# CHAPTER ONE HUNDRED FIFTY THREE

#### Steady Flows In The Nearshore Zone

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#### Abstract

Field measurements using electronmagnetic flowmeters on two natural beaches are presented. Mean flows are compared to theory. The horizontal and vertical structure are discussed.

### Introduction

It has long been suggested that steady nearshore currents redistribute sediment entrained by the more energetic wave motions. This understanding has been the basis for many of the bulk sediment transport formulas developed. Coastal engineers have traditionally been concerned primarily with the shore parallel component of steady flows. Cross-shore flows generally are much smaller in magnitude and do not result in a large net transport of sediment. Nevertheless a large body of work has indicated that steady cross-shore flows generated by low frequency wave motions may generate various barred profiles (3). More recent work has indicated that quite small cross-shore mean flows can be quite significant for profile development and maintenance (2). The spatial structure of these mean flows has obvious implications for sediment transport and nearshore morphology. Theoretical models of the flow due to wind, wind waves and low frequency motions have been developed but field verification is lacking. Until field programs reliably measuring the magnitude and structure of nearshore flow fields are completed, application of these models to sediment transport estimates is unrealistic.

The work described here is a preliminary attempt to describe steady flows in the nearshore zone. Results from two field experiments will be presented. Farticular attention will be paid to the vertical structure of such flows. Field measures of vertical structure have previously been neglected due to the expense and, perhaps,

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the questionable reliability of such measures. Knowledge of vertical structure is important for verification of theory as well as interpretation and use of single point measures. In addition, the offshore spatial structure will be described. Results to date indicate that commonly accepted ideas concerning steady nearshore flows may be difficult to support on all but the simplest of natural beaches.

#### Background

Steady nearshore currents may result from a variety of generating mechanisms. Here we shall consider flows averaged on time scales long compared to the group or surf beat period. Wind and tidally forced flows are neglected where possible, although both mechanisms may result in significant flows. Of primary concern here are those currents driven by higher frequency, "wind wave", motions. While it is impossible to rigourously divide measured means into components based on forcing the condition of this study is such that flow associated with other forcing mechanisms should be small.

Measures of shore parallel flows have been more extensively reported than cross-shore flows. Theoretical treatments have been quite successful and are an integral part of longshore sediment transport models. Longshore flows have been modelled and observed to result from longshore gradients in the mean sea level due to low frequency edge wave motions. (5). A more prevalent mechanism is the forcing due to the oblique incidence of wind waves. This mechanism, as described by Bowen (6) and Longuet-Higgins (12) results in forcing due to gradients in the longshore component of the radiation stress. These models, which rely on empirical relations for frictional and lateral mixing effects have been found to compare quite favourably with experimental data (11).

The offshore structure of longshore flows depends primarily on the shore normal gradient of the radiation stress, and thus the wave shoaling and dissipation processes. The theories also describe an offshore dependence due to variation of lateral mixing. Field results seem relatively insensitive to the mixing parameterization chosen; probably because of the smearing effect of a finite bandwidth spectrum (15). The vertical dependence of longshore flows has been largely neglected by the above, depth averaged, treatment. Knowledge of the vertical structure is critical for attempts to estimate stresses acting on the bed. Simple riverine velocity profiles might be applied but in a wave dominated field such models are unlikely to be correct. Theoretical treatment of cross-shore flows has advanced to levels well beyond our ability to verify in the field (i.e. 9) The theory of Longuet-Higgins (14) and the subsequent lab work of Russell and Osorio (16) has resulted in the commonly accepted picture of two dimensonal nearshore flows. Near bed flows are assumed to be onshore outside the <urf zone and offshore inside the breaker line (10). These wave generated mean flows result from the presence of viscous boundary layers and the associated production and transport of vorticity. The Longuet-Higgins theory for waves over a horizontal bed predicts, given a time invariant eddy viscosity, flows in the direction of wave propagation at the top of the bottom boundary layer. Above this the flow structure is quite sensitive to conditions at the free surface as well as the particular form of eddy viscosity chosen.

Seaward bottom flow within the surfzone may be attributed to the effects of a mean set-up (10), a mass flux to balance that associated with a translating bore (8) or a surface stress due to breaking waves. If we extend the Longuet-Higgins (13) model to include horizontal gradient terms then:

 $d/dx (\tilde{u}^2) + d/dz (uw + u'w') = -d/dx(g\bar{\eta})$ 

where u is the wave motion, u' the turbulent motion and  $\eta$  is the mean change from still water. Further, allowing the depth to be a function of x and assuming

 $u'w' = -A_{r} \partial \langle u \rangle / \partial z$  (where  $\langle u \rangle$  is the mean velocity)

we can solve for the mean flow. By assuming

 $\langle u \rangle = 0$  at the bed,  $A_{ij} = constant$ 

and

$$\int_{-b}^{n} u \, dz = 0$$

we arrive at

 $F(\mathbf{x}) = \sigma \, \partial \bar{\eta} / d\mathbf{x} + \partial / \partial \mathbf{x} \, (\mathbf{u}_0^2 / 2) \quad \mu = (\sigma / 2 \mathbf{A}_V)^{1/2}$  $\sigma = \text{freg}, \qquad \mathbf{k} = \text{wavenumber} \qquad \mathbf{h} = \text{depth}$ 

Even with the assumption that A is constant a number of solutions may arise depending on  $^V$ dh/dx and our method of solving for F(x). F(x) represents the loss of energy by the waves. If we assume that a =  $\alpha$ h, where  $\alpha$  is a constant, in the surf zone we may solve for F(x) by assuming that the momentum flux from the waves results in a stress acting on the free surface. In that case

 $\langle U \rangle (x, z, t) = -3 g \alpha^2 d^2 dd/\partial x f(z)/(16 A_y)$ +  $\alpha^2 g dd/dx g(z)/(32\sigma)$ +  $3\alpha^2 (gd)^{1/2} p(z)/32$ .

The full solution allows bottom flows in either direction within the surf zone on beaches of realistic slope, with steeper beaches exhibiting offshore flow at the bed. The above solution, while supported by laboratory experiments (6,10), is probably wrong in its simplistic modelling of the bottom stresses, but it does illustrate that almost any velocity profile can be constructed if one manipulates A and the boundary conditions. As of yet there is a paucity of field data to constrain such models.

Quite a number of laboratory experiments measuring cross-shore flows have been completed. Most find the Longuet-Higgins solution to be accurate near the bed and less accurate towards the free surface. Russell and Osorio (16) for example found extremely good agreement for values of kd between 0.5 and 7.2. No significant effects of a sloping bed of .05 could be seen. Russell and Osorio also saw a reversal of the near bottom flow associated with breaking waves. Further experiments, summarized by Sleath (18) have shown that bed roughness and higher harmonics may decrease the velocity, and in one experiment reverse the flow.

It is readily apparent that the longshore and crossshore theories of Longuet-Higgins have become quite entrenched. While the longshore current model seems to adequately predict the depth averaged flow little is known about the vertical structure. The laboratory work on cross-shore flows generally supports theoretical conclusions as to the direction of near bed flows but the magnitude of such flows as well as the flow structure above the bed are called into question (18). Reliable tests of the theory on natural beaches still need to be carried out. Sediment transport models are quite sensitive to the mean velocity (2). Thus it is imperative that we make some effort to evaluate theories predicting mean flows. The spatial structure of this flow field also needs investigation if errors due to the use of point measures are to be estimated.

#### Field Experiments

In order to study the vertical structure of mean flows a tripod mounted array of three Marsh-McBirney electromagnetic flowmeters were deployed on two Canadian beaches. The flowmeters were aligned to measure the two horizontal components of the flow. Velocity measures were taken at approximately 35 cm intervals with the bottom sensor ten to fifteen cm above the bed.

The initial experiment took place at Queensland Beach, Nova Scotia, a steep (slope = .1) sheltered pocket beach. Waves at Queensland are long crested and narrow banded in both frequency and direction. Lower frequency motions are quite energetic at times but all indications are that the beach is dominated by two-dimensional motions. Twenty to thirty minute data runs were taken at low and high tide over a two day period. The wave field was fairly stationary with kd  $\sim$  0.25, wave amplitude about 35 cm and a wave period of 8 sec with pronounced group structure.

A subsequent experiment was carried out at Pte. Sapin, New Brunswick. Pte. Sapin is a fairly steep (.06) beach which quickly gives way to a wide, flat rock platform extending well offshore. Wave conditions are complex with two predominant directions of approach. Waves tend to be obliquely incident, short crested and rather broad-banded in frequency. Longshore transport of sediment is extremely vigourous in storm conditions, as witnessed by the sediment trapping of a breakwater immediately to the south. Any assumptions of twodimensionality are suspect although no rip systems were observed. Run lengths were an hour in length taken over a variety of conditions. Wave heights ranged from .2 to 1.2 meters at the instrument position with periods from 3 to 8 seconds. Groupiness and angle of incidence varied over a similarly wide range. Ancillary data sets of wind speed and direction, offshore flow, and directional spectra were collected through the efforts of various researchers under the auspices of the National Research Council of Canada as part of the Canadian Coastal Sediment Study  $(C^{25})$ . 1C ۰s' ٤).

There are a number of problems with the experiment as described. Working on steep beaches resulted in all data

sets being outside the surf zone. The deployment of only one tripod also prevented simultaneous measures at more than one point along an offshore line. In addition, single point measures yield insufficient information about the lower frequency motions present. These problems have been addressed as we prepare the next  $C^2S^2$  field study but they limit information content of this data set.

The Marsh-McBirney flow meter is a rugged device but it has some limitations. Firstly, it is unclear how near the bed or free surface such an instrument can be deployed. As well, the current meters must be separated by a similarly unknown distance. Our results indicate that ten centimeters is a safe distance; but one that is uncomfortably large for resolving near bed flows. In addition the EM flowmeter measures the Eulerian portion of the flow. For many applications the Lagrangian transport would be more meaningful. Estimates of the Lagrangian velocity indicate it is only slightly different but in cases of small velocities it may be a significant difference.

Recently the response characteristics of Marsh-McBirney flow meters has been questioned (1). Aubrey found that the current meters were unreliable in combined steady oscillatory flows. Errors in the measured mean were 1-6 cm/sec. Problems also arose in areas of large ambient turbulence. Aubrey questioned the reliability of such meters in calculating the higher moments as well. The accuracy of means measured in the field is difficult to estimate but some subjective evaluations can be made. More convincing arguments may be made for the reliability of the moments. The data was approached with some care and the current meter performance checked where possible.

### Results

The mean flows discussed here will be averages over an entire data run. Table 1 shows means averaged over shorter intervals and it is apparent that the means are fairly stationary over time scales of 15 minutes to an hour. The variance is also calculated. Since the records are highly autocorrelated the variance does not allow direct error estimates. Given the length of the data run the statistical uncertainty is nonetheless small with respect to possible sensor errors. The means are small in Table 1 and difficult to evaluate given the problems suggested by Aubrey (1). The variances are heartening with comparable magnitude for the two sensors and showing similar behaviours with time. The higher moments are similarly well behaved indicating that the electromagnetic flow meters are guite well behaved. Sensor Direction Mean/Variance  $(cms^{-1}/cm^2s^{\div 2})$ 

- 1 x 1.92/2.51 1.49/2.06 1.35/1.77 1.49/.87 1.54/1.69 y-2.53/.14 -2.60/.13 -2.84/.14 -2.87/.15 -2.59/.14
- 2 x 2.07/2.37 2.28/2.18 2.30/1.88 1.49/2.01 1.45/1.85 y 1.05/.15 -1.22/.14 -2.23/.14 -2.42/.17 -2.64/.17
- Table 1. Means and variance calculated for consecutive 10 minute data sections on two sensors at different heights. x represents on-offshore flow, positive offshore.

Near normal wave incidence resulted in small longshore currents at Queensland. The cross-shore flows are plotted in Figure 1. Also plotted is the Eulerian part of the Longuet-Higgins solution. The agreement in the lower two-thirds of the water column is amazingly good. As the data points represent runs separated by up to 24 hours it appears a consistent, long term flow pattern exists. Real values of the velocity range from near zero to approximately 10 cm/sec. The agreement with theory suggests, once again, that the sensors may be quite reliable.

The only systematic deviation from theory is in the top of the water column. This is consistent with lab work (16, 18) and careful analysis of the data suggests it is not a sensor malfunction due to proximity to the free surface. The measured profile indicates, as expected, that the Longuet-Higgins model is inaccurate as one approaches the free surface. This is hardly surprising as the boundary conditions which apply are unknown.

The cross-shore data from Pte. Sapin, similarly plotted, bears no resemblence to the Longuet-Higgins solution (Figure 2). Dimensional velocities ranged from 0 to 9 cm/sec in magnitude. The profiles resulting show no consistency from run to run on the basis of kd values, wave direction or wind direction. In all cases bottom velocities are offshore and maximum velocities are significantly smaller than those predicted by the Longuet-Higgins theory. The question of three-dimensional effects can not be easily addressed. Calculation of the depth averaged flow required to balance the Stokes drift indicates that the measured flow is generally of the right order of magnitude with a tendency to be somewhat smaller. Under any circumstances the indication is strong that the Longuet-Higgins solution for bottom drift is not relevant even 3 to 4 surfzone widths offshore.

Figure 3 shows an indication of two profile types.

# NEARSHORE ZONE FLOWS



Figure 1 Total data of cross-shore means from Ftc. Sapin. Note that all bottom flows are offshore.

This is rather a dangerous trick when working with only three data points in the vertical. The profile represented by the circles has onshore flow in the middle of the water column while the triangle profile exhibits offshore flow accelerated relative to the bottom velocity. The profile types are demonstrably not related to kd values, wave direction, or wind direction and speed. Figure 4, which shows the bottom velocities indicates that the profiles may be separated on the basis of nondimensional distance offshore. It should be noted that the three inshore points represent a range of conditions from long waves to small values of dimensional distance offshore and include both extemes in values of kd. A similar plot could be constructued using the skewness of the velocity distribution rather than distance offshore. Thus it appears that the two profile types reflect some aspect of the shoaling process.

It should be noted in Figure 4 that the bottom velocity itself seems independent of the distance offshore. The profile shape and the direction of flow in the center of the water column are somehow related to wave assymetry. This is to be expected as mean flows result from the vorticity generation associated with dissipation and shoaling. The data does not allow much speculation about near surface flows.

The cross-shore flows measured seem to change sensibly with wave conditions. Large waves generate large flows. Flows also increase towards the breaker line. The form of the velocity profile is stationary over fairly long time scales. Figure 5 shows results from three pairs of data runs. The pairs represent separations in time of two (crosses), four (circles) and nine hours (triangles). Wave conditions and dimensional velocities changed somewhat but the non-dimensional profile changes very little. Apparently similar conditions separated by longer periods (days to weeks) show quite dissimilar profiles. Figure 5 indicates that flow fields may be stationary over the duration of a storm event. The results again, give us some confidence in the performance of the flow meters.

Longshore flows at Pte. Sapin were variable ranging from 0 to 20 cm/sec. Depth averaged flows are plotted vs. the Longuet-Higgins (11) solution in Figure 6. Measured flows are certainly the right order of magnitude, tending to be somewhat large. This is partially due to wind driven currents also present. Flows are especially large far offshore and these flows probably contain a relatively large wind driven component as they represent small wave conditions. Pte. Sapin waves tend to be locally generated so it is especially difficult to separate wind and wave effects.



Figure 4 Bottom velocities from Pte. Sapin. Symbols are identical to those in Figure 3.



Figure 5 Velocity profiles from Pte. Sapin, see text for description of symbols.



Figure 6 Depth averaged longshore flows where VO is the Longuet-Higgins solution and XB is the distance to the breaker line. F is the mixing parameter as described in (12).



Figure 7 Longshore velocities vs. height above bed where delta is the boundary layer thickness. Symbols represent different data runs.

Measured vertical structure is shown in Figure 7. Also plotted is the standard riverine Z 1/7 formulation. Such a profile fits only when flows are most vigorous. Otherwise flows are somewhat surface intensified relative to the bottom with the maximum velocity in the middle of the water column. Again this may be due to the relatively greater importance of wind stresses during low wave conditions.

#### Conclusion

The data collected so far leads to somewhat negative conclusions. On the simplest of beaches, such as Queensland, prediction of bottom velocities may be made with some measure of confidence. Pte. Sapin suggests that flows on more complex beaches are, at present, unpredictable and point measures of velocity are of guestionable value.

Vertical and horizontal profiles are complex but may exhibit some systematic variation on a particular beach. Horizontal changes appear to be closely associated, as expected, with the shoaling process. Changes in the vertical are less well described. For further progress to be made we need to better measure the wave field present as well as gain a measure of the 3-D nature of the system. In addition, Lagrangian measurements, and simultaneous observations along a longshore transect would better constrain our results.

In a very subjective way it appears that EM flowmeters behave in a reasonable manner. Further work needs to be done to address this problem particularly.

Finally, our results are not inconsistent with those found by other researchers. Surf zone flows have been found by a number of researchers to be directed offshore in the lower and middle portions of the water column (7, 17). Our findings, although outside the surf zone, also exhibit offshore flows. Such flows need to be rigourously measured and explained, especially, as their impact on sediment transport raises obvious problems as to the maintenance of the bed profile.

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