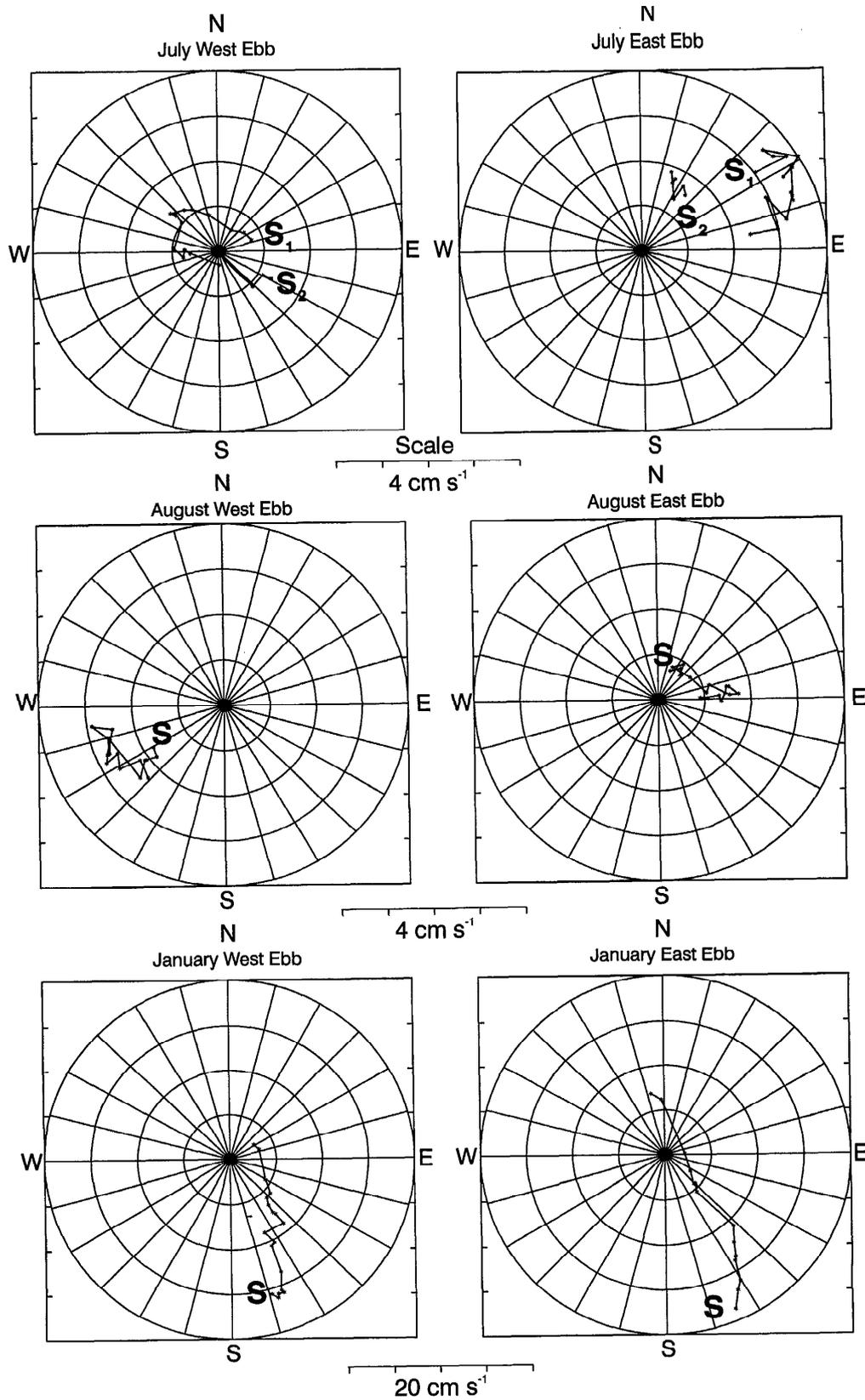


Fig. 8. Depth-averaged velocities at the west and east sites during ebb tides in July, August (in hydrilla stand), and January (without hydrilla) at the Woodrow Wilson Bridge. Measurements are 20 min apart. Velocity is shown here as the compass direction and speed an arrow would indicate if drawn from the center of the compass to each point on the line. An S indicates the start of the sequence.

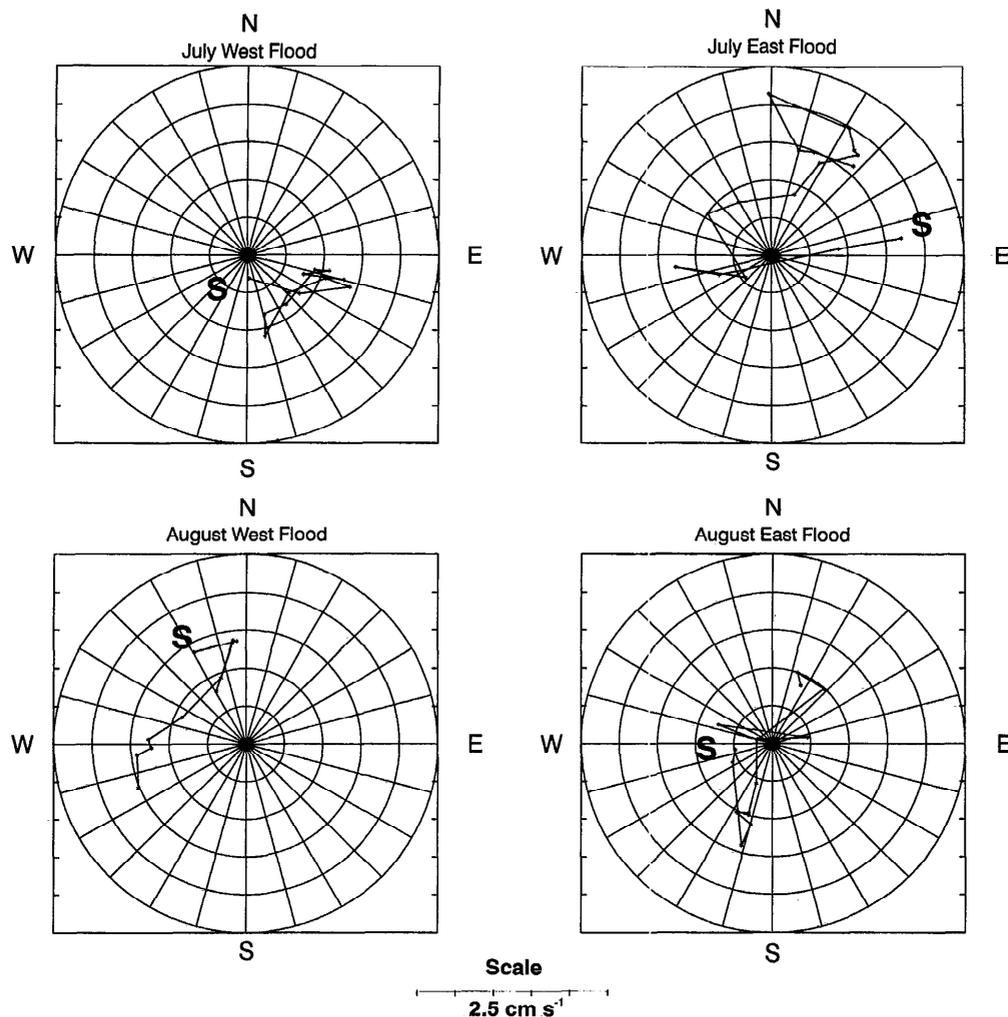


Fig. 9. Depth-averaged velocities at the west and east site in the hydrilla stand for flood tides in July and August. Measurements are 20 min apart. Velocity is shown here as the compass direction and speed an arrow would indicate if drawn from the center of the compass to each point. An S indicates the start of the sequence.

channel during the flood and throughout the ebb (Fig. 6C, D).

Depth-averaged flow was faster and direction was much less variable on the unvegetated shoal in January than it was in summer. Figure 8 shows that the flow direction in both shoal locations was toward the southeast throughout most of the ebb and was parallel to flow in the channel.

Flow direction, Elodea Cove—This site behaved in a similar way to the WWB sites at ebbtide. During the ebb, flow in the hydrilla stand was variable yet had a strong component perpendicular to the edge of the stand (Fig. 7A, B). Water moved, on average, in a direction roughly perpendicular to flow in the channel.

Flow speed and direction analyzed by plant density strata; the effect of plant biomass—The mean biomass (dry wt) of 12 0.3-m-square samples at WWB was 747 g m^{-2} (SD = 218) in July and 675 g m^{-2} (SD = 163) in August. July

biomass was not significantly different from August biomass. The four biomass profiles showed that plant biomass was lowest in the bottom 50 cm (below the plant canopy) at both high and low tide and increased toward the top of the plant canopy (Fig. 10). At low tide, the biomass in the top 25 cm (within the plant canopy) was nearly three times (July) to four times (August) greater than biomass below the plant canopy. At high tide, the biomass in the plant canopy was ~ 1.5 times (July) to 2.6 times (August) greater than biomass below the plant canopy. The difference in biomass within and below the plant canopy was much greater at low tide than at high tide.

We hypothesized that, despite bottom friction, velocities would be greatest near the bottom as a result of lower plant density. Figure 11 shows the average velocity within each of the defined strata (above, within, and below the plant canopy) as a function of time and water level in August at the west site. At all sites, the velocity profiles over a tidal cycle were qualitatively the same. The velocity was gener-

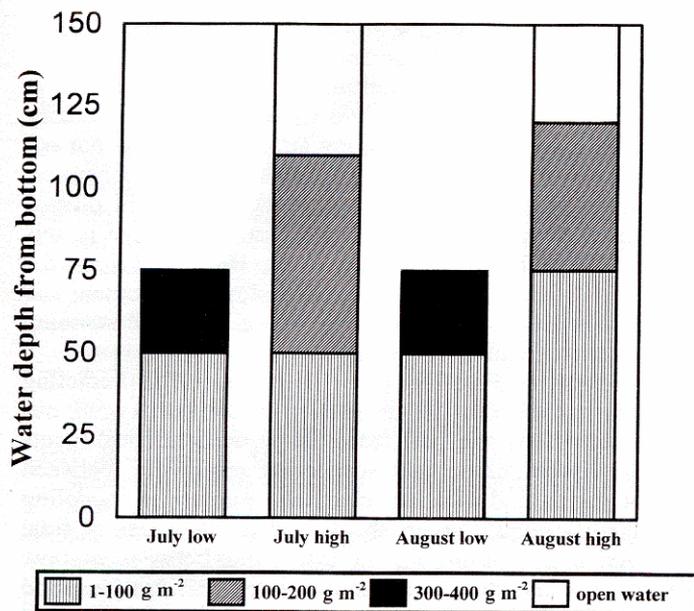


Fig. 10. Hydrilla biomass (dry weight) at 25-cm intervals from the bottom at high and low tide in July and August 1990.

ally greater below the plant canopy than within the plant canopy near the time of low tide (particularly in July at the east site and in August at both sites); however, velocity was generally greater within the plant canopy than below the plant canopy near the time of high tide. Throughout most of the tidal cycle the plants filled the water column; therefore, few velocity measurements were made above the canopy. When measured, velocity above the plant canopy was relatively slow, possibly because of friction from the top of the plant canopy.

At WWB and Elodea Cove water flowed in a similar direction within and below the plant canopy. Flow direction was similar (maximum directional spread was 98°) in all strata except during July ebbtide at the west site and during August floodtide at the east site at WWB, when flow above the plant canopy was the opposite to flow in the two strata below. On these two occasions, flow in opposing directions resulted in a low overall average flow velocity (Fig. 6A, D).

Discussion

A 1960 dye study in the Potomac River near Washington, showed that flow on the shoal and adjacent channel was parallel before the aquatic plants vegetated the shoals (Wilson et al. 1969). The results of the dye transport study showed that this was not the case when the shoal was vegetated. These observations prompted further investigation into water-surface elevation gradients and velocities in the hydrilla stand and the adjacent channel leading to a better understanding of tidal flux between the two areas.

Hydrilla presence affects the rate that the water level can change over the shoal. In cases where the water level over the shoal cannot change as rapidly as that in the channel, a relative water-level difference results. Differences in water level between the hydrilla stand and the river channel gen-

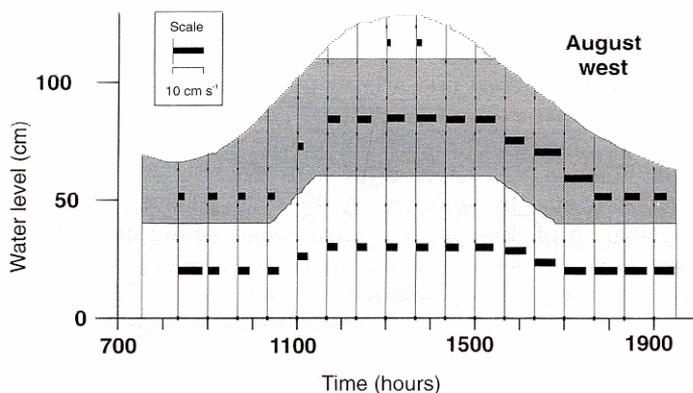


Fig. 11. Average velocity (speed) above, within (shaded area), and below the plant canopy at 40-min time intervals throughout a tidal cycle in August at the west site.

erate a cross-stream pressure gradient. If this hydraulic gradient is sufficiently large and dominates other forcing factors, the flow between the stand and the channel is expected to be along the gradient rather than in the direction of flow in the channel, possibly even perpendicular to channel flow. The dye study and the ebbtide velocities for the July, August, and September tidal-cycle experiments demonstrated this.

Floodtide velocities were not always perpendicular to the channel flow and edge of the hydrilla stand. This is surprising because the largest water-level gradients occurred consistently during the flood. A possible explanation for this is that heterogeneity in the bottom and in the hydrilla stand create features that interrupt, detain, and(or) channelize the flow through the hydrilla stand. In the submersed aquatic plant beds in the Potomac River, there is no evidence of the formation of incised, meandering channels, but boat propellers scar the plant stand and create paths that are detectable (for weeks) at low tide and then refill with a tangle of erect, buoyant stems and leaves at high tide.

A closer look at the physical sequence of conditions prevailing in the hydrilla stand throughout a tidal cycle provides insight into the observed asymmetry between mean ebb and flood flow. At high tide the concentration of plant stems and foliage tends to be least dense and most uniformly distributed throughout the water column; therefore, the plant stand is more uniformly penetrable with the onset of ebb flow. Thus, the combination of drag and frictional forces acting throughout the water column at the onset of the ebb cycle tends to be spatially more homogeneous than at other times. During this period, flow in the hydrilla stand tends to be spatially uniform and in the direction prescribed by the maximum pressure gradient.

At low tide a different set of conditions prevails. The water column, itself, is only a fraction of its high-tide depth. Thus, any bathymetric perturbations that occur have a more pronounced as well as more local frictional effect on flow across the bottom than would be the case at high tide. Moreover, not only are plant stems and foliage more highly concentrated, they are more unevenly distributed in the water column. The highest concentration of plant materials is in the upper portion of the foreshortened water column where it presents a significant, energy-dissipative impediment to

flow through that portion of the column. Flow below the plant canopy, while less impeded by stems and foliage, is typically sandwiched into a layer of varying thickness as a result of bathymetric variations and bounded by the bottom below and the dense, highly dissipative, plant canopy overhead. Flow in this lower layer may even "pinch out" in some locations. In summary, at the onset of flood tide the combination of drag and frictional forces acting upon flow throughout the water column tends to be highly variable, vertically, as well as, spatially. Consequently, during the flood cycle of the tide, when water-level gradients are consistently the greatest, flows respond to the set of time varying paths of least energy loss due to the drag and frictional forces. Paths of least resistance, whether the result of "propeller cropping" or some other phenomena, thus afford directional avenues for flooding the interior of the hydrilla stand.

Based on the observations made in these studies, we strongly suspect that the number and orientation of paths or boat propeller scars in the hydrilla stand have a substantial influence on mass flux in summer. We suspect that the difference in water level between the bed and hydrilla stand decreases as the number of propeller scars in the hydrilla stand increases. In addition, differences in water level between the channel and hydrilla stand are probably greater when paths run parallel, rather than perpendicular, to the channel. We also make the assumption that friction is greatest at low tide, decreases and increases substantially just before and after high tide, and is lowest during high tide. A numerical modeling study is currently underway to investigate the relationship between the number and orientation of propeller scars and water-level differences between the channel and hydrilla stand.

Spatial and temporal variation in the hydrilla stand affected speed and direction of point-velocity measurements but was obscured in the brief, spatially averaged, dye study. The 1989 dye study integrated those factors for a distance of 30 m and a period of 1.5 h when the plants filled the entire water column. The 1990 point-velocity measurements showed the same general trends as determined during the dye study, but many more variables were introduced by increasing the duration of the experiment to include an entire tidal cycle.

Point velocities measured within and below the plant canopy revealed flow differences between the two strata. These velocity differences between plant-density strata may create microhabitats. Velocity was generally greatest below the plant canopy near low tide and greatest within the canopy near high tide. Variation in flow within and below the plant canopy may increase mixing and distribution of dissolved constituents (Dawson and Robinson 1984). The flux of organic and inorganic compounds between the sediment and the water below the plant canopy may be affected by increases in water velocity near low tide. Near high tide, during the day, trends toward low concentrations of dissolved inorganic carbon (Losee and Wetzel 1988) and high pH and dissolved oxygen (photosynthesis products) are probably diminished in the plant canopy as a result of increased water velocities and increased exchange of water in the plant canopy. Increased velocity and mixing can increase photosyn-

thetic ability compared to a more stagnant condition (Losee and Wetzel 1988).

Based on the negative relationship between plant density and predation success (Heck and Crowder 1991) predatory fish would avoid the plant canopy strata at low tide but occupy this strata near high tide. The physical and biochemical fluctuations in the plant stand could play a role in diurnal distribution of fish and other fauna that find refuge in this habitat (Marshall and Westlake 1990; Heck and Crowder 1991). Plant-density strata form a complex environment and additional research is needed to improve our understanding of this environment.

This information on tidal flux could be useful in predicting flux of dissolved constituents such as dissolved oxygen, nutrients, herbicides and pesticides, or particulate constituents such as phytoplankton and suspended sediments, between hydrilla stands and adjacent channels. Interest in modeling water-quality conditions in shoals and embayments of tidal rivers and in accounting for the interaction between shallow embayments and the main channel is increasing. Kuo and Park (1995) made the assumption that there is no water-level difference between the shoals and the channel; in densely vegetated areas, that assumption may be invalid.

References

- BATIUK, R. A., AND OTHERS. 1992. Chesapeake Bay submerged aquatic vegetation habitat requirements and restoration goals: A technical synthesis. U.S. EPA CBP/TRS 83/92.
- CALLENDER, E., V. CARTER, D. C. HAHN, K. HITT, AND B. I. SCHULTZ. 1984. A water-quality study of the tidal Potomac River and Estuary: An overview. U.S. Geol. Surv. Water-Supply Pap. 2233.
- CARTER, V., J. W. BARKO, G. L. GODSHALK, AND N. B. RYBICKI. 1988. Effects of submersed macrophytes on water quality in the tidal Potomac River, Maryland. *J. Freshwater Ecol.* **4**: 493-501.
- , AND N. B., RYBICKI. 1986. Resurgence of submersed aquatic macrophytes in the tidal Potomac River, Maryland, Virginia, and the District of Columbia. *Estuaries* **9**: 368-374.
- , ———, AND R. HAMMERSCHLAG. 1991. Effects of submersed macrophytes on dissolved oxygen, pH, and temperature under different conditions of wind, tide, and bed structure. *J. Freshwater Ecol.* **6**: 121-133.
- CERCO, C. F. 1994. Workplan for tributary refinements to Chesapeake Bay eutrophication model package. U.S. Army Eng. Waterways Exp. Sta. Misc. Pap. EL-94-5.
- CHAMBERS, J. M., W. S. CLEVELAND, B. KLEINER, AND P. A. TUKEY. 1983. Graphical methods for data analysis. Duxbury.
- DAWSON, F. H., AND W. N. ROBINSON. 1984. Submersed macrophytes and the hydraulic roughness of a lowland chalkstream. *Int. Ver. Theor. Angew. Limnol. Verh.* **22**: 1944-1948.
- FONSECA, M. S., AND J. S. FISHER. 1986. A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Mar. Ecol.* **29**: 15-22.
- FRODGE, J. D., G. L. THOMAS, AND G. B. PAULEY. 1990. Effects of canopy formation by floating and submergent aquatic macrophytes on the water quality of two shallow Pacific Northwest lakes. *Aquat. Bot.* **38**: 231-248.
- GREENING, H. S., AND R. M. ECKENROD. 1995. Watershed management in Tampa Bay: A progress report. *Fla. Sci.* **59**: 117-122.

- GREGG, W. W., AND F. L. ROSE. 1982. The effects of aquatic macrophytes on the stream microenvironment. *Aquat. Bot.* **14**: 309–324.
- HECK, K. L., AND L. B. CROWDER. 1991. Habitat structure and predator-prey interactions in vegetated aquatic systems, p. 288–299. *In* S. B. Bell et al. [eds.], *Habitat structure*. Chapman and Hall.
- HUBBARD, E. F., F. A. KILPATRICK, L. A. MARTENS, AND J. F. WILSON, JR. 1982. Measurement of time of travel and dispersion in streams by dye tracing. U.S. Geol. Surv. Tech. Water-Resour. Invest. Book 3, Chapter A9.
- KOUWEN, N. 1988. Field estimation of the biomechanical properties of grass. *J. Hydraul. Res.* **26**: 559–568.
- KUO, A. Y., AND K. PARK. 1995. A framework for coupling shoals and shallow embayments with main channels in numerical modeling of coastal plain estuaries. *Estuaries* **18**: 341–350.
- LOSEE, R. F., AND R. G. WETZEL. 1988. Water movement within submersed littoral vegetation. *Int. Ver. Theor. Angew. Limnol. Verh.* **23**: 62–66.
- MADSEN, T. V., AND E. WARNCKE. 1983. Velocities of currents around and within submerged aquatic vegetation. *Arch. Hydrbiol.* **3**: 389–394.
- MARSHALL, E. J. P., AND D. F. WESTLAKE. 1990. Water velocities around water plants in chalk streams. *Folia Geobot. Phytotaxon.* **25**: 280–289.
- PARKER, G. W., G. S. WESTERMAN, G. S. HUNT, AND G. L. MORRILL. 1983. Time of travel and dispersion study in the Androscoggin River Basin, Maine. U.S. Geol. Surv. Tech. Water-Resour. Invest. 83-4232.
- PITLO, R. H., AND F. H. DAWSON. 1990. Flow-resistance of aquatic weeds, p. 73–84. *In* A. H. Pictorse and K. J. Murphy [eds.], *Aquatic weeds*. Oxford.
- RANTZ, S. E., AND OTHERS. 1982. Measurement and computation of streamflow. V. 1. Measurements of stage and discharge. U.S. Geol. Surv. Water-Supply Pap. 2175.
- WILCOXON, F. 1945. Individual comparisons by ranking methods. *Biometrics* **1**: 80–83.
- WILSON, J. F., JR., E. D. COBB, AND N. YOTSUKURA. 1969. Movement of a solute in the Potomac River Estuary at Washington, D.C. at low inflow conditions. U.S. Geol. Surv. Circ. 529-B.

Received: 27 June 1995

Accepted: 3 July 1996

Amended: 27 November 1996