Efficiency of Large-Volume Plankton Pumps, and Evaluation of a Design Suitable for Deployment from Small Boats[1]

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A critical review of previously published studies, and evaluation of a newly developed pump system, showed the often stated shortcomings of large-volume pumps as instruments for sampling plankton communities (e.g. damage to organisms sampled, volumes too small to estimate plankton density accurately, and systems too cumbersome to handle) to be invalid. Previously published estimates of the comparative efficiency of large-volume pump samplers and tow nets should, however, be viewed with caution because the techniques used to estimate pumped volume are error prone. In-line flow meters are essential for accurate volume estimation. Comparative efficiency tests of a newly developed large-volume pumping system deployed simultaneously with 80- and 153-μm mesh standard plankton nets revealed that the pump, while sampling only 8% of the volume sampled by the nets, was equally effective in capturing capelin (*Mallotus villosus*) larvae (5-mm length), herring (*Clupea harengus*) larvae (9-mm length), large copepods (>750 μm), small jellyfish, and hyperiid amphipods. The pump was superior to nets in sampling crab zoea and megalops larvae and becomes more efficient at capturing euphausiids and chaetognaths as their natural densities increase. Nets were superior in the capture of fish eggs (primarily cunner, *Tautogolabrus adspersus*), possibly due to the vertical distribution of eggs in the water column. The average length of capelin larvae captured by pumping was consistently 0.2 mm longer than that of larvae taken in nets, but the length–frequency distribution of larvae sampled was similar to that of larvae entering the pelagic environment. Attaching the pump intake to the cod-end of a rigid tow net is suggested as a method of surmounting potential errors when sampling organisms at densities below 1–5/m^3.

Un examen détaillé des publications et l'évaluation d'une pompe récemment mise au point ont révélé que les imperfections souvent mentionnées pour les pompes à grand volume servant à l'échantillonnage des communautés planctoniques (par ex. dommages aux organismes, volumes trop petits pour l'estimation précise des densités, appareillage trop encombrant) n'étaient pas fondées. Les estimations publiées de l'efficacité comparative de pompes d'échantillonnage à grand volume et de filets à plancton doivent être considérées avec prudence, les techniques utilisées pour l'estimation du volume pompé étant sujettes à erreur. Des débitmètres en ligne sont essentiels pour l'estimation précise du volume. Des tests de l'efficacité comparative d'une pompe à grand volume, récemment mise au point et déployée simultanément avec des filets à plancton standards à mailles de 80 et 153 μm, ont révélé que la pompe, même si elle ne recueillait que 8 % du volume échantillonné par les filets, était aussi efficace pour la capture de larves de capelan (*Mallotus villosus*, longueur : 5 mm) et de hareng (*Clupea harengus*, longueur : 9 mm), de gros copépodes (>750 μm), de petites méduses et d'amphipodes (Hyperiidae). La pompe s'est révélée supérieure aux filets pour l'échantillonnage des zoés et des mégalopes de crabe et plus efficace pour la capture des euphausiacés et des chétognathes à mesure que leur densité naturelle augmentait. Par contre, les filets se sont révélés supérieurs pour le prélèvement des œufs de poisson (surtout de la tanche-tautague *Tautogolabrus adspersus*), probablement à cause de la répartition verticale des œufs. La longueur moyenne des larves de capelan capturées à l'aide de la pompe était constamment supérieure de 0,2 mm à celle des larves recueillies au moyen d'un filet, mais la distribution des fréquences des longueurs des larves prélevées était semblable à celle des larves se déplaçant vers la zone pélagique. Le raccordement de la prise d'eau de la pompe au cul d'un filet à plancton rigide est suggéré comme méthode permettant d'éviter les erreurs lors de l'échantillonnage d'organismes dont la densité est inférieure de 1 à 5 individus/m^3.

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The use of pumps for plankton sampling began in 1887 (Gibbons and Fraser 1937; Aron 1958). Pumps have not, however, been widely used primarily because of three perceived shortcomings: (1) pumps damage or destroy the organisms they sample, (2) volumes sampled per unit time are too small, and (3) pump systems capable of sampling sufficient volume are too cumbersome to operate, particularly from small boats (Snyder 1983).

The increasing awareness that the time and space scales involved in sampling zooplankton (Steele 1978; Mackas and Boyd 1979; Haury and Wiebe 1982; Fiedler 1983) and

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ichthyoplankton (Smith 1978; Sharp 1980; Owen 1980; Fortier and Leggett 1982, 1983; Frank and Leggett 1982; Legendre and Demers 1984) should be appropriate to the biological processes being investigated has highlighted the deficiencies of standard plankton sampling gear (reviewed in Tranter and Fraser 1968; Bowles and Merriner 1978) and standard sampling methods (Omori and Hamner 1982), especially when high-frequency sampling of discrete water masses is required. This fact, coupled with the recent advances in pump design, has resulted in renewed interest in the use of pumps for plankton sampling.

Several important advantages accrue if pump sampling can be shown to yield unbiased results. First, sampling at biologically relevant time and space scales is possible; second, sample volume can be reduced, thereby minimizing processing time and eliminating the errors frequently associated with splitting of large samples (Van Guelpen et al. 1982); third, simultaneous sampling of all size-classes down to the smallest determined by the filtering mesh size used can be achieved at the same time and place; fourth, the biasing effects of varying and different filtering efficiencies, induced by clogging and the use of multiple deployed nets at different times and/or places, are eliminated.

In this paper we briefly review the literature relating to the efficiency of large-volume pumps (here defined as pumps that deliver $>0.5\,m^3/min$) used primarily in the study of larval fishes. We also describe and evaluate a recently developed large-volume pumping system suitable for deployment from small boats (~6 m). Our criterion in designing this system was that a relatively small pumped water volume integrated over the same time and distance as a standard net tow should provide estimates of the diversity and density of plankton not significantly different from estimates derived from simultaneous towed net samples.

Efficiency of Pumps versus Nets

Five major studies using large-volume pumps have investigated the relative efficiency of pump systems and two nets (Table 1). These studies yield useful generalizations concerning pump-related damage and comparative efficiency. They also raise serious questions concerning the accuracy of the techniques used to determine volumes sampled.

All of the studies examined samples for pump-related damage (see also Lenz 1972; Icanberry and Richardson 1973; Coughlan and Fleming 1978). Only Gale and Mohr (1978) found such evidence and in this case further testing demonstrated that the incidence of damage was greatly reduced by decreasing the filtering mesh size and adjusting the length of the net so that it "ballooned" during sampling. These studies also generally found that the density of organisms sampled with pumps was equal to that sampled by towed net samplers. There were, however, important differences in the efficiency of sampling various larval fish length classes (Portner and Rohde 1977; Leithiser et al. 1979; Cada and Loar 1982). Sampling efficiency also differed between day and night (Cada and Loar 1982).

In these studies, tow net diameters, pump intake diameters, the presence or absence of intake screens or expanders, intake velocities, filtering mesh sizes, and deployment varied greatly. In only two studies was the pump intake propelled through the water, and in neither case was tow speed given (Aron 1958; Cada and Loar 1982). The remaining three studies were stationary sampling comparisons that relied on local currents to move organisms past the pump intake and to fill fixed nets. The above variability may account for some of the differences in the results obtained; however, we were unable to identify anything systematic.

Only one of the studies (Portner and Rohde 1977) employed an in-line flow meter in the pump system. All others relied on previously determined volume/time calibrations to estimate volume during timed sampling. Basic hydraulic theory dictates that two conditions *must* be met for this method to be accurate: (1) pump rpm must not change during or after calibration and (2) there must be no change in total head (static head + discharge head + velocity head + head due to friction, entrance and exit losses) during or after calibration. Hence, any alteration in pump speed, length, and/or curvature of the suction or discharge hose, static head (elevation of pump with respect to water level of source), discharge head (elevation of discharge outlet with respect to pump) will significantly alter flow rate. Accumulated volumes derived from time measurements will thus be inaccurate if any one of these criteria is not met. Few papers on plankton pumps address hydraulic theory in the design and operation of pump systems (see Quayle and Terhune 1967 for one that does), and we recommend the detailed and readable paper by Miller and Judkins (1981) to any researcher using or considering the use of pump systems.

It is important to recognize the magnitude of the errors that can occur by assuming constant flow. We calculated the effect on flow of varying either rpm or head when using the pump we describe in this study (see below). At a fixed rpm of 1250, a change in total head from 9.1 to 10.6 m ($\Delta 14\%$) reduced flow rate from 0.95 to $0.63\,m^3/min$ ($\Delta 34\%$). Similarly, a reduction in rpm from 1250 to 1150 ($\Delta 8\%$) at constant head reduced flow rate from 0.95 to $0.57\,m^3/min$ ($\Delta 40\%$). This clearly demonstrates that minor changes in either head or rpm can have major effects on estimates of volume sampled. As the above criteria were not explicitly met in the studies reviewed, the pumped volumes reported should be viewed with caution. This renders the net/pump efficiency comparisons questionable. Portner and Rohde (1977) suspected that their flow metering system was inaccurate primarily because it may have averaged flow over too great an area.

The volumes of water pumped in the studies reviewed ranged from 15 to $86\,m^3$ (Table 1). If volumes of this magnitude are required to obtain equivalent density estimates as nets then the potential usefulness of pump samplers is defeated. Such volumes take more time to collect with pumps, the resulting large samples are costly to sort, and the potential scale advantages are lost.

Large-Volume Pump System

Description of Pump System

The system we developed employs a Gorman-Rupp T3A3-B self-priming centrifugal pump with an open 22.2-cm-diameter impeller capable of handling a 6.4-cm-diameter spherical solid. The pump delivers water at up to $1.7\,m^3/min$ (depending on total head) when driven at 2150 rpm with a single V-belt coupling to a 3-hp (minimum acceptable hp) Briggs & Stratton gasoline engine. We operated the pump at a nominal 650 rpm to prevent cavitation and to minimize velocity and pressure changes. A nominal flow rate of $0.8\,m^3/min$ was achieved at 650 rpm when coupled to 10-m (intake) and 3-m (discharge) lengths of 7.62-cm inside diameter (ID) heavy duty wire-wrapped suction hose. Time for passage through the system,

TABLE 1. Summary of major studies designed to comparatively evaluate the sampling efficiency of various large-volume pumps and tow nets.

Reference	Pump				Tow net and mesh size (µm)	Tow or current speed (m/s)		Volume sampled (m^3)		Gear comparison protocol
	Type and mesh size (µm)	Flow (m^3/min)	Suction							
			Diameter (m)	Velocity (m/s)		Pump	Net	Pump	Net	
Aron 1958	Centrifugal, 544 silk	1.514	0.076	5.55	0.5-m-dia. std., 476 nitex	1.7^{a}	1.7^{a}	15	200	50 paired hauls "near surface" (marine)
Portner and Rohde 1977	Tandem propeller, 500 nitex	8.6	0.20	4.60	0.5-m-dia. std., 500 nitex	Local current 0.4		86^{a}	44^{a}	111 paired stationary samples at 4.5, 8, and 9 m (riverine)
Gale and Mohr 1978	Open impeller centrifugal, 400 × 800 nitex	2.5	0.10 (0.24)^{b}	5.30 (0.92)^{b}	0.24 × 0.54-m-rect., 400 × 800 nitex	Local current "moderate–strong"		—	—	7 stationary sets of 4 pump and 8 net replicates at surface and bottom (riverine)
Leithiser et al. 1979	Fish transfer, 335 nitex	2.1	0.15	1.92	(a) 1-m-dia. cyl.-cone, 335 nitex	Local current (a) 0.26		(a) 62	121	(a) 10 stationary pairs at 0.5–1.5 m depth (riverine)
					(b) as in (a) and 0.5-m dia. std., 363 nitex	(b) 0.30		(b) 64 64	414 105	(b) as in (a) above
Cada and Loar 1982	Open impeller 243 nitex	1.10	0.076 (0.021)^{b}	4.04 (1.1)^{b}	0.5-m-dia. Hensen net, 243 nitex	"Slowly"	1.2–1.9	17	85–100	3 sets of 3 replicates not paired in time at 0–0.5 m depth (riverine)

[a] Estimated from data provided in paper referenced.

[b] Measured at intake, which differs in size from suction hose.

TABLE 2. Quantitative aspects of sampling technique for each series of net and pump comparisons. Average values and one standard deviation (in parentheses) for each variable are given.

Year	Tow net mesh (μm)	N	Tow speed (m/s)	Tow time (min)	Tow distance (m)	Net volume (m^3)	Pump volume (m^3)	Pump flow (m^3/min)	Intake velocity (m/s)
1981	80	6	1.6 (0.21)	3.3 (0.14)	323 (31.8)	37.1 (3.66)	2.20 (0.048)	0.66 (0.017)	2.4 (0.06)
1982	153	4	1.1 (0.23)	2.0 (0.00)	127 (27.5)	20.4 (4.16)	1.63 (0.035)	0.82 (0.017)	3.0 (0.07)
1983	153	10	1.2 (0.15)	4.3 (0.22)	301 (36.7)	53.0 (5.83)	3.68 (0.063)	0.85 (0.039)	3.1 (0.014)

determined by fluorometric measurement of the passage of concentrated rhodamine dye, was 6.0 s. Complete flushing of the dye from the system was achieved after an additional 2.5 s.

Flow rate was continuously monitored with a Signet MK315 paddle-wheel sensor housed in the discharge hose. The sensor drove a 12-V Signet MK375 flowmeter providing both flow rate (±10 L/min) and accumulated volume (±50 L). This allowed accurate determination of volume sampled irrespective of changes in pump speed or total head during sampling. The meter was calibrated by determining the time required to pump a known volume of water while the entire system was in a fixed position.

The end of the discharge hose was fitted with a 90° PVC elbow joined to a 1-m section of PVC tubing. The end of the PVC tube was fitted with a rubber lip to prevent chafing of the filtering net. A 1.5-m-long, 80-μm plankton net fitted with an 80-μm cod-end was choked around the rubber lip during sampling. This permitted the discharge tube and net to trail freely in the water, thus minimizing abrasion (Gale and Mohr 1978) and eliminating the need for an on-board collection system (Leithiser et al. 1979).

Sampling to 16-m depth required 22 m of suction hose. We employed 3.3 and 6.6-m sections equipped with "quick-fit" couplings. The sampling intake was a 7.62-cm-ID smooth bore coupler to which we attached a 20-kg Scripps wire depressor on a 0.5-m lead. The intake was suspended from a 3.2-mm steel cable leading to a 12-V reversable boom-mounted winch. Vertical winch speed under tow was 0.12 m/s. Depth integration of a sample could be achieved by continuously varying the intake depth between predetermined limits. Diver observation of the system while underway confirmed that the intake was consistently oriented in the direction of travel and parallel to the surface.

A Data Instruments pressure transducer (model AB, $0-7.0 \times 10^5$ Pa) hardwired to a digital voltmeter was mounted on the intake pipe immediately behind the intake. Transducer voltage output was used to determine and regulate sampling depth (±0.3 m at 35-m maximum pressure). The total cost of the system as described was approximately $4000 Cdn. in 1981.

The pumping system and winch (total weight 300 kg) was mounted in a 4-m rubber inflatable (Dunlop), which was towed alongside a 5.6-m Boston Whaler powered with a 70-hp outboard engine. The discharge hose was mounted on the whaler and was attached with a quick-fit coupling to the pump. This configuration allowed the whaler to be easily and quickly disconnected from the inflatable. When cruising from one station to another, the suction hose was floated by raising the intake above the surface while the pump was operating. This reduced drag on the system and prevented fouling the intake when operating in very shallow water. The intake is easily towed at speeds of 1–2 m/s during sampling.

Evaluation Methods of Pump Efficiency

The sampling efficiency of the pump was evaluated by comparing the catch per unit volume of several planktonic taxa sampled simultaneously by the pump and a 0.5-m-diameter porous 2-m cylinder–cone standard net. Nets of 80- and 153-μm mesh sizes were used, and each was fitted with an 80-μm mesh window cod-end.

While the mesh sizes of nets used in our comparison were smaller than those used in other studies (see Table 1), we were concerned with evaluating the capture efficiency of small zooplankters as well as fish larvae, and the short tow duration (<5 min) ensured a constant filtration efficiency. In addition, Fortier and Leggett (1983) have shown that a fixed (current-force filtration) 80-μm, 0.5-m-diameter standard net did not differ significantly from a 151-μm mesh bongo sampler towed at 1.8 m/s in capturing small capelin (*Mallotus villosus*) and herring (*Clupea harengus*) larvae.

Water volume sampled by the nets was measured with a General Oceanics 2030 flowmeter mounted between the center and the rim of the net (Tranter and Fraser 1968). Tow speed was measured by trailing a second flowmeter abeam the boat at 0.2-m depth. Care was taken to minimize local acceleration effects. All sampling comparisons were made between 400 and 800 m seaward of the shore at Bryants Cove, Newfoundland.

Three sets of comparisons were made. In 1981 an 80-μm net was towed immediately below the surface 2 m behind the pump intake. In 1982 and 1983 a 153-μm net was towed immediately below the surface 13–15 m astern of the pump sampler. The pump intake was maintained at a depth of 0.25 m for all comparisons. Quantitative details of the sampling technique are provided in Table 2.

All nets were thoroughly rinsed after each tow and the cod-end contents were immediately preserved in 4% formalin–seawater buffered with sodium borate. Samples were completely sorted for capelin (*Mallotus villosus*) larvae, other fish larvae (86% herring, *Clupea harengus*), chaetognaths, jellyfish (mainly *Rathkea*, *Bougainvillia*, and *Aglantha* spp.), hyperiid amphipods, crab zoea and megalops, and euphausiids. Indivials of these taxa were counted and removed. The remainder of each sample was filtered through a 750-μm mesh and all fish eggs and copepods in the extract were counted. If the number of copepods or eggs in the extract was large (>400) the extract was fractionated using the HML beaker technique (Van Guelpen et

TABLE 3. Number of individuals/10 m^3 of each taxon sampled by paired pump (P) and tow net (N) in 1981 (80-μm tow net) and 1982–83 (153-μm tow net) (p = probability that density estimates are not significantly different under a Wilcoxon matched-pairs signed-ranks test).

	Capelin larvae		Other larvae		Copepods >750 µm		Chaetognaths		Jellyfish		Hyperiid amphipods		Crab zoea		Crab megalops		Euphausiids		Fish eggs	
Year	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P	N	P
1981	2.2	0.0	—	—	1873.0	2000.0	1.9	0.0	—	—	2.2	0.0	42.1	170.0	197.0	1463.0	4.1	13.8	133.0	87.0
	1.4	0.0	—	—	4002.0	4525.0	3.8	0.0	—	—	65.5	55.8	28.7	27.9	150.0	205.0	1.4	0.0	241.0	642.0
	1.9	4.6	—	—	1503.0	1747.0	1.9	0.0	—	—	57.9	59.6	22.6	27.5	392.0	541.0	3.1	4.6	76.0	184.0
	2.2	0.0	—	—	238.0	518.0	1.5	9.2	—	—	141.0	91.7	37.7	55.1	569.0	1789.0	17.5	4.6	20.0	64.0
	12.3	13.8	—	—	77.0	41.0	2.2	4.6	—	—	51.9	142.0	34.8	55.1	445.0	1298.0	32.4	27.5	20.0	18.0
	0.8	4.7	—	—	59.0	23.0	1.8	0.0	—	—	28.0	32.7	14.4	60.8	127.0	808.0	11.1	9.4	15.0	23.0
p	0.688		—		0.156		0.563		—		1.00		0.031		0.031		0.688		0.219	
1982	67.5	215.0	38.6	38.0	19084.0	21266.0	95.8	88.6	90.4	203.0	—	—	5.4	24.3	—	—	153.0	215.0	253.0	75.9
	320.0	285.0	104.0	48.5	28537.0	22061.0	91.2	54.5	337.0	291.0	—	—	24.7	103.0	—	—	341.0	388.0	224.0	90.0
	556.0	533.0	32.8	36.4	38264.0	37430.0	264.0	249.0	206.0	255.0	—	—	8.9	78.8	—	—	203.0	285.0	991.0	588.0
	654.0	570.0	30.9	48.5	40033.0	36364.0	199.0	315.0	370.0	333.0	—	—	59.3	255.0	—	—	169.0	152.0	1672.0	1218.0
p	0.875		0.875		0.375		0.875		1.00		—		0.125		—		0.250		0.125	
1983	275.0	173.7	0.2	0.0	153.0	113.0	2.4	0.0	3.9	7.9	—	—	0.0	0.0	—	—	5.6	10.5	159.0	94.7
	123.0	67.6	0.0	0.0	165.0	75.7	1.0	0.0	8.6	2.7	—	—	0.0	0.0	—	—	12.6	5.4	142.0	83.8
	53.0	25.0	0.6	0.0	237.0	169.0	1.3	0.0	14.8	16.7	—	—	0.0	0.0	—	—	28.5	13.9	117.0	77.7
	55.7	61.1	0.4	0.0	146.0	128.0	2.4	0.0	14.0	5.6	—	—	0.0	0.0	—	—	26.9	0.0	92.2	97.2
	32.5	18.9	0.0	0.0	90.3	130.0	1.8	2.7	16.9	16.2	—	—	0.0	0.0	—	—	5.2	0.0	91.9	59.5
	26.5	44.4	0.0	0.0	128.0	172.0	1.0	2.8	25.7	25.0	—	—	0.0	0.0	—	—	9.2	11.1	132.0	106.0
	38.2	51.4	0.6	0.0	142.0	281.0	2.0	0.0	22.5	21.6	—	—	0.0	0.0	—	—	7.2	2.7	122.0	108.0
	41.2	40.5	0.2	2.7	329.0	338.0	1.9	0.0	33.6	27.0	—	—	0.0	2.7	—	—	17.7	5.4	124.0	103.0
	44.1	37.8	0.2	0.0	345.0	349.0	2.7	2.7	36.3	10.8	—	—	0.0	2.7	—	—	16.3	10.8	149.0	83.8
	20.3	2.7	0.0	0.0	196.0	276.0	3.0	0.0	46.3	43.2	—	—	0.0	0.0	—	—	7.1	5.4	168.0	64.9
p	0.232		0.193		0.695		0.049		0.160		—		1.00		—		0.020		0.002	
p (total)	0.216		0.625		0.571		0.076		0.463		—		0.001		—		0.409		0.033	

al. 1982), and one fraction was counted. All counts were standardized to number per 10 m^3. Capelin larvae from the first four sample pairs collected in 1983, and all sample pairs collected in 1982, were measured for total length. Herring larvae from samples collected in 1982 were also measured for total length.

The concentration of each taxon in the sample pairs was compared using the Wilcoxon matched-pairs signed-rank test following the reasoning of Posgay and Marak (1980) (i.e. small number of samples, non-normal distributions, variances not independent of means). Differences of less than 1.0 in sample comparisons were considered as zero differences except for those samples where densities were very low. Signs were randomly assigned to zero differences and tied ranks were broken by random ordering (IMSL 1979). Significance was assessed using a two-tail, $\alpha = 0.05$ criterion. Exact probability tables were consulted (Lehmann 1975). This analysis was found to be more sensitive to detecting differences in the data set than either a Wilcoxon rank-sum test or a χ^2 test. Overall correlation between sample pairs for each taxon and across all taxa was measured after a square-root transformation on the count data. The average length of capelin larvae and the average length of herring larvae in the sample pairs were compared using a Student's *t*-test ($\alpha = 0.05$, two-tail).

Efficiency of Sampling

There were no significant differences in the abundances of six of eight taxa sampled simultaneously with the pump and the 80-μm tow net. Crab zoea and megalops were sampled more effectively with the pump (Table 3).

The pump and 153-μm tow net consistently sampled five of eight taxa without significant differences when deployed simultaneously. There were, however, differences in sampling efficiencies for chaetognaths, euphausiids, and fish eggs between years. In the 1982 comparisons (153-μm net), pump efficiency for these taxa was equivalent to net efficiency. In 1983 the net was more effective. Cunner (*Tautogolabrus adspersus*) eggs constituted ~80% of the eggs sampled. The most probable cause of the greater catchability of fish eggs in nets is the typically neustonic distribution of cunner eggs in the water column (Williams 1968). As deployed, the net sampled a vertical distance of 0.5 m centered at 0.25-m depth, while the pump intake sampled a vertical distance of 0.07 m centered at 0.25-m depth. If a greater proportion of the eggs were at or very near the surface their vulnerability to net sampling would be higher. A similar result was observed by Portner and Rohde (1977) when sampling eggs of striped bass (*Morone saxatilis*). They suggested the result might be explained by innaccurate flow measurements in either the net or pump, or differential destruction. Differential destruction of eggs between the two samplers in our study is rejected as the cause of differences because there was no difference in sampling efficiencies between gear type for small jellyfish, which are extremely delicate, and because sampling fish eggs with large-volume pumps has been shown not to affect their viability (Aron 1958; Manz 1964). In addition, none of the organisms we collected by either gear showed evidence of differential damage or destruction. The absence of difference in the number of eggs sampled by the pump and the 80-μm net is enigmatic.

The superiority of nets over the pump in the capture of chaetognaths and euphausiids in 1983 may result from differential avoidance. This interpretation is given with the caveat of the low number of organisms sampled, particularly as the differences were not apparent in the 1982 data set when natural densities were significantly greater.

TABLE 4. Correlation and regression statistics for numbers per taxon caught by net vs. pump (*n*, sample size; *r*, correlation coefficient; *a*, intercept; *b*, slope). Numbers/10 m^3 were square-root transformed. Intercepts not significantly different from 0.0 and slopes not different from 1.0 at $\alpha = 0.05$ are denoted by an asterisk.

Taxon	*n*	*r*	*a*	*b*
Capelin larvae	20	0.956	0.662*	0.973*
Other larvae	14	0.905	0.207*	1.020*
Jellyfish	14	0.957	0.836*	0.902*
Fish eggs	20	0.879	1.352*	1.008*
Copepods	20	0.996	−1.309*	1.037*
Euphausiids	20	0.960	1.490*	0.801
Crab zoea	20	0.916	0.174	0.524
Chaetognaths	20	0.968	1.039	0.850
Hyperiid amphipods	6	0.797	2.165	0.674*
Crab megalops	6	0.546	—	—
Overall	160	0.988	−0.381*	1.008*

The efficiency of the pump sampler was equal to that of the nets in sampling capelin larvae, other fish larvae, copepods, and small jellyfish. The absence of significant differences may be sample size related. Similar results were obtained when all sets of comparisons were pooled within taxa for analysis, however (Table 3).

The efficiency of the two gear types was consistent across the range of densities observed in five of the taxa considered. For capelin larvae, other fish larvae, jellyfish, fish eggs, and copepods the slopes of relationships between the transformed count data for nets and pump did not differ from 1.0 and the intercepts did not differ from 0.0 (Table 4). Regression analyses indicate that the pump was consistently more efficient in the capture of crab zoea but became progressively more efficient in the capture of euphausiids as the natural densities of these animals increased. Chaetognaths and hyperiid amphipods were captured more effectively with the net at low density ($<50/10\ m^3$), but at higher densities the pump was superior.

The average lengths of capelin larvae captured by the pump (1982, 5.02 mm; 1983, 5.09 mm) were slightly but significantly different from the average lengths of larvae captured by the net (1982, 4.87 mm; 1983, 4.82 mm). The absence of between-year differences in average length of larvae captured by net and by pump justified pooling the data within gear type. The difference in average length of larvae sampled by net and pump was 0.2 mm. This slight length difference (4%) may be of little biological importance (approximately the growth over 1 d (Jacquaz et al. 1977; Frank and Leggett 1982)) but the frequency distributions of the larval length-classes sampled indicate a systematic bias of less than 1 mm (Fig. 1A). Proportionately more large larvae were captured by the pump than the net, while the net captured more small larvae.

We also determined the size–frequency distribution of larvae collected from the beach sediments at Bryants Cove. These collections were made during a period of actual larval emergence and on the same day in 1982 as the tow comparisons. Not unexpectedly the average length of larvae collected from the sediments (4.76 mm) was slightly but significantly smaller than postemergent larvae sampled by either the net (4.85 mm) or pump (5.06 mm) (Fig. 1A). The size–frequency distributions of

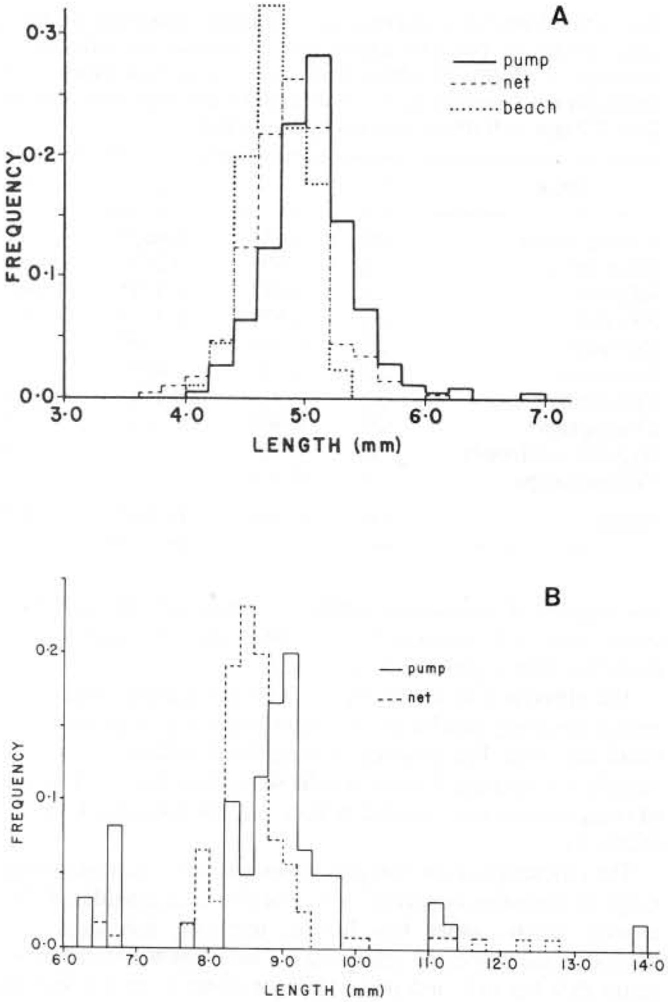

FIG. 1. Length–frequency distribution of (A) capelin larvae sampled simultaneously by pump, net (153 μm), and sampled from beach sediments and (B) herring larvae sampled simultaneously by pump and net. See text for average lengths and length differences.

beach-, net-, and pump-sampled larvae were very similar, however.

The difference in sizes of larvae sampled by pump and net is also apparent in the frequency distribution of herring larvae sampled in 1982 (Fig. 1B). In the case of herring, the average length of larvae captured by the net (8.59 mm) was smaller but not significantly different from that of larvae captured by the pump (8.78 mm). Hay (1981) reported that larvae of Pacific herring (*Clupea harengus pallasi*) experienced a shrinkage of between 13 and 17% if towed in a 350-μm net for between 1 and 3 min. He attributed the reduced length to rapid shrinkage immediately after death which occurred in the net and found that this phenomenon was independent of shrinkage due to fixation in formalin alone and that delayed fixation increased the amount of shrinkage. Qualitative observations of larvae captured by our pump showed that most, but not all, were alive and swimming immediately prior to fixing. Possibly the apparent systematic shift in length–frequency distributions results from differences in the death rate of larvae from net and pump sampling and differences in shrinkage related to death. It may also reflect microscale differences in the vertical distribution of different sizes of larvae (see foregoing discussion on vertical distribution of fish eggs).

Inferences and Application of Pump Sampling

The statistically similar density estimates obtained by simultaneous pump and net sampling for a wide variety of taxa were achieved in spite of pump volumes, which never exceeded 8% of the volumes sampled by nets. This ability to sample small volumes without compromising the accuracy of density estimates has not been addressed by previous comparative studies and has several distinct advantages: (1) a greater number of samples can be taken per unit time and per unit area, making possible greatly increased spatial and temporal resolution of plankton distributions; (2) volumes sampled are virtually error free, as net clogging, extrusion, and varying filtration efficiencies are eliminated; (3) larvae and their planktonic food can be sampled at precisely the same time and same place.

One limitation of the pump system as deployed is the time required to obtain volumes sufficient for accurate estimates of planktonic organisms occurring at densities below $1–5/m^3$. This limitation may not be important in lacustrine, estuarine, or coastal environments where densities of planktonic organisms are relatively high, but in offshore marine environments the limitation may be severe. This difficulty could be surmounted by attaching the pump intake to the cod-end of a tow net mounted on a rigid frame (see Tonolli 1951; Sasada 1982), thus eliminating net clogging and decreased filtering efficiency, which frequently occurs during prolonged net tows. Coordination between sampling depth and initiation of filtration at the discharge could serve as an "opening/closing" system. This would eliminate both the need to retrieve the net after each sample and the need to rely on mechanical opening/closing mechanisms, which frequently fail (Tuel and Knauer 1982).

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