Water Movement in the Bay of Fundy Cannot Be Measured by Gypsum Dissolution Method

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ABSTRACT

Wildish, D. J., J. D. Trynor, and H. M. Akagi. 2000. Water movement in the Bay of Fundy cannot be measured by gypsum dissolution method. Can. Manuscr. Rep. Fish. Aquat. Sci. 2537: iii + 18 p.

We sought a practical, inexpensive way to measure water motion, as for example, mean velocities at a salmon farm. The method tested was based on the dissolution rate of pre-cast gypsum cylinders of ~250-g mass, expressed as the percentage loss of weight of each cylinder (F%). F% is given as velocity or cumulative flow for a specified exposure period based on data from flume calibration. Comparisons made between gypsum dissolution rate methods and standard current meters (S4 and acoustic doppler current profiler) showed that the gypsum dissolution method overestimates mean velocities. It was concluded that the gypsum dissolution method cannot provide a measure of mean velocity in the well mixed waters of the Bay of Fundy.

RÉSUMÉ

Wildish, D. J., J. D. Trynor, and H. M. Akagi. 2000. Water movement in the Bay of Fundy cannot be measured by gypsum dissolution method. Can. Manuscr. Rep. Fish. Aquat. Sci. 2537: iii + 18 p.

Nous avons cherché un moyen pratique et peu coûteux de mesurer le mouvement de l'eau, par exemple la vitesse de passage moyenne dans une pisciculture de saumon. La méthode mise à l'essai était basée sur un taux de dissolution de cylindres de gypse préfabriqués d'environ 250 g, exprimé en pourcentage de perte de poids de chaque cylindre (F%). F% représente la vitesse de passage ou le débit cumulatif pour une période de contrôle donnée, selon les données sur l'étalonnage du canal de jaugeage. Il ressort de comparaisons faites entre la méthode basée sur le taux de dissolution du gypse et les courantomètres habituels (S4 et système profileur de courant acoustique Doppler) que la méthode basée sur la dissolution du gypse surestime la vitesse de passage moyenne. On en est donc venu à la conclusion que la méthode mise à l'essai ne constitue pas une méthode fiable de mesure de la vitesse de passage moyenne dans les eaux homogènes de la baie de Fundy.

INTRODUCTION

The conventional way of measuring water motion caused by tidal flows is with an *in situ* recording, current meter (e.g. Trites and Petrie 1993, 1995). Such devices continuously record current direction and velocity at a single moored location. The disadvantages of this method for coastal zone management purposes are that:

- some types of water movement may be excluded by the recording device, i.e. wind/wave effects;
- high initial capital costs are involved;
- high operating costs are involved because of the need to maintain and calibrate fairly complex electronic/mechanical systems.

Deployment at more than a few sites makes the use of current meters expensive.

For these reasons, we sought a secondary method with the following criteria:

- that can measure all types of water movement, inclusive of wind/wave motion for short periods of time;
- the initial capital costs of the method are to be modest;
- the operating costs associated with it are to be low; and
- the measure obtained could be simultaneously applied at a large number of stations for modest costs.

The gypsum dissolution method was originally introduced by freshwater ecologists in streams and rivers (McConnel and Siegler 1959; Petticrew and Kalff 1991). Subsequently, the method was adopted by marine biologists (Muus 1968; Doty 1971; Gerard and Mann 1979; Santschi et al. 1983; Atkinson and Bilger 1992; Jokiel and Morrissey 1993; Thompson and Glenn 1994) for a wide variety of purposes where water movement data were required. Our objectives were to present adaptations of the gypsum dissolution method for Bay of Fundy conditions, to test the assumptions necessary for the method in a unidirectional flow-through flume and, finally, to compare it with conventional current meters in field conditions.

THEORY

The rate limiting step for the dissolution of gypsum, $CaSO_4 \bullet 2H_2O$, is probably transport through the diffusive sublayer, rather than release of ions from the crystal structure itself (Lui and Nancollas 1971). Thus, any increase in water movement past the diffusive sublayer enhances the transport of ions and results in increased dissolution. This is a result of the decrease in the thickness of the boundary layer (BBL) and/or an increase in the concentration gradient across it by reduction in the Ca^{++} and $SO_4^{=}$ ions in the bulk layer seawater.

The dissolution rate of gypsum follows a first order kinetic equation (Lui and Nancollas 1971):

$$dm/dt = KA(cs-c) \qquad (1)$$

where m = kg of ($CaSO_4 \bullet 2H_2O$) dissolved at time,t, in seconds;
$K = m \cdot s^{-1}$, a rate constant;
$A = m^2$, the area exposed to the flow;
$cs = kg \cdot m^3$, the saturation constant of gypsum; and
$c = kg \cdot m^3$, the dissolved gypsum at time, t.

Following Petticrew and Kalff (1991), the above equation can be rearranged as a flux, F, as follows:

$$F = D(cs-c)/BBL \qquad (2)$$

where $F = kg \cdot m^{-2} \cdot s^{-1}$;
$D = m^2 \cdot s^{-1}$, the diffusion coefficient; and
(BBL) = the thickness of the benthic boundary layer in meters.

The dissolution rate of gypsum is both temperature and salinity dependent. With respect to temperature, the effect is caused by changes in viscosity which affects the diffusion coefficient, D, as well as the thickness of the boundary layer. Lui and Nancollas (1971) describe an Arrhenius dependence of K on T as follows:

$$K = a\, e^{-b}/T \qquad (3)$$

where ln(a) and b are respectively intercept and slope constants;
e is the basis of natural logarithms; and
T = degrees Kelvin.

The empirical relationship between salinity on the x axis and gypsum dissolution rate was found to be unimodal with a peak near 15‰. Dissolution increased as salinity increased from 0 to 15‰ salinity, but at >15‰, dissolution was a decreasing function of salinity (up to 35‰ S tested) as determined by Jokiel and Morrissey (1993). This is probably related to the solubility effect of seawater ions on Ca^{++} and $SO_4^{=}$ and/or the buffering effects which change with salinity.

METHODS

MATERIALS

Commercially available forms of gypsum were used, inclusive of dental plaster, plaster of Paris, or proprietary wall patch compounds which were locally available (see Appendix 1). Each was tested for its suitability in Bay of Fundy conditions for gypsum dissolution measurements of cumulative flow speed. Our specific requirements were for a well made cylinder that did not have air bubbles and did not crack or crumble during field exposure, and a cylinder that lasted from 12-72 h in local conditions, during which it lost ≤30% of its initial mass. Very high tidal flow speeds are found in the upper part of the Bay of Fundy, e.g. ≥400 $cm \cdot s^{-1}$ in Minas Basin (Wildish et al. 1986), so we expected rapid dissolution rates.

Initial tests with dental plaster suggested that it dissolved so rapidly in field conditions as to be useless for our purpose. The addition of resin glue to the mixture, as recommended by Jokiel and Morrissey (1993), to form a slower dissolving solid, resulted in little improvement. Of four formulations of gypsum tried (Appendix 1) during preliminary work on this method, we chose wall patch compound.

MIXING AND CASTING CYLINDERS

The best hydrodynamic shape for a dissolving body when currents might come from any direction is a solid sphere. Because of the difficulty of making a mold for, and handling spherical bodies, we used the next best shape, which was a cylinder with both blunt ends being covered with silicone sealant so they were not dissolving surfaces.

The cylinders were cast in molds made by cutting and reaming out recycled, plastic wood available from local hardware stores in suitable planks of 217-cm thickness. This material can be cut by saw to make the molds as shown in Fig. 1. The advantage of plastic over natural wood is that the former does not warp after repeated wetting and drying, as occurs in natural wooden molds. A drill bit of 3.8-cm diameter was used to ream out to a depth of 15 cm in two halves of plastic wood planks as shown in Fig. 1A. Each half was connected by two hinges (Fig. 1A). Four molds were produced and the cylinder dimensions of each are shown in Table 1. Plastic-coated wire (see Appendix 2) was cut and twisted as shown in Fig. 1B so that a piece protruded at each end, one through a groove made in the bottom of the mold. So that each cylinder would be individually recognized, a uniquely numbered spaghetti tag (see Appendix 2) was twisted into the larger wire (not shown in Fig. 1).

The inside of each mold was sprayed with a kitchen cooking spray to help prevent sticking during cylinder drying. After thoroughly mixing gypsum powder (two parts) with deionized water (one part, by mass), the smooth, semi-liquid was poured into each mold, held together by a pair of G clamps (Fig. 1B). To help remove air bubbles, a blunt glass rod was moved up and down for 1-2 min. Additional gypsum slurry was heaped around the top wire and the mold left to harden overnight.

Partially dried cylinders were removed from the molds by banging on the sides with a hammer and prying open the mold with a screwdriver. Overhanging pieces of plaster were broken off and each end cut with a knife to a slightly conical shape. The cylinders were then air dried in the laboratory for ≥48 h. The cylinders were lightly sanded to remove casting imperfections and the top and bottom of each was coated with silicone sealant.

CYLINDER MASS AND DIMENSIONS

The surface area is S in cm^2 and the working surface of each cylinder could be determined from:

$$S = \pi DL \qquad (4)$$

where D = diameter in cm; and
L = length in cm.

The dimensions of a cylinder were measured with dividers and a ruler (L) to 0.1 cm and with electronic dividers (D) to 0.1 mm (see Appendix 2). Cylinder mass was determined on a top-loading electronic balance accurate to the nearest 1 g to give the initial weight, W_0, after air drying as described above.

Typical cylinder dimensions for each of the molds used are shown in Table 1 from original data shown in Appendices 3 and 4. Variation in mass as 1 standard deviation varied from 2-6% of the initial mass with n=10, but where n was increased (Table

2), this dropped to $\leq 1\%$. Average cylinder mass for each of the molds used is shown in Table 2, based on original data in Appendices 3 and 4.

DEPLOYMENT

Field deployments at sea were made with an anchor and buoy system as shown in Fig. 2. Local suppliers for most parts of this system are shown in Appendix 2. Steel wire frames were welded (Fig. 2A) and the whole frame could swivel in the current because one end was supplied with a plexiglass plate (50 x 30 cm x 5 mm width), allowing it to act as a vane. Four cylinders were positioned in the frame just prior to deployment by rubber bands passed over steel hooks on the frame. As a safety measure, we employed double rubber bands tied to the wire eye on each cylinder. The frame was kept vertical at 5 m above bottom by a floatation buoy on a 5-m long line. The anchors used were cement blocks connected by a lead weighted line. A line from a second anchor to the surface (Fig. 2B) and a float facilitated the retrieval of the whole deployment. Our method avoided the need for a SCUBA diver, and two people, inclusive of a winchman, could set out, or retrieve, the cylinders in seaworthy conditions.

After a suitable exposure period at the site, determined by trial and error, the cylinders were retrieved, carried to the lab, wrapped in soft tissue paper. After removing the rubber bands, the cylinders were air dried in the laboratory until no further weight change (usually ~48 h), followed by weighing to give W_1.

ANALYSIS

The percent loss of weight for each cylinder was calculated as follows:

$$F\% = (W_0 - W_1)/W_0 \times 100 \qquad (5)$$

During dissolution of cylinders, there is a loss in surface area which might change the initial surface area:weight relationship during exposure. Petticrew and Kalff (1991) examined this in fresh water by recording the initial and final surface areas (see equation 4) after exposure. Calculations based on the initial and final surface areas in relation to the initial weight of cylinders showed differences in flux rate of <8.2%. Consequently, we did not correct for changes that occurred in cylinder surface area during deployment. In addition, we followed the rule of thumb suggested by Jokiel and Morrissey (1993) to limit cylinder exposure periods to changes of <30% of initial mass, which should minimize differences between initial and final surface areas to 16%.

From field flume calibrations, F% can be expressed as a velocity, U, in units of $cm \cdot s^{-1}$, or as a cumulative flow:

$$CF = U(km \cdot d^{-1}) \times \text{exposure time in days} \quad (6)$$

where $km \cdot d^{-1} = cm \cdot s^{-1} \times 1.157$.

FLUME CALIBRATION

The outside field flume described by Wildish and Kristmanson (1988) was used with the internal dividing walls removed. Because the pump available did not provide enough flow, it was necessary to decrease the width of the flow channel (Fig. 3) to achieve flows >20 $cm \cdot s^{-1}$. Flow rate through the channel was varied by closing the inlet valve and adjusting rubber bungs in the perforated bulkhead that formed the outlet for the flume. Unfiltered seawater was used from the Biological Station supply at ambient temperature and salinity.

We used a portable velocity meter (PVM) manufactured by American Sigma Inc. (available from 11601 Maple Ridge Road, P.O. Box 820, Medina, NY, 14103, USA; 24-h help line: 1-800-635-1230). This device (manufactured in 1994) relies on the Doppler principle to measure moving particles in seawater. It was necessary to provide aeration (small air bubbles) near the sensing head to allow sufficient particles for this method to work effectively. We found that this velocimeter was inaccurate at <10 $cm \cdot s^{-1}$. Its rated maximum limit is 300 $cm \cdot s^{-1}$. Previously, we had calibrated the Sigma PVM against the Nixon flowmeter in the Saunders-Hubbard flume.

The Sigma PVM was connected to a potentiometric chart recorder (Servogor 25, available from Goerz Electro, Ges. m.b.h., A-1101 Wien, Postfach 204, Austria) so that the velocity was continuously recorded during the gypsum cylinder exposures. The recorder was set in linear mode and at a slow chart speed (2.5 $cm \cdot h^{-1}$). The chart was read by noting 20 randomly spaced points along the record for one exposure, followed by taking the average of these readings. Temperatures were recorded during each flume run by deploying a small continuous temperature recorder in the flume (Hobo XT temperature logger from Onset Instrument Corp., P.O. Box 3450, Pocasset, ME, 02559, USA).

We also determined the gypsum cylinder loss in weight in still seawater at known temperatures. This was achieved in a 1-m diameter circular fish tank of 330 L volume, filled with seawater of 30 PSU which was heated or cooled by a Mini-Cool device within the range 5-20°C. Five or six gypsum cylinders were suspended in the middle of the tank to mid-depth for the required period.

FIELD TESTS

We compared the weight difference, W_0-W_1, with the cumulated velocity recorded by an electromagnetic current meter (Model S4, InterOcean Systems Inc., San Diego, CA, USA). The current meter was mounted and deployed with the same anchor and buoy system used to expose the gypsum cylinders. The comparative field deployments were made in the fall of 1996. In the fall of 1998, we compared the gypsum dissolution method with an acoustic doppler current profiler (RD Instruments, San Diego, CA, USA). In this case, the profiler and gypsum cylinders were deployed separately but within 10-20 m of each other.

RESULTS

Although some of the authors mentioned in the Introduction have tested assumptions required for the gypsum dissolution method in flume flows, we have repeated some of them as shown in Table 3.

MOTIONLESS SEAWATER AND TEMPERATURE

The original purpose of these experiments was to assist in obtaining an estimate of the diffusion factor of Doty (1971) which requires that the gypsum flux in still water is obtained. The results shown in Table 4 suggest that increasing temperature does cause an increase in F%. As assessed by a "t" test for the difference between two sample means (Kelley et al. 1992), four of six pairs of means are significantly different, thus supporting H_1 in hypothesis 1 of Table 3.

Plotting all of the data in Table 4 after expressing F% as $F\%\cdot d^{-1}$, against temperature, x, in °C suggests a linear relationship, but with some scatter. The fitted regression line is:

$$F\%\cdot d^{-1} = 0.2055x + 1.6768 \qquad (7)$$
$$R^2 = 0.58;\ n = 9$$

Due to the variability in these tests, we abandoned the diffusion factor method of calculating flow rates as described by Doty (1971).

FLUME CALIBRATION

The results of 12 calibration tests in a unidirectional flow flume are shown in Table 5. From this data we have tested the hypothesis #2 (Table 3) that exposure time influences cylinder weight loss by selecting those experiments (#10, 11 and 12) where flow rates were similar and then determining the fitted linear regression constants:

$$F\% = -0.248 + 8.561 \text{ Exposure time} \qquad (8)$$
$$R^2 = 0.76,\ n = 12$$

which supports H_1 of hypothesis 2, that in nearly constant flume flows gypsum cylinder exposure time is linearly related to cylinder weight loss.

We have also tested the hypothesis (#3, Table 3) that unidirectional flow influences cylinder weight loss by selecting constant 2-d exposure time experiments (#1, 7, 8, 9 and 11 in Table 5). The fitted linear regression is:

$$F\% = 2.832 + 1.073U \qquad (9)$$
$$R^2 = 0.85,\ n = 20$$

which supports H_1 of hypothesis 2, that is, that for a constant exposure time gypsum cylinder weight loss has a linear relationship to flume flow.

Because of (8) and (9) above, we feel justified in regressing cumulative flow (CF) on the percent loss of weight of each cylinder (F%). The scatter diagram (Fig. 4) and regression constants,

$$F\% = 0.4713\ CF - 0.8975 \qquad (10)$$
$$R^2 = 0.82,\ N = 40$$

or

$$CF = (F\% + 0.8975)/0.4713$$

were then used to calibrate field exposure of gypsum cylinders. Observed temperatures during these calibration experiments (Table 5) vary from a mean of 10.3-12.2°C and because of the known dependence of gypsum dissolution on temperature, the results apply only to this temperature range.

In experiments 4 and 6 (Table 5), the flow was changed during the test. We compare the cumulative flow obtained in each experiment and calculate the predicted values from equation (10) to compare with the observed values shown in Table 6. The results are in reasonable agreement with prediction, given the variance in the observed results. However, one F% value in experiment 4 (see Table 5), 41.73, exceeds the 30% value we tried to adhere to during this work.

FIELD TESTS

The field results that follow are based on the flume calibration data in Table 5 and equation (10). Differences in temperature (and salinity) between flume and field tests have not been accounted for and, thus, may affect the accuracy of our calibration procedure.

Initially, we compared gypsum cylinder weight losses with an S4 electromagnetic current meter on the same mooring at Brandy Cove, near the St. Andrews Biological Station. The results (Table 7) show differences that are up to four times greater than that produced by the current meter.

We repeated these observations near salmon farms (Table 8), so that the gypsum cylinders were deployed 2 m above the S4. Current meter and gypsum cylinders were deployed for various equal periods of time (~24 h) and the results are given as F% in Table 8. Again, the current meter mean velocities for the same time period were significantly lower than those estimated by gypsum dissolution and calibration by flume calibration equation (10). Current meter estimates of U are 45-941% of those calculated by gypsum cylinder dissolution, with an average difference for all data in Table 8 of 240%.

In another series of comparisons between gypsum dissolution and currents measured by an acoustic doppler velocimeter, we compared the mean flows by each method (Table 9). Results show again that the gypsum dissolution calibrated by flume flows are in substantial disagreement

DISCUSSION

The necessary assumptions that both exposure time and water flow influence weight loss of gypsum cylinders are corroborated in results expressed by equations (8) and (9), respectively. In still seawater tests, we also show that temperature has an effect on dissolution rate. However, the large variance associated with the correlation between these variables, with $r^2 = 0.58$, precluded its use in diffusion factor estimates as in Doty (1971) and Jokiel and Morrissey (1993). The variance associated with flume calibration as in equation 10 is less, with $r^2 = 0.85$, suggesting that gypsum dissolution rates can directly be related to U or CF. We point out some difficulties in using a single flume calibration for all of the field data acquired over a long period. This is because the assumption that must be made to do this is that the salinity and temperatures experienced in the flume and the field are the same. Clearly this was not the case with the data presented here.

Another problem perceived during this work concerned the calibration technique. The gypsum cylinders were placed in a unidirectional flow flume and, at the maximum velocity tested where $R_e = 9312$ (defined by $R_e = DU/\mu$, where D = diameter of cylinder, 3.9 cm, U = mainstream flow, 25 $cm \cdot s^{-1}$, and μ = kinematic viscosity of seawater at 20°C, 35 PSU = 1.047×10^{-2} $cm^2 \cdot s^{-1}$), the cylinders do not experience fully turbulent wake conditions (see Vogel 1981). Thus, we would not expect differential erosion on the downstream side of the cylinder, although we saw this on some field-exposed cylinders. Therefore, the flume flow experiment may not simulate the higher tidal flows experienced by field-deployed cylinders (which swivel on their frame so that they face into tidal flows), and does not simulate wind/wave orbital water motion very well.

A comparison of the gypsum cylinder dissolution method and the S4 current meter method indicates significantly less velocity by the latter method. Two possibilities could explain this:

a) that the additional velocity indicated by the gypsum dissolution method is due to wind/wave motion. This is consistent with the functioning of the current meters, since they did not monitor the orbital motions due to waves.

b) that the flume calibration for the gypsum dissolution method is inadequate for both tidal and wind/wave motions, and leads to significantly high estimates.

From the above options, we conclude that b) is most probably the correct one. Recent studies by Porter et al. (2000) provide experimental evidence in support of this conclusion. Porter et al. (2000) evaluated gypsum dissolution in flume laboratory-simulated steady flows, fluctuating flows and mixed flows, and showed conclusively that gypsum dissolution rates were different in each flow environment. Also, steady and fluctuating flows were not additive during mass transfer of gypsum ions. The results of Porter et al. (2000) are consistent with the results presented here - that we could calibrate velocity and gypsum dissolution rates in a field flume (steady flow), but not in Bay of Fundy field conditions (mixed flows) where this method variably overestimated flow rates. The mixed flows of the Bay of Fundy are due to strong tidal currents, stochastic wind/wave oscillations, turbulent mixing, as well as water movements due to density differences and interactions with the topography.

One alternative strategy might be to calibrate gypsum cylinder dissolution directly with a current meter deployed at the same time as the cylinders. But, because the physical forces involved change so rapidly, it would not be possible to provide a useable calibration. This is borne out by regressing the data shown in Tables 7, 8 and 9 where x = mean U, $cm \cdot s^{-1}$ from the current meter and y = F% d^{-1}. The result,

$$y = 0.4585x + 5.2083, N=22, r^2 = 0.26,$$

shows that variance associated with the regression is unacceptably high.

The importance of water motion in dispersing particulate wastes from salmon farms is understood (Wildish et al. 1990) but, until recently, site-specific information concerning it had been difficult to obtain. This has changed recently and two models (Trites and Petrie 1995; Greenberg et al. 1998) are available for some parts of the Bay of Fundy mariculture area. Sedimentary effects of particulate wastes are scale-dependent. At a local or regional level, flushing times or, failing this, mean velocities for a specified area of interest are required to assess and model them. We conclude that the gypsum dissolution method cannot provide useful input data of this kind.

The gypsum cylinder project was started at about the same time as the preparation of "Benthic Suspension Feeders and Flow" (Wildish and Kristmanson 1997). Before the critical field tests with current meters were undertaken, our preliminary results were included in the book to provide a crude, inexpensive means of measuring water movement. Our results presented here show that this inclusion was based on premature judgement. We fully agree with Porter et al. (2000) that the gypsum dissolution technique does not provide a general index of water movement in well mixed water bodies like the Bay of Fundy.

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Table 1. Cylinder mass (g) and dimensions (cm) as mean ± standard deviation (SD), where n = 10 (the number of cylinders measured - five separate measurements made on each cylinder). See Appendix 3 for original data. S = πLD, units cm^2.

Mold	L±SD (cm)	D±SD (cm)	S±SD (cm^2)	Mass±SD (g)
A	15.48±0.16	3.91±0.07	189.99±2.53	246.0±14.39
B	15.22±0.12	3.81±0.02	182.22±2.12	240.2± 5.14
C	15.23±0.14	3.85±0.06	184.30±3.32	247.2± 6.89
D	15.24±0.21	3.84±0.04	183.53±2.77	246.5±14.71

Table 2. Initial cylinder mass as the mean ± 1 standard error, SE, where n = number of observations (from Appendices 3 and 4).

Mold	Dry weight (g) mean ± SE	n
A	254.3±1.61	39
B	238.6±1.79	37
C	249.2±1.78	35
D	243.5±2.60	25

Table 3. Testing some assumptions of the gypsum cylinder dissolution method in the flume laboratory.

Hypothesis #	H_0/H_1	Description
1	H_0	Temperature has no effect on gypsum cylinder weight loss in seawater
	H_1	Temperature increases gypsum cylinder weight loss in seawater
2	H_0	Exposure time has no effect on gypsum cylinder weight loss in flowing seawater
	H_1	Exposure time has an additive effect on gypsum cylinder weight loss in flowing seawater
3	H_0	Water motion has no effect on gypsum cylinder weight loss
	H_1	Water motion increases gypsum cylinder weight loss

Table 4. Percentage gypsum loss (F%) for different temperature and exposure times in still seawater of salinity 30±2‰ and tank volume of 330 L. Five or six cylinders (n) exposed at a time. Asterisks indicate significant difference at $p = 0.05$, N.D. = not significantly different at this level of significance.

Experiment #	Temperature (°C) mean±SD	F% mean±SD	n	"t"
12-h exposure				
1	4.7±0.42	1.90±0.53	5	1.63 N.D.
2	9.5±0.35	1.43±0.23	5	5.51 **
3	19.9±1.50	3.75±0.81	5	
24-h exposure				
4	8.7±0.93	3.87±0.30	6	8.40 **
5	11.3±0.34	5.29±0.23	6	0.89 N.D.
6	21.5±0.30	5.16±0.23	6	
48-h exposure				
7	4.2±0.41	2.53±0.76	5	6.54 **
8	11.3±0.41	6.48±0.94	5	2.93 **
9	19.7±1.26	9.76±2.03	5	

Table 5. Calibration data obtained in the field flume. Flows measured acoustically by Sigma PVM.

Expt.	Flow ($cm \cdot s^{-1}$)	Approx.period (d)	Individual cylinders, F% 1 2 3 4	Temperature (°C) mean±SD
5	3.75	4	8.82, 6.20, 7.17, 4.98	11.68±0.50
9	5.25	2	5.51, 4.60, 4.68, 3.70	12.18±0.44
8	8.64	2	4.66, 3.59, 4.15, 6.15	11.84±0.57
2	11.23	3	12.00, 15.87, 21.46, 19.03	10.33±0.62
3	12.36	4	18.88, 24.90, 22.63, 17.95	10.61±0.50
7	15.55	2	13.99, 14.17, 12.80, 15.13	11.79±0.48
12	16.85	1	7.88, 7.32, 8.47, 6.94	12.32±0.33
11	17.45	2	20.61, 16.67, 18.11, 17.39	12.30±0.35
10	18.14	3	22.28, 26.80, 16.31, 33.71	12.15±0.46
1	14.77	2	10.74, 9.92, 10.97, 10.44	10.41±0.62
4A	12.53	2		
4B	14.00	2	41.73, 23.17, 22.92, 15.73	- -
6A	14.69	3		
6B	15.55	1	28.99, 21.05, 21.58, 25.10	11.75±0.43

Table 6. Predicted values of F% calculated from equation 10 and corresponding observed experimental values.

Experiment #	Predicted F%	Observed F% mean±SD
4	24.11	25.89±11.11
6	27.20	24.18± 3.68

Table 7. Gypsum cylinder (n=4) dissolution method comparison with an S4 current meter at Brandy Cove between 27 June and 5 July, 1996. Site coordinates: 45°05'00"N, 67°05'09"W.

Period	Elapsed time (h)	F% mean±SD	U ($cm \cdot s^{-1}$)	CF (km)	Current meter ($cm \cdot s^{-1}$) mean±SD
1140, 27/6-1525, 29/6	51.75	27.44±3.37	32.28	60.13	10.49±7.04
1525, 29/6-1725, 1/7	50.00	26.89±0.90	32.76	58.96	8.04±5.55
1730, 1/7-1330, 3/7	44.00	25.14±4.48	34.88	55.26	8.96±6.27
1345, 3/7-0845, 5/7	43.00	27.57±2.36	39.02	60.41	9.99±7.44

Table 8. Gypsum cylinder weight loss (n=3 or 4) as F% for 14 salmon farms sampled between 15 August and 1 October 1996. Estimates of U are based on equation (10). Independent estimates of mean U are based on S4 current meter.

Coordinates		Exposure	F%		U	CF	Current meter	
Latitude	Longitude	h^{-1}	Mean	SD	($cm's^{-1}$)	(km)	Mean ($cm{\cdot}s^{-1}$)	% difference
45°02'96"	66°49'65"	19.25	11.42	3.46	37.16	32.19	6.84	443
45°02'46"	66°49'51"	24.00	11.50	2.67	30.43	26.30	13.03	134
45°04'21"	66°43'59"	23.08	9.82	0.81	27.27	23.57	2.62	941
45°00'48"	66°55'56"	22.08	9.17	1.66	26.68	23.06	12.09	121
45°03'21"	66°49'25"	23.92	9.96	2.79	26.73	23.10	17.54	52
45°02'49"	66°53'57"	24.25	9.35	2.21	24.91	21.53	9.8	152
44°38'57"	66°50'30"	21.17	7.89	2.91	24.15	20.87	9.74	149
44°56'75"	66°54'97"	22.33	6.78	4.16	20.09	17.37	3.44	484
44°57'80"	67°00'83"	24.33	6.37	1.21	17.62	15.23	5.70	209
45°07'68"	67°00'83"	23.92	5.26	0.62	15.66	13.11	4.41	244
45°01'71"	66°50'32"	23.92	4.99	0.60	14.50	12.53	9.38	53
44°59'57"	66°56'64"	24.08	4.83	1.77	14.01	12.11	9.65	45
45°03'79"	66°49'74"	20.92	3.53	1.52	12.15	10.50	5.82	109
44°43'08"	66°43'47"	24.08	2.75	0.44	8.93	7.72	2.73	227

Table 9. Gypsum cylinder weight loss (n=4) for locations sampled in 1998. Estimates of U are compared to the mean speed computed from an acoustic doppler current profiler.

Date	Coordinates		Mean F%, d^{-1}	U, $cm{\cdot}s^{-1}$	ADCP	
	Lat.	Long.			Mean ($cm{\cdot}s^{-1}$)	% difference
02/11	45°00'15"	66°59'90"	15.95*	35.75	19.09	87
23/11	45°00'15"	66°59'90"	10.69	24.59	10.33	138
02/11	45°02'78"	67°01'54"	9.93	22.97	12.87	78
18/09	45°04'20"	67°00'20"	5.73	14.06	8.06	74

*>30% lost during deployment.

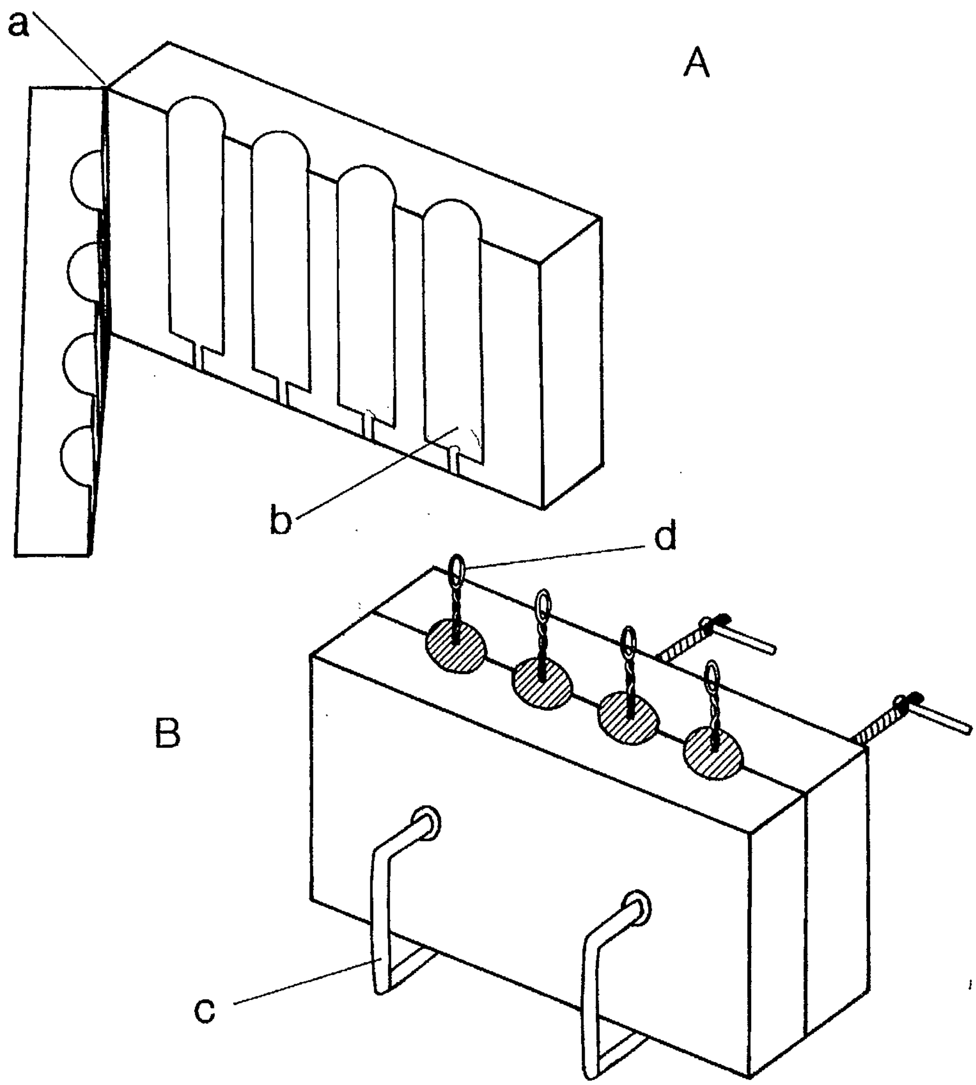

Fig. 1. Mold construction and its use in casting gypsum cylinders. A - open mold; B - closed mold with gypsum cylinders drying. a - hinge, b - groove made by reaming two pieces of plastic wood clamed together, c - G clamp, d - plastic wire.

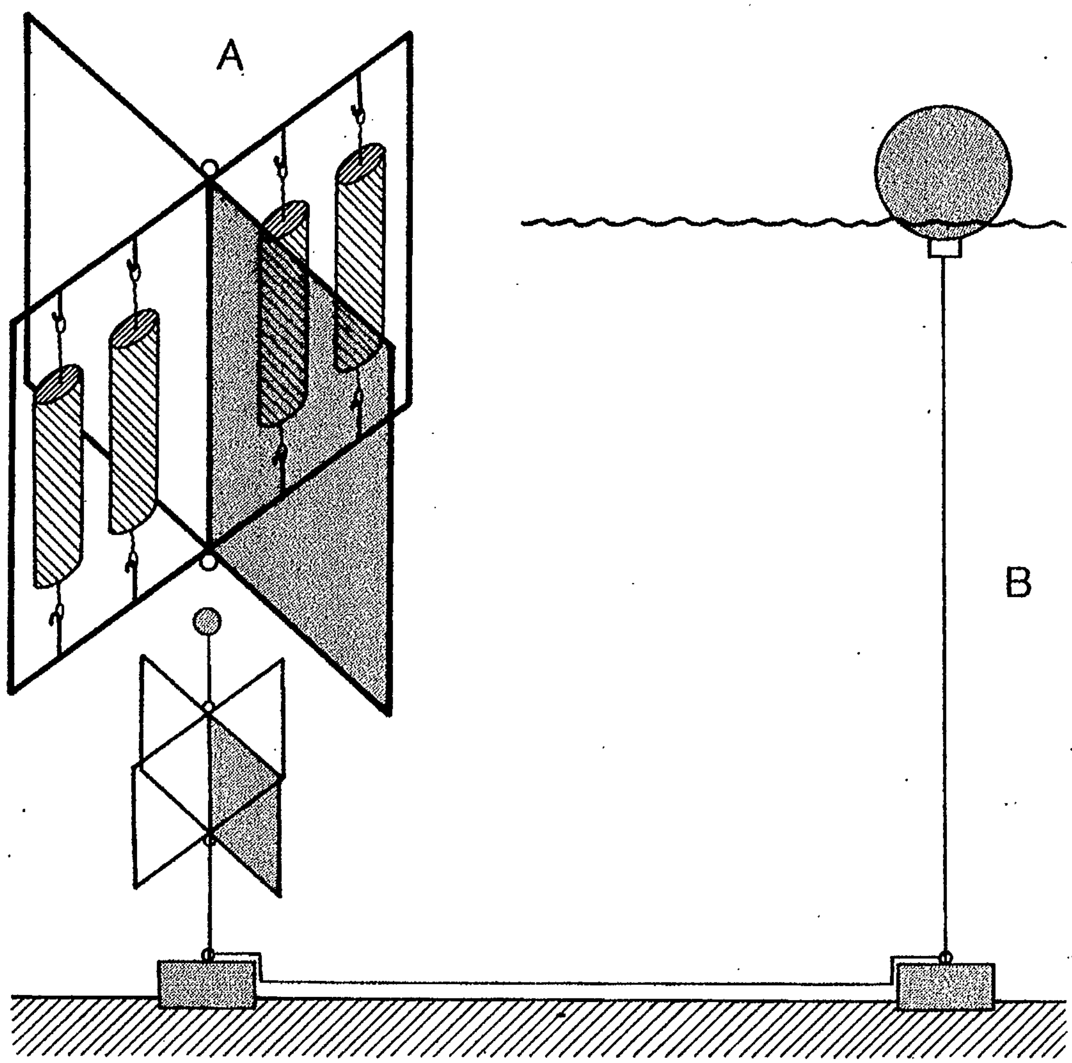

Fig. 2. Anchored buoy mooring to suspend gypsum cylinders. A - wire frame and directional vane causing swivelling normal to the flow; B - concrete block anchors and buoy mooring.

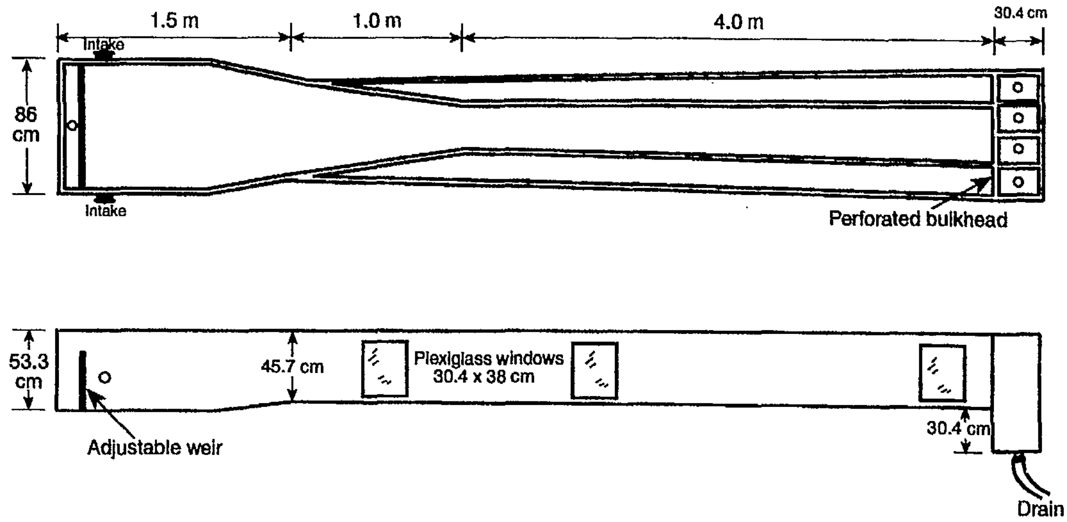

Fig. 3. Field flume of Wildish and Kristmanson (1988) modified for gypsum cylinder calibration.

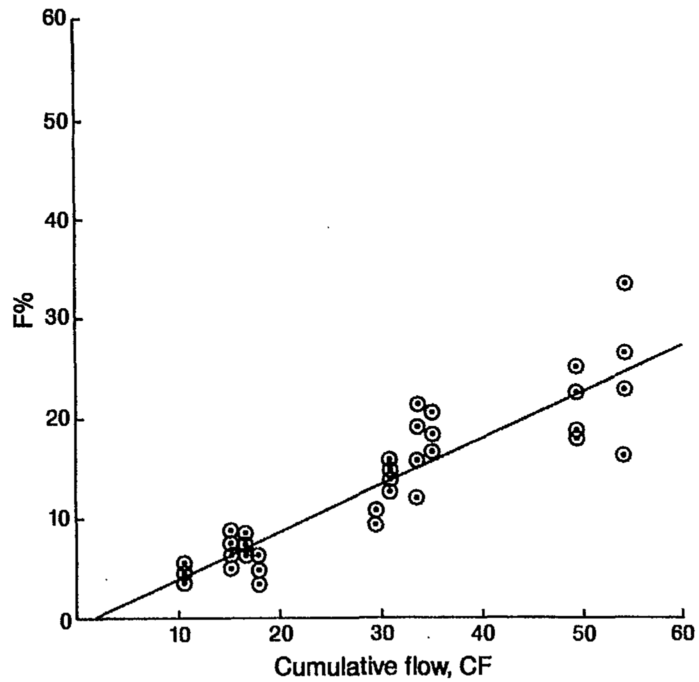

Fig. 4. Scatter diagram and fitted linear regression suitable for calibration purposes.

Appendix 1. The sources of gypsum used in testing materials to construct dissolution cylinders.

Recipe#	Gypsum sources
1	Dental plaster, Ash Temple Ltd., Saint John, NB, originally from Kerr Manufacturing Co., Romulus, MI, 48174, USA Snow white plaster, No. 2 - 40 lb [Also available: lab plaster - regular or fast; and Ortho-Model Mix - regular, hard or extra hard - all in 50-lb lots - not tried] Proportions: 3 parts plaster: 2 parts distilled water Conclusion: Field dissolution rate two rapid
2	DAP Plaster Wall Patch from DAP Inc., Dayton, Ohio, 45401, USA Powdered Resin Glue from DAP Inc., obtained from Johnsons, Calais, ME, USA Proportions: 10.5 wall patch: 1 part resin glue: 5 parts distilled water Conclusion: Too many air bubbles
3	As #2 above but with vacuum pressure at >25 psi. Proportions: as in #2 Conclusion: Placing the mixture in a vacuum oven removed some air bubbles. Field dissolution rate now too slow
4	Wall Patch compound as in #2 Proportions: 2 parts wall patch: 1 part cold, distilled water by weight Conclusion: Few air bubbles (and these could not be removed in the vacuum oven) and satisfactory dissolution times

Appendix 2. Manufacturers or suppliers of materials used in constructing cylinders, measuring and deploying them in seawater to depths of 40 m.

Item	Manufacturer
Plastic wood	Lepage Ltd., Brampton, ON, L6T 2J4
Plastic coated wire (PVC hook-up wire #8500)	Belden Wire and Cable, P.O. Box 1980, Richmond, Ind., 47375, USA
Spaghetti tags	Floy Tag & Manufacturing Inc., 4616 Union Bay Place, Seattle, Washington, 98105, USA
Silicone	Loctite Canada Inc., 270 Britannia Road East, Mississauga, ON
Rubber bands	Genary #64 - 3 1/2" long by 1/4" wide by 1/32" thick
Stainless steel rod	Local supplier
Swivels	Plants Lobster, 3628 Turner Ridge, Somerville, ME, 04348, USA
Plexiglass sheet	Warehouse Plastic Sales Inc., 13 Blackburn St., ON, M4M 2B3
Lead weighted line	P.O. Box 31448, Halifax, NS, B3K 5Z1
Electronic dividers	Mitutoyo Digimatic caliper, Mitutoyo Mfg., Co., Ltd., Landu Mita Building, 31-19 Shiba 5-Chome, Minoto-ku, Tokyo 108, Japan

Appendix 3. Dimensions and dry mass of cylinders from four separate molds (A, B, C and D) after air drying for ≥48 h.

#	Length	Diameter, mm	Mass, g
Mold A			
01119	15.5, 15.1, 15.4, 15.5, 15.4	37.90, 39.00, 38.30, 38.50, 38.70	260
01091	15.5, 15.5, 15.5, 15.8, 15.6	40.70, 39.90, 39.00, 39.20, 38.60	253
01121	15.5, 15.2, 15.5, 15.1, 15.4	39.97, 38.87, 38.30, 39.03, 38.96	255
01111	15.6, 15.2, 15.5, 15.1, 15.3	40.96, 40.88, 39.76, 38.99, 38.45	260
01167	15.6, 15.7, 15.6, 15.7, 15.7	40.04, 38.76, 37.58, 38.31, 38.43	231
01165	15.4, 15.5, 15.5, 15.5, 15.5	38.51, 38.92, 39.16, 40.60, 40.76	236
01163	15.8, 15.8, 15.7, 15.6, 15.7	38.24, 38.19, 37.53, 37.92, 37.97	230
01092	15.4, 15.4, 15.4, 15.5, 15.5	41.09, 40.60, 39.78, 39.03, 38.34	252
01166	15.6, 15.7, 15.6, 15.6, 15.6	38.00, 38.13, 38.14, 38.92, 38.68	223
01120	15.4, 15.3, 15.2, 15.4, 15.2	40.55, 40.65, 40.18, 39.05, 38.39	260
Mold B			
01074	15.2, 15.0, 15.1, 15.1, 15.2	38.09, 28.01, 38.02, 37.90, 38.09	241
01148	15.0, 15.2, 15.1, 15.1, 15.2	37.74, 37.71, 37.78, 37.59, 37.53	232
01104	15.3, 15.4, 15.3, 15.5, 15.3	38.53, 38.27, 38.42, 38.36, 37.99	246
01140	15.1, 15.3, 15.3, 15.2, 15.3	38.47, 38.22, 38.33, 38.18, 37.81	236
01105	15.4, 15.2, 15.2, 15.1, 15.4	38.54, 38.03, 38.15, 38.11, 37.77	248
01139	15.2, 15.2, 15.3, 15.2, 15.1	37.56, 38.11, 38.21, 38.58, 38.55	238
01106	15.4, 15.3, 15.2, 15.4, 15.5	38.54, 38.22, 38.58, 38.08, 38.46	246
01142	15.3, 15.2, 15.2, 15.3, 15.3	38.50, 38.37, 38.02, 38.01, 37.31	236
01127	15.2, 15.2, 15.1, 15.1, 15.0	37.74, 38.22, 38.20, 38.31, 38.56	239
01128	15.0, 15.1, 15.0, 15.2, 15.1	37.74, 38.16, 38.05, 38.17, 38.69	240
Mold C			
01089	15.3, 15.2, 15.5, 15.4, 15.3	38.1, 38.5, 38.3, 38.5, 38.2	248
01087	15.3, 15.4, 15.3, 15.2, 15.5	38.7, 40.3, 40.5, 39.1, 38.1	260
01069	15.1, 15.0, 15.1, 15.1, 15.4	38.8, 40.5, 40.5, 38.8, 37.9	244
01071	15.2, 15.4, 15.4, 15.5, 15.4	38.1, 38.5, 38.1, 38.1, 38.1	239
01090	15.3, 14.9, 15.1, 15.1, 15.2	37.9, 38.0, 38.0, 38.0, 37.7	251
01125	15.1, 15.1, 15.1, 15.1, 15.0	39.0, 40.6, 41.1, 39.2, 38.1	253
01199	15.4, 15.4, 15.3, 15.3, 15.4	38.0, 38.0, 37.9, 38.0, 38.0	241
01122	15.1, 15.0, 15.0, 15.3, 15.1	37.8, 37.9, 37.9, 37.7, 37.8	238
01123	15.1, 15.1, 15.3, 14.9, 15.0	38.3, 38.3, 38.1, 38.5, 38.5	247
01098	15.2, 15.4, 15.4, 15.7, 15.5	38.6, 39.3, 38.7, 38.5, 38.4	251
Mold D			
01063	15.5, 15.2, 15.1, 15.2, 15.1	38.1, 37.9, 37.9, 37.9, 37.7	223
01113	14.7, 15.0, 15.0, 15.0, 15.0	37.9, 39.0, 38.9, 38.6, 38.4	249
01152	15.4, 15.7, 15.5, 15.6, 15.5	38.1, 37.9, 37.6, 37.8, 38.0	224
01102	15.2, 14.8, 15.0, 15.1, 15.2	38.0, 38.8, 38.8, 38.8, 38.5	268
01146	15.2, 15.3, 15.2, 15.2, 15.1	38.6, 38.5, 38.6, 38.2, 38.2	242
01115	15.1, 15.1, 15.0, 15.0, 15.0	38.4, 38.3, 38.0, 38.0, 37.9	246
01145	15.4, 15.4, 15.4, 15.5, 15.5	39.1, 38.3, 37.8, 37.9, 38.1	252
01144	15.0, 15.0, 15.5, 15.4, 15.2	38.9, 40.2, 39.1, 38.7, 37.9	262
01101	15.4, 15.3, 15.5, 15.3, 15.4	39.4, 38.1, 38.2, 37.9, 38.1	257
01151	15.5, 15.5, 15.6, 15.5, 15.6	38.7, 39.7, 38.8, 38.5, 38.0	242

Appendix 4. Dry mass of cylinders after drying overnight, followed by cooling and weighing to ±1 g. Letters refer to four different molds used in casting the cylinders.

A	B	C	D
263	248	240	240
267	240	241	254
261	237	240	262
268	258	246	246
262	238	253	254
262	235	248	244
250	239	259	245
256	233	253	242
261	237	259	235
256	233	259	245
246	233	250	244
252	236	230	246
248	235	246	247
256	236	243	227
244	234	251	222
254	223	248	
261	218	260	
262	222	254	
256	244	261	
253	245	253	
234	244	258	
241	244	246	
249	239	227	
241	242	251	
243	260	255	
266	243		
253	246		
249			
260			