J. Aquat. Plant Manage. 31: 232-240

Distribution of Submersed Macrophytes by Echo-sounder Tracings in Lake Saint-Pierre, Québec

GUY R. FORTIN[1], LOUISE SAINT-CYR[2] AND M. LECLERC[2]

ABSTRACT

A DE-719 Precision Survey Fathometer was utilized to map the distribution and coverage of dominant submerged aquatic vegetation at maximum seasonal development in Lake Saint-Pierre, Québec. The acoustical transects covered an area of 205 km² in depths ranging from 0.6 to 14 m. Three basic acoustical patterns corresponding to different vegetation structures, or phytoacoustic facies, were recognized. The first facies was associated with tall plants returning echoes near the water surface; the second facies was related to shorter species producing echoes in the water column well below the water surface, and; the third facies was produced by plants that give rise to a linear series of echoes near lake bottom. The plant beds were subdivided into phytoacoustic units that represent areally definable, two-dimensional entities characterized by a dominant phytoacoustic facies and vegetation cover. Underwater data collected with SCUBA show good agreement between the basic phytoacoustic facies and the three dominant plant species identified in Lake Saint-Pierre: potamogeton (*Potamogeton richarsonii* Benn.), vallisneria (*Vallisneria americana* Mich.) and nitella (*Nitella* sp.).

Key words: submersed macrophyte mapping, vegetation cover, phytoacoustic facies, *Potamogeton* sp., *Vallisneria* sp., *Nitella* sp.

INTRODUCTION

Knowledge on the distribution and abundance of submersed aquatic vegetation (SAV) is required in many environmental studies. Ecologists are concerned about estimating macrophyte standing stock as an indication of overall lake production (Tessier et al. 1984, Wiley et al. 1984), as well as mapping SAV as potential zones for accumulation and transfer of nutrients and contaminants to other trophic levels (Crowder et al. 1988, Crowder and Bristow 1986, Carignan and Kalff 1982, Jacoby et al. 1982, Landers 1982). Sedimentologists are interested in vegetation-covered areas as zones of deposition, stabilization or temporary accumulation of contaminated sediments (Rukavina et al. 1990; Dushenko et al. 1988). Hydraulic and civil engineers consider SAV as a significant source of friction to river flows (Boudreau et al. 1993, Carlier 1960). As a result, there has been in recent years an increasing demand for detailed mapping of submersed vegetation, including species distribution and coverage.

Acoustical tracings produced by echo-sounder devices have been used for more than 60 years to obtain continuous water bottom profiles (Trabant 1984, Le Tirant 1976). Only in the last decade, was this technique used successfully to gather information on distribution and biomass estimation of SAV in shallow lakes and reservoirs (Thomas et al. 1990, Duarte 1987, Stent and Hanley 1985, Maceina et al. 1984, Maceina and Shireman 1980) and to map eelgrass meadows along the California Coast (Spratt 1989). The objective of this paper is twofold: (1) to describe an extensive SAV survey carried out by echo-sounding with precise positioning over a large lake; and (2) to test a procedure for differentiation and cover estimation of SAV based on their acoustic signature. The test was provided by groundtruth as a field survey was also carried out at approximately the same time, near the seasonal maximum biomass. SCUBA divers collected plants for biomass quantification, density estimation and plant identification at individual sampling locations in the lake. An attempt was made to demonstrate that the echo-sounder method provides a simple and cost-effective way to survey both small and large water bodies, compared to direct SAV sampling and airborne survey methods.

MATERIALS AND METHODS

Lake Saint-Pierre (72°50′ W, 46°10′ N), a 300 km² shallow broadening of the St-Lawrence River is located some 100 km downstream from Montréal, Québec (Figure 1). Except for the navigation seaway dredged to depths exceeding 10 m, the lake is about 4 m deep and water is slow moving (0.1-0.5 $m \cdot s^{-1}$). These conditions favour extensive colonization of SAV. The lake is thus particularly suited for SAV surveying by acoustical methods. Five major tributaries, draining vast agricultural lands (>1000 km²), flow into the lake near its entrance. They are the Richelieu, St-Fraçnois, Yamaska, Maskinongé and Du Loup Rivers.

Field investigations. The SAV survey was carried out between August 25th and September 6th, 1990, at a time when aquatic plants exhibited maximum biomass. Acoustic data was gathered by means of an analog DE-719 Precision Survey Fathometer (Raytheon Marine Co.)transmitting a brief (0.2 ms) ultrasonic pulse every tenth of a second at a nominal frequency of 208 kHz with a beam angle of 8°. The transducer was mounted to the hand rail of the 7 m fiberglass boat powered by two 75 h.p. outboard motors and maintained as close as possible to the water surface (<30 cm). This set-up allowed sounding of near-surface canopies of leaves, while ensuring continuous transducer immersion in rough conditions. Floating and drifting vegetation frequently became tangled with the transducer,

[1]Environment Canada, St-Lawrence Center, 1141 de l'Église Road, P.O.B. 10 000, Sainte-Foy (Qc), Canada, G1V 4H5.

[2]Institut National de la Recherche Scientifique - Eau, 2800 Einstein St., Suite 105, P.O.B. 7500, Sainte-Foy (Qc), Canada, G1V 4C7. Received for publication October 5, 1992 and in revised form April 7, 1993.

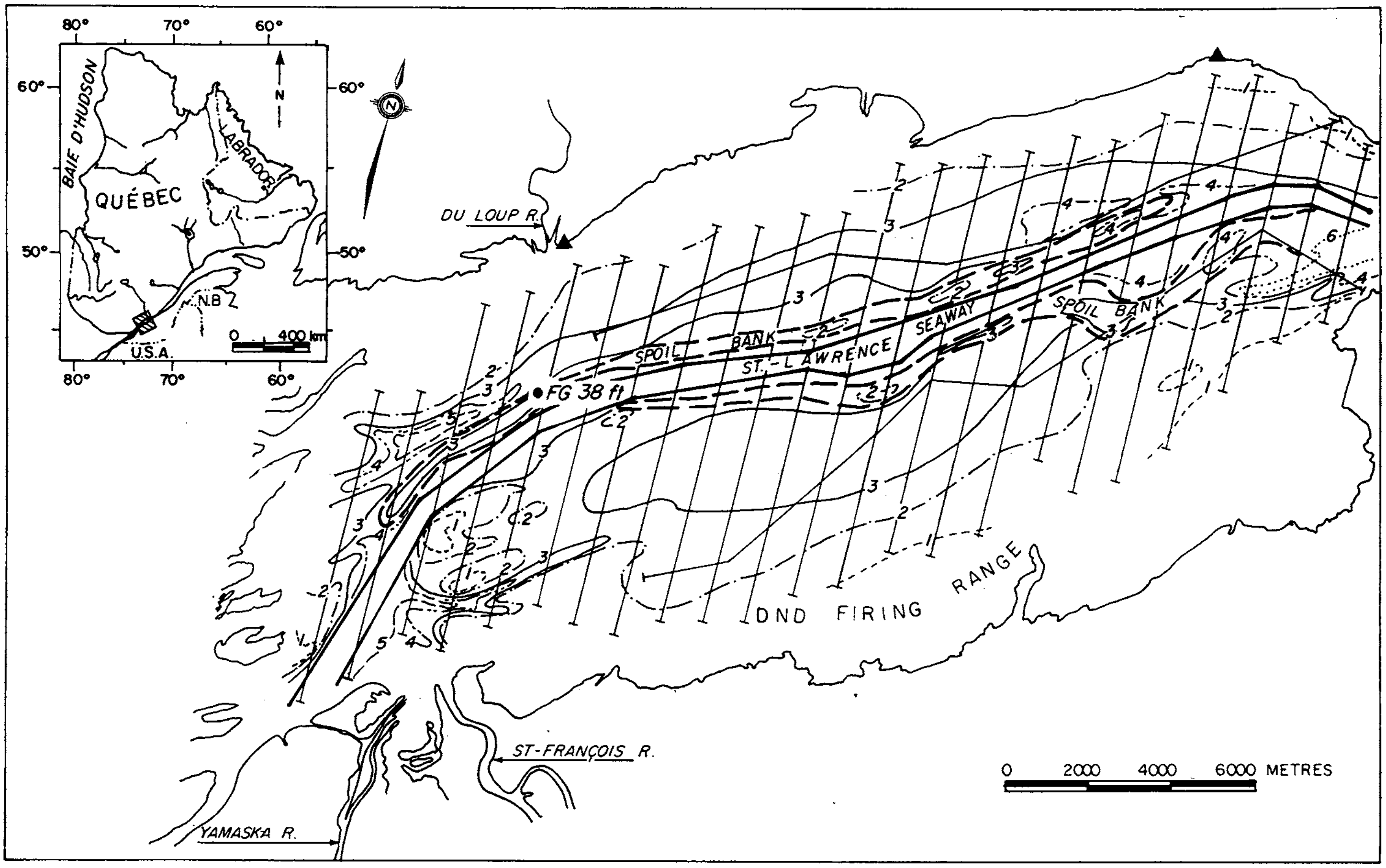

Figure 1. Map of Lake Saint-Pierre showing vegetation transects, location of remote positioning antennae (▲), man-made bottom morphologies and water depths (m) at time of survey.

forcing regular inspection and cleaning of the transducer to avoid transmission loss.

After corrections for speed of sound in water and transducer immersion, the echoes were recorded with minimum signal amplification on graphed paper chart (or echogram), 18 cm wide, at a feeding paper speed of 5 cm min^{-1}. Efforts were made to cruise at a constant speed during vegetation surveys in order to ensure a uniform sound sweeping of the lake bottom. In most areas, the boat speed ranged between 125 and 150 m min^{-1} (or 4.4 and 5.3 knots) yielding a variable horizontal scale of 3.3 to 4.0 cm of echogram per 100 m of surveyed distance. However, survey speed was considerably reduced (50 to 100 m min^{-1}) while surveying through dense floating macrophytes at the fringe of the lake.

Accurate positioning and navigation of the boat along the transects were obtained using a Mini-Ranger (MRS-III) radio positioning system and a NavBox navigation computer (MacDonald 1981). The positioning network included a receiver-transmitter assembly with antenna aboard the boat and two remote transmission antennae situated at precisely known positions on the north shore (Figure 1). Calibration of the Mini-Ranger was performed in the field according to the procedure recommended by the International Hydrographic Bureau (1977). The positioning accuracy was checked every morning by approaching the boat antenna to a bench mark established on the first level of the lighthouse FG-38ft located in the survey area (Figure 1). These daily checks showed that position accuracy was better than ±9 m. In addition to displaying useful information (e.g. course deviation and speed), the navigation computer provided position data at one minute interval fix mark on the chart paper.

Twenty-three acoustical transects at 1 km intervals and two tie lines totaling 245 km in length were recorded in the 205 km^2 study area (Figure 1), which corresponded to 70% of Lake Saint-Pierre's total area. Because of the tranducer immersion depth and the outgoing pulse line[3], the soundings are limited normally to the aquatic zone where water depths are greater than 60-70 cm. Other factors such as propeller entanglements causing complete stops in very dense meadows, erratic positioning in the area between the two shore antennae, and minimum water clearance required for safe navigation in the Department of National Defence (DND) firing range (Figure 1) prevented surveys closer to the shoreline areas.

[3]The transmitted burst into the water column is recorded as a thick line (see Figure 2(a)) that merges in the vegetation echo patterns, preventing the top 30 cm of plant from being distinguishable on the chart paper.

A field survey with SCUBA was carried out from August 1^{st} to 17^{th}, 1990 (Saint-Cyr et al. 1992). Plant identification and vegetation cover were recorded at 25 sampling locations. Sampling stations were precisely located on the lake with a positioning system similar to that used for the acoustic survey. Identification of aquatic plants was done according to Marie-Victorin (1964), with the exception of *Nitella* (Fassett 1966) and *Myriophyllum spicatum* (Aiken et al. 1979). Plant cover was noted following a numerical code system (Dushenko et al. 1988) ranging from 0 to 4 where 0 = no vegetation[4], 1 = scarce (occasional plants), 2 = moderate (beds occurring in regular patches), 3 = dense (extensive beds but well below water surface) and 4 = very dense (extensive beds reaching the water surface and posing difficulties for navigation).

Phytoacoustic facies. The significance of acoustic sounding in relation to large scale SAV mapping is poorly known since little work dealing with vegetation differentiation by echosounding has yet been published. The echo-sounder profiles the water column and provides acoustical pictures of most of the SAV above bottom. Analysis of the echograms allows the indentification of distinct acoustical patterns or "phytoacoustic facies" representing the acoustic signature of the dominant growth form in a stand. Duarte (1987) has already proposed a growth form classification based on plant architecture, dividing dominant submerged macrophyte species into three major classes, for echosounder surveys of lakes. Class 1 represents tall canopy-forming species that reach the surface to flower. Class 2 consists of understory species of which only the peduncles supporting flowers attain the water surface. Class 3 includes the species that lack flowers and those that, while able to form flowers, never do so in nature. The same classification is used here and three basic phytoacoustic facies, following these three classes, have been identified in Lake Saint-Pierre:

- •Facies 1: was characterized by a series of vertically discontinuous and dense echoes that arise in the immediate vicinity or at the lake surface[5] (Figure 2(a));
- •Facies 2: was characterized by a variety of echo configurations that include hummocky surfaces with frequent spiky echoes, disrupted crests with spiky echoes, and isolated spiky echoes reflecting changes in SAV cover. The echoes do not reach the lake surface and are recorded somewhere in the water column (Figure 2(b));
- •Facies 3: was characterized by a succession of narrow echoes occurring near the lake bottom. The echoes form a laterally continuous but slightly irregular reflector that lies almost parallel to the bottom (Figure 2(c)).

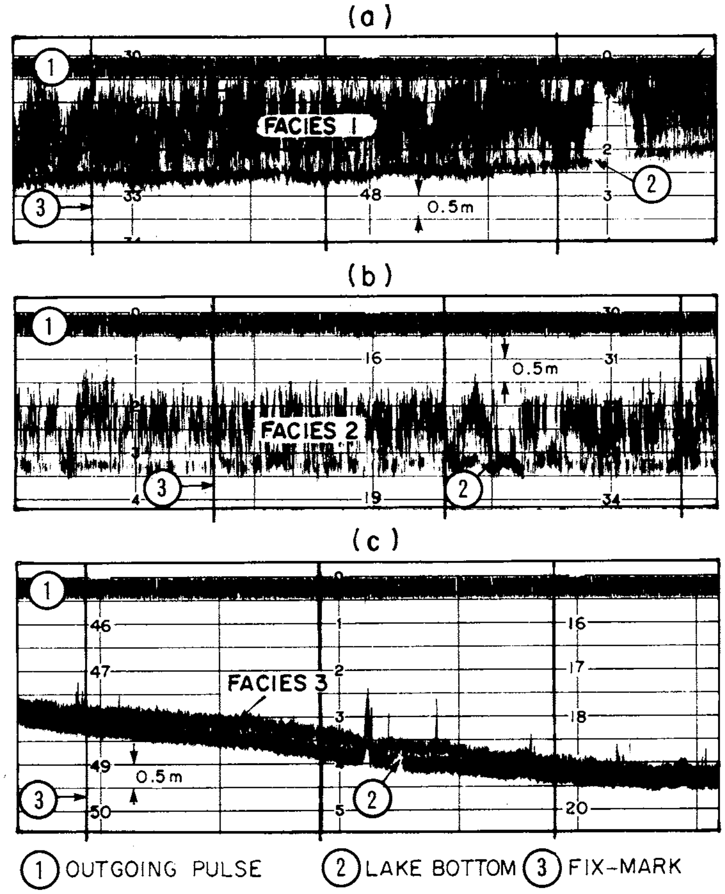

Figure 2. Echogram segments showing the three basic phytoacoustic facies, or dominant growth forms, identified from echo patterns recorded in Lake Saint-Pierre: (a) Facies 1, macrophytes reaching the lake surface; (b) Facies 2, understory species growing below water surface; and (c), Facies 3, carpet-like algae on lake bottom.

In certain plant beds of Lake Saint-Pierre, the echograms display more than one phytoacoustic facies which suggests the presence of more than one growth form in the plant community (Figure 3).

Phytoacoustic unit. A "phytoacoustic unit" is the horizontal or aerial distribution of each basic phytoacoustic facies. More specifically, the phytoacoustic units are delineated chiefly by recognition of the distinctive phytoacoustic facies within the stand and by estimation of vegetation cover. The SAV cover is characterized according to the numerically coded system proposed by Dushenko et al. (1988), but the acoustic profiles allow subdivision of code 4 into 4^+ and 4^-, corresponding to a continuous and discontinuous cover respectively. As mentionned previously, the same coding was utilized by SCUBA to visually describe submergent vegetation cover. Figure 4 (a) through (f) illustrates the acoustic representations of the six codes (0 to 4^+) used to characterize the vegetation cover in the present study. The combination of basic phytoacoustic facies and density codes yields subdivision of the SAV into six phytoacoustic units (Table 1).

After preparation of a sounding plan at a convenient scale (1:50,000) showing the SAV transects and fixmark positions, the acoustical profiles were interpreted according to the following procedure. From upstream to down-

[4]In some areas, it is difficult to judge whether or not plant beds are present as a result of the vertical resolution (~ 30 cm) on lake bottom of the echosounder used in this study.

[5]When submersed vegetation approaches the water surface, visual observations and field notes are useful to ascertain whether or not stems and leaves reach the lake surface.

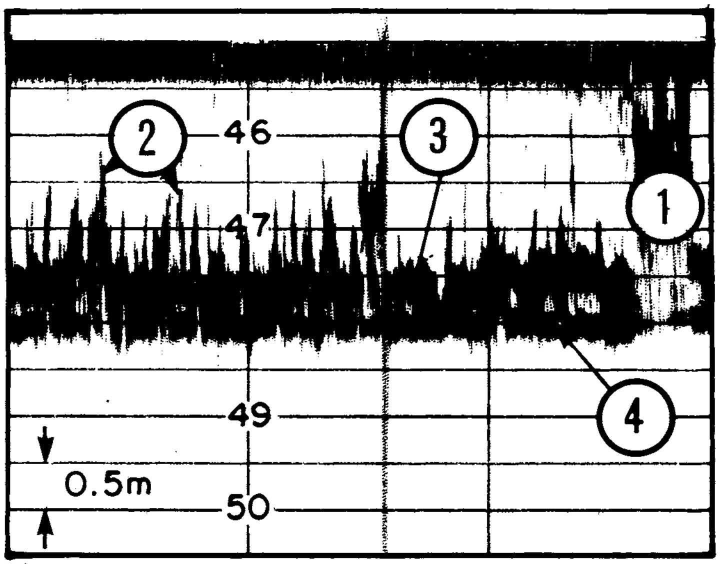

Figure 3. Echogram segment recorded through a diverse SAV stand that exhibited three growth form classes: species of Facies 1 reaching the water surface (1); understory species of Facies 2 growing at mid-depth (2); and, short species of Facies 3 (3) covering lake bottom (4) in the absence of tall plants (1 and 2).

stream, each individual echogram was examined for recognition and delineation of phytoacoustic facies. They were subdivided into phytoacoustic units according to vegetation cover (codes 0 to 4^+). If secondary growth forms were present within the stand, their lateral extension was noted. The fixmark-referenced unit boundaries were picked on the echograms and then transposed to their actual location on the sounding plan. Finally, the boundaries were cross-correlated from line to line in order to construct maps of the phytoacoustic units showing the distribution of the three basic phytoacoustic facies. In most places, the echoes corresponding to the lake bottom were visible through the vegetation cover and estimations of plant heights above ground were obtained. The average plant height within a phytoacoustic unit is estimated as the midheight between the shallowest and the deepest echoes recorded in the water column.

RESULTS AND DISCUSSION

Distribution of phytoacoustic facies. Phytoacoustic units dominated by Facies 1 growth forms cover an area of 53 km^2 (Figure 5(a)). They are mostly located at the fringe of the survey area and are also scattered throughout the pelagic zone of the lake. In these units, tall growth forms having a cover density of 4^+ or 4^- predominate and roughly extend away from the lake shore to the 1.5 m depth (Figure 1). Between the 1.5 and 2.5 m depths, Facies 1 growth forms are co-dominant with other growth forms (Facies 2 and 3). The spoil bank lying north of the St-Lawrence Seaway (Figure 1) also supported a number of various growth forms. These units were nearly absent in water depths greater than 3 m. Phytoacoustic units dominated by Facies 2 growth froms are the most widespread, covering an area of 113 km^2 (Figure 5(b)). Facies 2 growth forms were recognized within elongate phytoacoustic units that extend along the lake axis at water depths ranging between 1 and 4.5 m. The average plant height above lake bottom ranged from 0.5 to 2 m. The plant coverage was quite variable within Facies 2, allowing subdivision of large SAV communities into three phytoacoustic units with density codes varying from 1 to 3. The cover density in Facies 2 seems to be independent of water depth but on the whole, there is a decrease in density from entrance to lake outlet. There are a few units dominated by Facies 3 growth forms (Figure 5(c)). These units are located near the lake entrance and within the two bathymetric depressions bordering the St-Lawrence Seaway (Figure 1). Corresponding phytoacoustic units include species that do not exceed 30-50 cm in height. Facies 3 growth forms were found preferentially in zones of scarce understory species (Facies 2) and at water depths greater than 3 m. Lake bottom areas supporting these growth forms total only 17 km^2. Figure 5(d) illustrates zones devoid of submergent vegetation (density = 0) or with severely depauperate flora (patchy cover).

TABLE 1. THE SIX PHYTOACOUSTIC UNITS USED IN THE PRESENT STUDY TO MAP THE DISTRIBUTION OF THE THREE DOMINANT SAV GROWTH FORMS, OR PHYTOACOUSTIC FACIES, IN LAKE SAINT-PIERRE.

Phytoacoustic units	Phytoacoustic facies	Vegetation cover	Acoustical signature
1	1	4^+	Figs 2(a) and 4(a)
2	1	4^-	Fig. 4(b)
3	2	3	Figs 2(b) and 4(c)
4	2	2	Fig. 4(d)
5	2	1	Fig. 4(e)
6	3	--*	Fig. 2(c)
No apparent vegetation		0	Fig. 4(f)

*: Estimation of plant coverage was not possible.

In situ calibration. The biological significance of the phytoacoustic facies is strengthened by groundtruth data collected by SCUBA (Saint-Cyr et al. 1992). Although these data were gathered originally as calibration points for airborne imagery (MEIS-II sensor), they provide direct correlations between groundtruth and acoustic data at 11 stations (offset <10 m) and useful information on SAV stands at 14 other stations (Table 2; see Figure 6 for station locations). Vallisneria was identified as the dominant plant species in Lake Saint-Pierre. It is an understory plant, often accompagnied by *Heteranthera dubia*, which cover a high percentage of the bottom of the lake, down to 3.7 m in depth. Vallisneria has tufts of long ribbon-like leaves reaching 1.9 m in length, attached to a short buried stem; the plant does not reach the surface, except in very shallow waters. Leaves are not rigid and follow the movement and current of the water. Potamogeton, another dominant species in the lake, forms locally very dense beds. It is a tall plant with an extensively branched stem bearing many clasping-leaves. Potamogeton frequently reaches the water surface, accompagnied by *Potamogeton pectinatus* in the southwest sector of the lake. Vallisneria is often also present in potamogeton beds. Finally, a carpet of nitella, a macro algae, covers areas of the lake partially devoid of taller species. The other species encountered during direct SAV harvest include *Elodea canadensis*, *Myriophyllum spicatum*, *Ceratophyllum demersum*, *Potamogeton crispus* and filamentous algae.

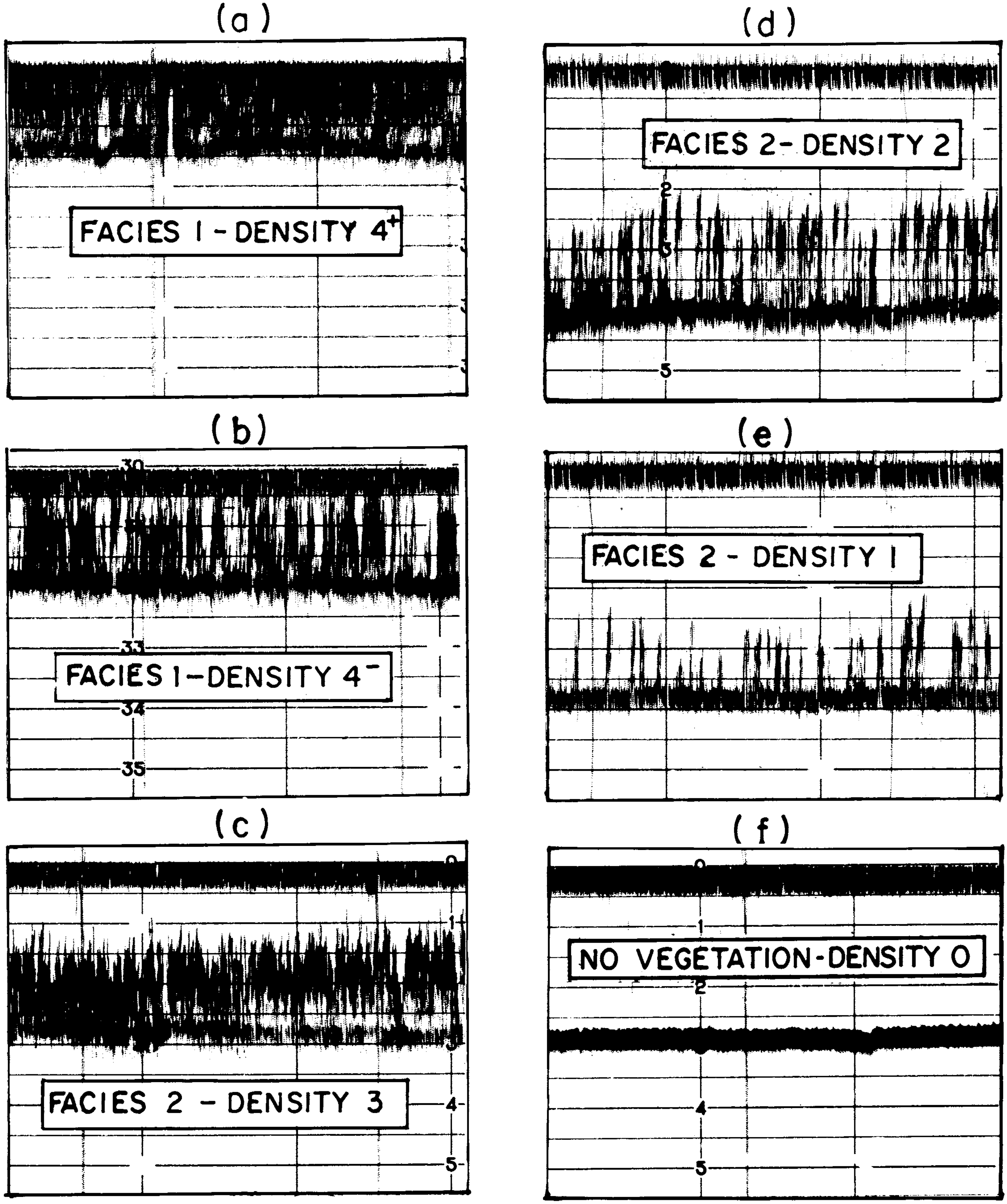

Figure 4. Acoustic representations of the numerical code system used in this study to characterize vegetation cover: (a) density 4^{+}, very dense and continuous cover; (b) density 4^{-}, very dense but discontinuous cover; (c) density 3, dense cover below water line; (d) density 2, moderately dense cover; (e) density 1, occasional plants; and (f) density 0, no apparent vegetation.

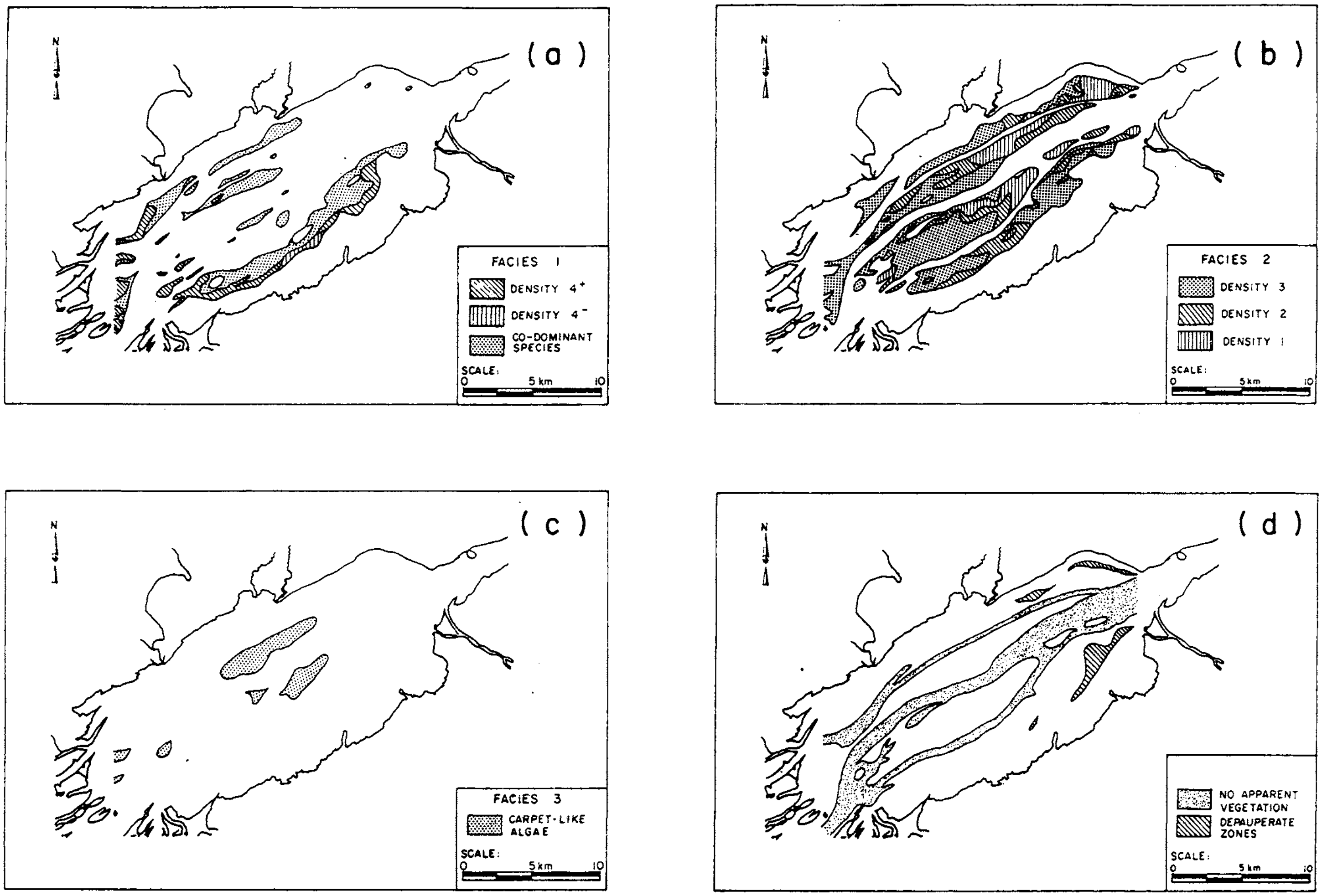

Figure 5. Distribution of the three basic phytoacoustic facies, or dominant growth forms, identified in Lake Saint-Pierre: (a) phytoacoustic units of Facies 1 (potamogeton); (b) phytoacoustic units of Facies 2 (vallisneria); (c) phytoacoustic units of Facies 3 (nitella); and (d) non-covered and depauperate zones.

Except for station No 21 (Table 2), direct calibration (offset <10 m) indicates that vallisneria was the predominant species growing at stations (No 1, 2, 3 and 13) located in Facies 2. Potamogeton was the dominant species, along with vallisneria, for those stations (No. 17 and 30) where Facies 1 occurs as co-dominant phytoacoustic facies. Nitella was encountered as the dominant species at the two stations (No 11 and 16) that include Facies 3. For most of the other stations (offset >10 m in Table 2), the dominant species identified by direct harvest within a plant community correspond to the phytoacoustic facies defined by echo-sounder tracings. This indicates that Facies 1 stands are dominated by potamogeton. Facies 2 and 3 are dominated by vallisneria and nitella respectively. As shown in Table 2, the estimations of vegetation cover by echo-sounding and diving show a reasonably good agreement since the difference between the ECHO and SCUBA density codes is equal to either zero or one unit. However, it must be stressed that the diver estimations were limited to 7 m x 7 m areas, while the SAV cover is characterized using all the echogram segments crossing the phytoacoustic unit.

Distribution of SAV. Figure 6 shows a composite picture illustrating the interplay between the basic phytoacoustic facies, the vegetation cover and the non-covered zones. Of particular interest in Lake Saint-Pierre are the two narrow channel-like features, designated as North Passage and South Passage (Figure 6). It is hypothesized that plant rooting is difficult in these areas, primarily as a result of the strong currents (>1 $m \cdot s^{-1}$) prevailing at the lake entrance (Boudreau et al. 1993), which are funnelled upslope through small channels fading out over a short distance in the shallow areas (Figure 1). Although the passages have no evident bathymetric expression further downstream, it is likely that this momentum is accentuated during seasonal SAV growth since the flow is confined to a narrow corridor present throughout the plant beds. Support for this hypothesis come from current measurements carried out on August 30th, 1990 (Leclerc et al. 1992), and from direct observations of high water turbidity while conducting acoustical transects across the passages. The currents were five to ten times faster in the South Passage (0.5 to 0.9 $m \cdot s^{-1}$) than in the fringing plant beds (0.05 to 0.2 $m \cdot s^{-1}$).

The echo-sounder technique suffers from some disadvantages compared to other remote sensing methods, specifically MEIS-II sensor images and aerial photographs, which also produce an imagery that requires *in situ* calibra-

TABLE 2. COMPARISON OF ECHOSOUNDER TRACINGS (ECHO) AND DIRECT HARVEST BY DIVERS (SCUBA) FOR ASSESSING DISTRIBUTION AND COVER OF DOMINANT SAV IN LAKE SAINT-PIERRE.

Station	Offset[a]	Species		Cover	
		ECHO	SCUBA	ECHO	SCUBA
1	< 10 m	Facies 2	*Va,Pr,Ni*	1	1
2	< 10 m	Facies 2	*Va*	1	2
3	< 10 m	Facies 2	*Va,(Pr,Ni)*[b]	2	2
4	< 10 m	no vegetation	no vegetation	0	0
7	< 10 m	no vegetation	no vegetation	0	0
11	< 10 m	Facies 2,(3)[b]	*Va,Ni*	1	2
13	< 10 m	Facies 2	*Va*,fa,(*Hd*)	1	2
16	< 10 m	Facies 2,(3)	*Va*, (*Ni*)	2	3
17	< 10 m	Facies 2,(1)	*Va,Pr*	3	3
21	< 10 m	Facies 1,(2)	*Pp*,(*Pr*, *Va*)	3	3
30	< 10 m	Facies 2,(1)	*Va,Pr,Ni*,(*Ec*)	3	2
14	50 m	Facies 2,(1)	*Va,Pr*	3	3
5	100 m	Facies 2	*Va*,(*Hd*)	1	2
9	100 m	Facies 2	*Pr*, fa(*Va,Hd*)	2	2
37	130 m	Facies 2	*Va*	3	2
26	140 m	Facies 2,(1)	*Va,Pp,Pr*	3	3
23	150 m	no vegetation	no vegetation	0	0
15	160 m	Facies 2,(3)	*Va,Ni*	2	2
33	190 m	Facies 2	*Va*	3	2
40	200 m	Facies 2,(1)	*Va*,fa	4	3
18	225 m	Facies 2,(1)	*Va*	3	2
28	230 m	Facies 2,(1)	*Va,Pr*	3	4
32	380 m	Facies 2,(3)	*Va,Pr,Ni*	2	2
24	480 m	Facies 2	*Va*	3	2
19	500 m	Facies 2	*Va*	1	2

[a]distance between diving station and sounding line.
[b]() = Subdominant growth forms or species: *Ec* = *Elodia canadensis*: fa = filamentous algae; *Hd* = *Heteranthera dubia*; *Ms* = *Myriophyllum spicatum*; *Ni* = *Nitella*; *Pp* = *Potamogeton pectinatus*; *Pr* = *Potamogeton Richardsonii*; *Va* = *Vallisneria americana*.

tion. In practice, echosounder tracing is limited to the aquatic zone where water depth exceeds 60-70 cm and surveying of large water bodies may extend over several days of SAV growth. SAV is categorized according to dominant growth forms encountered along sounding transects and hence ambiguities may arise in diversified plant beds with tall plants acoustically shading understory species. Notwithstanding these limitations, acoustical profiles allow delineation of areas covered by SAV, identification of dominant growth forms and estimates of both plant height and cover, even in very turbid waters. These characteristics are useful for the assessment of SAV response to eutrophication, studies of water and habitat quality and sediment dynamics, and determination of Manning's friction coefficients in river flow modelling. Other applications may include studies of SAV growth rate and seasonal plant development and senescence by repetitive mapping, behavior of perennial species through winter, and species zonation in relation to water depth.

Costs and flexibility of field operations can be optimized by using a small boat equipped with an inboard turbo jet engine, a hull-mounted transducer and a Global Positioning System (GPS) with logging capability. In this way, it may be possible to reduce survey time to a narrow window of SAV development and to extend profiling further inshore in dense SAV cover. For certain applications, calibration of phytoacoustic facies could be achieved by using a large grab sampler (e.g. Shipek grab). Moreover, the echograms do not require tedious corrections of the data for atmospheric reflectance, geometric distorsion, water depth and turbidity of waters. Although acoustic surveys of SAV have some limitations, particularly in very shallow waters (<60 cm) and in dense beds approaching the water surface, it yields valuable information on SAV vertical structure and distribution at low cost and with minimum manpower. Preliminary echo-sounder data from other large lakes of the St-Lawrence system (lakes Saint-Francis and Saint-Louis) indicate that acoustic recording for vegetation surveys can be used in other areas.

ACKNOWLEDGEMENTS

We thank R. Lalumière from Groupe Environnement Shooner Inc. and Dr. P.G.C. Campbell for their useful comments on an earlier version of the manuscript.

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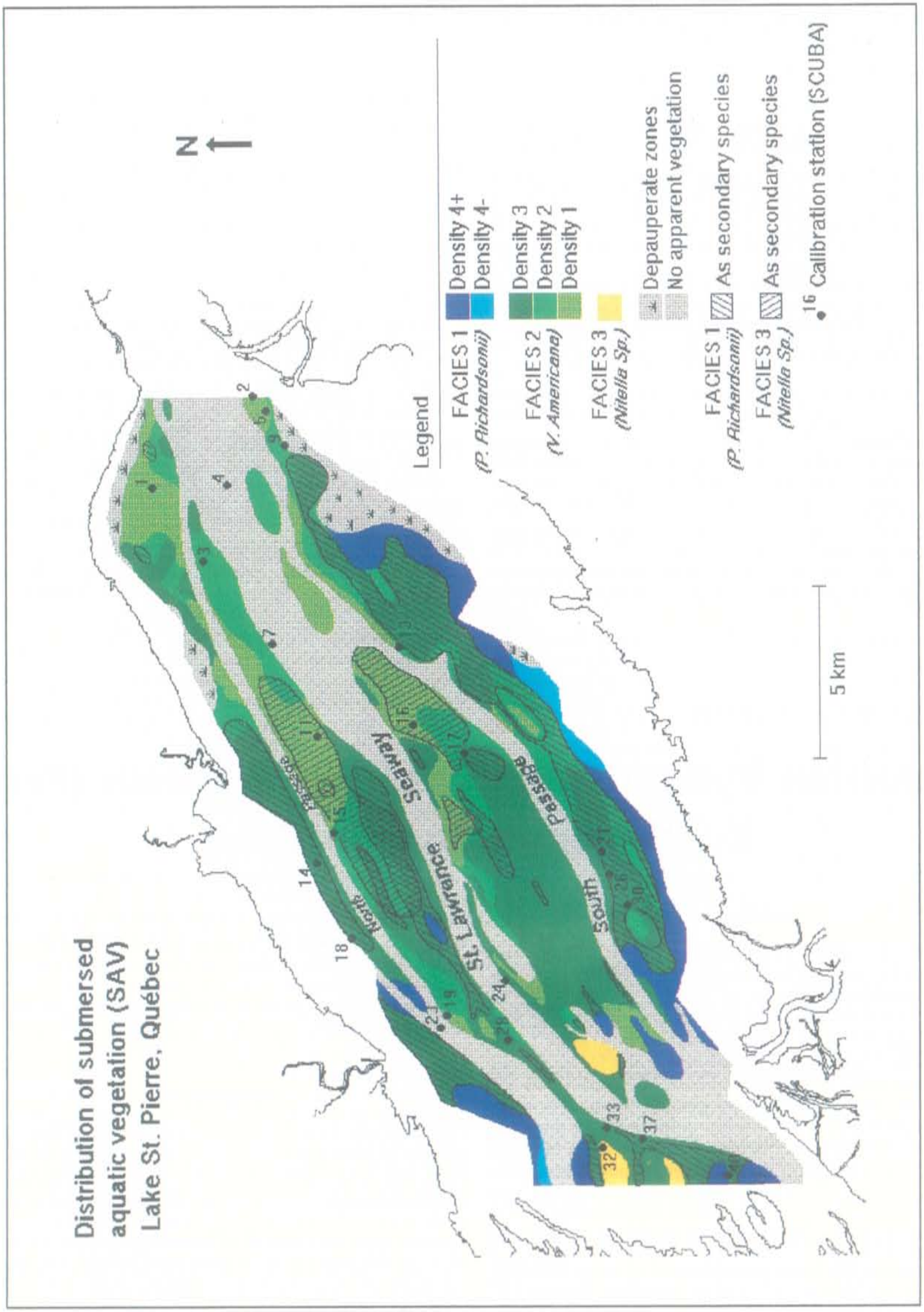

Figure 6. Composite map showing the distribution and cover of the three dominant SAV species growing in the aquatic zone of Lake Saint-Pierre.

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