CHAPTER 202

Field Tests of Radiation-Stress Estimators of Longshore Sediment-Transport

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Abstract

Surfzone measurements of longshore sediment-transport with optical backscatter sensors and current meters are compared to transport estimates from offshore wave data. Several methods from the Shore Protection Manual for computing longshore sediment transport from waves are compared and correlated. Some formulas work well some of the time. Circumstances of which equations perform well/poorly under which conditions are specified, and reasons for poor performances are speculated upon. Advice is given for placement of wave gages and methods of analysis, which would increase the probability of obtaining good estimates of longshore sediment transport from directional wave data.

Introduction

Comprehensive arrays of 43 sensors were deployed to measure waves, currents, tides, and sediment transport at a long straight beach with gently-sloping plane parallel contours near a river outlet, Colorado River, Texas. (See inset map in Figure 1.)

Several state-of-the-art instruments were deployed: a trawler resistant Directional Wave Gage (DWG), a puv gage of colocated pressure and current sensors, Optical Backscatter Sensors for suspended-sediment concentrations, electromagnetic current meters for velocities, a new cable with internally imbedded pressure sensors for surfzone waves, and Acoustic Doppler Current Profilers for inlet currents and sediment flux.

This project of monitoring the behavior of the jetty system had several objectives, only one of which was estimation of longshore sediment transport from the offshore wave gages, the topic of this paper. Table 1 lists the major objectives (hypotheses) of the monitoring project and the means by which various functions

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of the sediment transport (Q in volumetric terms) would be used to test the hypotheses. In addition to the engineering objectives in Table 1, there were several science objectives as well. The surfzone data are being used to test suspended-load transport theories at a point, in order to find the best ones to use in CERC's numerical models. This paper will describe only the results of the final objective: using the offshore wave data to predict longshore transport.

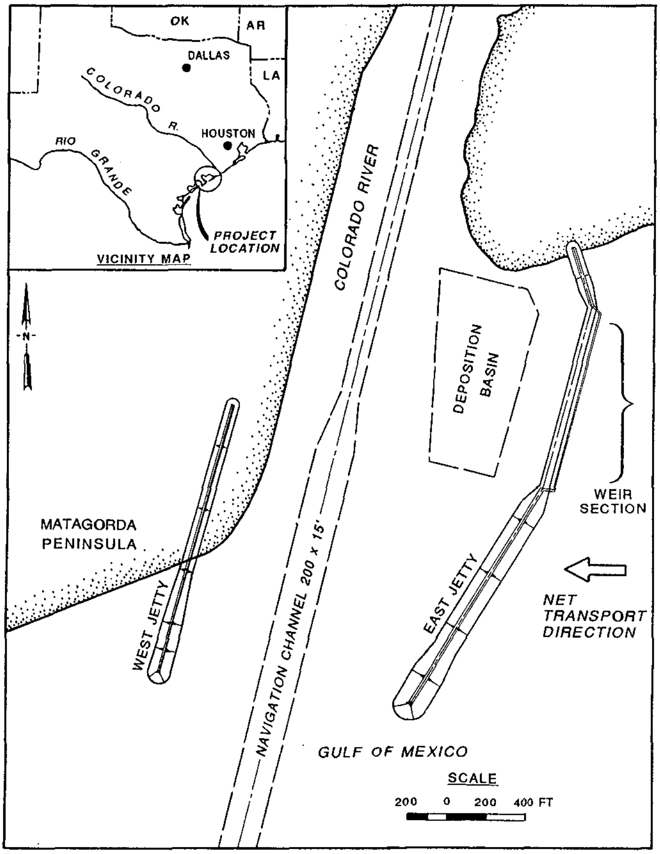


Figure 1. Colorado River location map (inset) and river mouth plan view. The weir section is underwater and allows some sediment to pass.

The purpose of this paper is to compare longshore sediment transport, as determined from both shoaled radiation stress and from transport measurements in the surfzone. For this reason, two sets of measurements were necessary: the offshore directional wave field and the sediment transport in the surfzone.

$\mathcal{MCCP}$ Colorado River, Texas

HYPOTHESES .... METHODS

1. Weir-Jetty System Hypotheses:

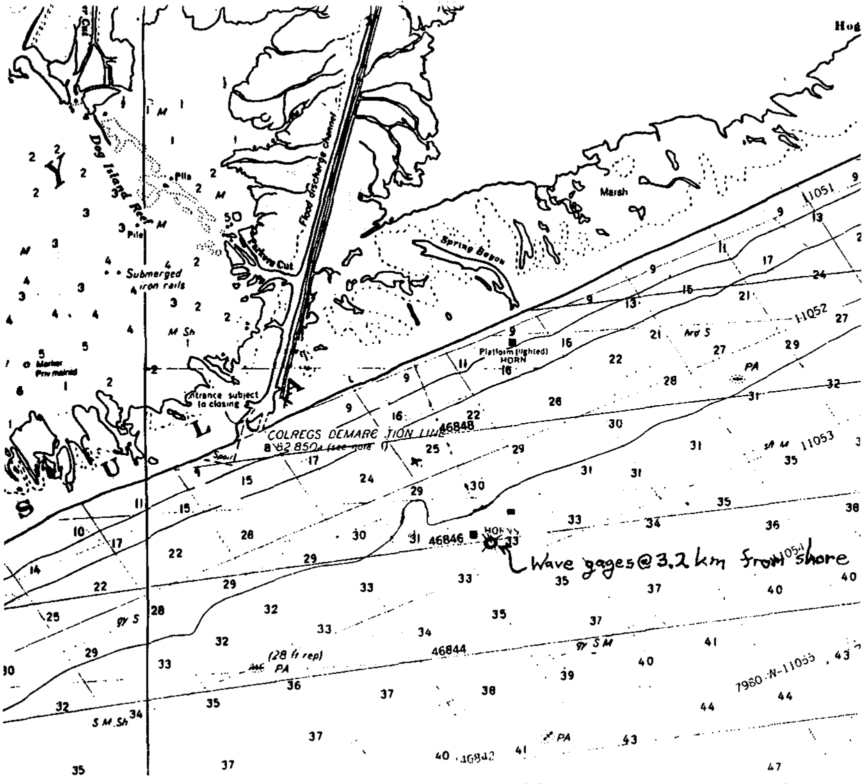
- Weir-trapping efficiency is high .... Compute $\frac{Q_{trap}}{Q_l}$ (Impoundment/Transport)
- Weir length should be 1000 feet .... Compute minimum of Q(x)
- Weir is in proper cross-shore location .... Compute $\frac{\partial Q}{\partial x}$
- Impoundment area is large enough .... Compute $\int Q dt$
- Anticipated dredging frequency is reduced by design .... Compute Required Dredging Frequency = $\frac{Q_{trap}}{V_{trap}}$
- Weir should be east of inlet .... $Q_+ \gg Q_-$
- Jetty length should be 1500 feet .... Bypassing efficiency = $1 - \frac{Q(x_{end})}{Q_{TOTAL}}$

2. Sediment-Transport Hypotheses:

- $I = KECn\sin(\alpha)\cos(\alpha)$ .... Compute Correlation Coefficient (absolute) and Confidence Interval (relative)
- $K = 0.7$ .... Compute ratio of Predicted to Predictor
- Offshore wave gage predicts I .... Correlations of S_{xy} and measured I

Radiation Stress Method

The offshore wave field was measured at 10m depth at approximately 3.2km offshore. As seen in Figure 2, the topography is quite linear (plane parallel contours) with very gentle slopes. When designing this project, it was hoped that if shoaled wave energy could be used to predict transport, the method ought to work better here than at many other sites, because of the gentle topography. Of course, it's always better to measure the waves close to where the data are needed (in this case, the breakpoint). But a very shallow gage deployment would have been unlikely to remain stationary over a long period, due to the stresses and topographic changes which are relatively large at 3m depth compared to 10m. Also the area is heavily trawled for shrimp, so gages were deemed more likely to survive in the area of offshore towers, which is where the gages were placed.



Wave gages @ 3.2 km from shore

Figure 2. Topographic map of the region offshore of the jetties, with wave gage site marked at 3.2km offshore and 10m depth (from NOAA/NOS Chart #11316, dated 31 May 1980).

The total-load alongshore sediment flux is determined by shoaling the radiation stress measured at offshore directional wave gages. The offshore directional wave field was measured by both "puv" colocated pressure and current sensors and by a new three-pressure-sensor Directional Wave Gage (Howell, 1992). For both sensor types, the measured wave data were first surface-corrected with the standard $\cosh k(z+h)/\cosh kh$ factor and then used to compute energy/frequency/direction spectra with the standard methods of Longuet-Higgins, Cartwright, and Smith (1963).

Once the direction/energy spectra are determined, they are used to estimate longshore sediment transport through the radiation-stress concept:

$$I_l = K\ C\ S_{xy} \tag{1}$$

where I_l is the immersed-weight longshore sediment flux, K is a coefficient (not necessarily constant, White and Inman, 1989), C is the wave phase speed, and S_{xy} is the longshore component of the cross-shore momentum flux, as determined from:

$$S_{xy} = E\ n\ \sin\alpha\cos\alpha \tag{2}$$

where E is the wave energy, n the ratio of group to phase speeds, and α is the angle of wave approach relative to beach normal.

The energy was then shoaled over the topography using the most common technique of placing the energy summed over the spectrum into the peak band. Using Snell's Law, the direction of propagation was then altered at each 3m horizontal progression of the energy along the beach-profile rangeline between the gage and the breakpoint.

The procedure given above, using equations (1) and (2) and then shoaling the energy to the breakpoint, is equivalent to the "exact" method listed in the Shore Protection Manual (1984) as its Equation 4-40 (although the listed requirement for *deep* water wave angle, rather than the angle at the location where transport is desired, is apparently a mistake) In addition to this exact method and three other functionally equivalent forms listed as equations 41, 42, and 43 in the Manual, there are four approximate methods for computing volumetric transport Q. These can be translated to immersed-weight transport I that we use, under the assumptions of constant densities, constant void ratios, and standard sand densities and voids, via $I[N/s] = Q[yd^3/yr]/4356$.

$$\begin{aligned} Q &= 0.884\rho g^{3/2} H_{sb}^{5/2} \sin 2\alpha_b & (3)\\ Q &= 0.05\rho g^{3/2} H_{so}^{5/2} (\cos\alpha_o)^{1/4} \sin 2\alpha_o & (4)\\ Q &= 0.00996\rho g^2 T H_{so}^2 \sin\alpha_b \cos\alpha_o & (5)\\ Q &= 1.572\rho g (H_{sb}^3/T) \sin\alpha_o & (6) \end{aligned}$$

where ρ is fluid density, g gravity, H_s significant wave height, α wave angle, T wave period, o the deep-water value, and b the breakpoint value. We also employed these four methods to compute longshore transport, using shoaled values (at "b") when the equations called for them. These four methods and the exact method were all compared to the sediment transport measured *directly* in the surfzone.

Direct Method

The surfzone transport was measured by cross-shore integration of the point measurements from three synoptic multi-sensor platform arrays of Optical Backscatter Sensors (OBSs) (Downing, Sternberg, and Lister, 1981) and Electromagnetic Current Meters (ECMs), sonars, and pressure sensors. Figure 3 shows a plan view of the site with various platforms of gages drawn in the general areas where they were deployed.

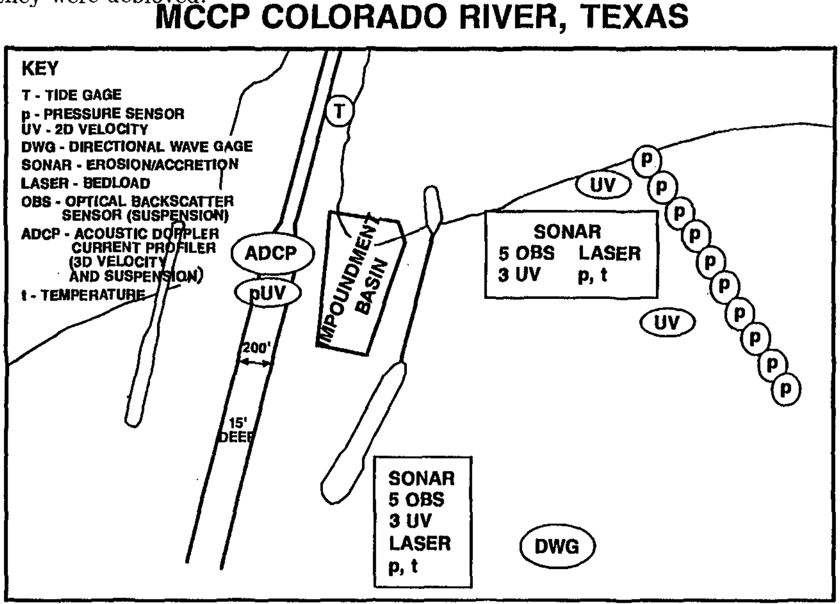


Figure 3. Areas of deployment of each gage type. Gage platforms are not to scale, but for visualization are drawn very large relative to the jetties. The lasers were replaced by micro-OBS gages for bedload.

The sediment concentration was measured with OBS2 optical backscatter sensors, which were each calibrated in a flow tank over a wide range of transport values. The sand from the site was sampled prior to each experiment and generally had a median size of 130 microns, with a size distribution that was always single-peaked. The sand from the site was used in the laboratory to calibrate the sensors over a wide range of transport values (from 1 to 300 grams per liter), both prior to and after each of the three experiments.

The currents were measured with standard 1-inch diameter Marsh-McBirney electromagnetic probes, calibrated just prior to use. Pressure sensors were used to determine the range of vertical integration for each platform, and also to determine when uppermost sensors were out of the water and thus not to be used.

The longshore sediment transport is the direct integration of the product of these two types of calibrated-sensor outputs, as measured in the surfzone:

$$I_l = (\rho_s - \rho) g N_o \int_0^{X_b} \int_0^{\eta} v(x,z) c(x,z) dz dx \tag{7}$$

where ρ_s is the sediment density, ρ the fluid density, g the acceleration of gravity, N_o the solids density (one minus porosity), v the longshore fluid velocity, c the sediment concentration, and the integral is taken over both the vertical surf depth and the cross-shore surfzone width.

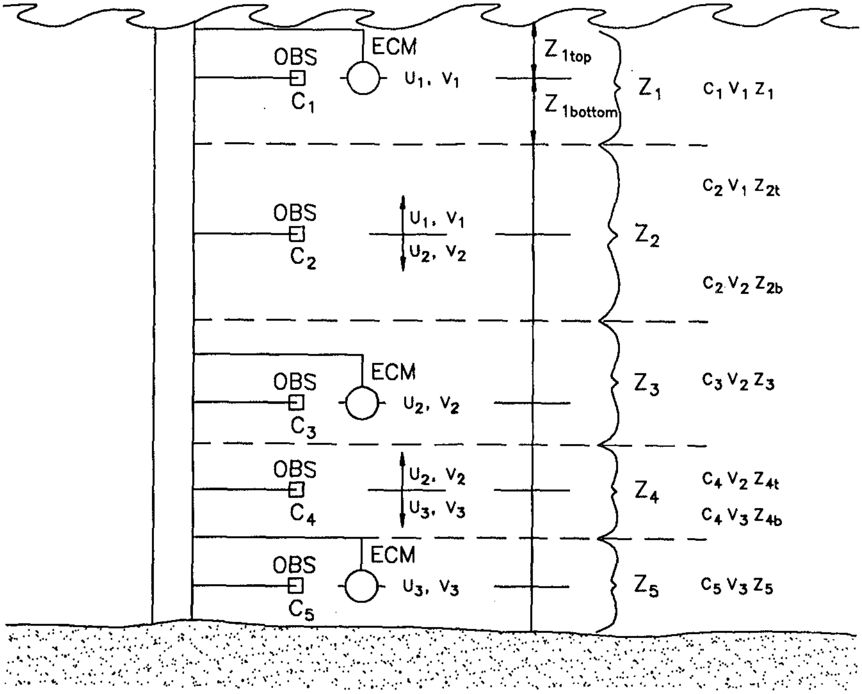


Figure 4. Regions of vertical integration of local sediment transport. Midpoints (dashed lines) between each gage of each type (both ElectroMagnetic Current meters and Optical Backscatter Sensors) separate each region. c = concentration, v = longshore velocity, z = vertical distance.

The above integration is first accomplished in the vertical at each platform location by vertically integrating the values of concentration c, longshore velocity v, and vertical range z, as shown in Figure 4. It is important to note that the vertical integration is performed *at each time step of 0.2 seconds*, and is thus unaffected by phenomena with longer time periods, such as bursts of sediment out of the boundary layer. Each sensor measures at one instant, and all the instantaneous products of c, v, and z are vertically summed before moving to the next 0.2s time step.

The direct measurements are also being used to test theories of suspended-load and total-load sediment transport, which will be done in other publications. These theories of sediment transport relate fluid forcing of waves or velocities to sediment flux on a "local" or point basis. The theories are tested by comparing the predicted transport from the theories with the measured surfzone transport.

Results

The longshore transport rates from the exact method, the four approximate methods, and the direct method were all computed for the one-week experiments, during which the surfzone platforms were deployed. The rates are listed in the following two tables for the June 1991 and January 1992 experiments. Note the considerable difference in transport values between the different methods. Individual estimates often differ as to the *direction* of transport. It is obvious that the different methods cannot be relied upon to produce comparable results for any specific set of wave conditions. But this is not generally what coastal engineers want to know. The more pertinent question is whether on a long-term basis (years), the wave-based methods can produce comparable transports to the real (measured) rates. The accumulation of the transport over months and years is the sand next to jetties, in navigation channels, or in impoundment basins, such as in Figure 1. Means of coping with this integral of the transport over time are what must be engineered.

Correlations over the 26 time periods in Table 2 and the 24 time periods in Table 3 were computed between the radiation-stress methods and the measured transport. Simple linear regression of the form $y = mx + b$ was used, where x are the radiation-stress methods, and y the measured values. Standard deviations were computed using N weighting, and thus the correlations are simply $r = m\sigma_x/\sigma_y$. Negative values represent anti-correlation. The r^2 values are the fraction of the total variance in the data explained by the method.

All the results of this paper are summed up in Table 4. One can reach different conclusions as to the effectiveness of a particular method, depending on which data set one examines. The July 1991 data show that *all* radiation-stress methods poorly predict measured rates. (The r^2 values are quite small.)

On the other hand, the January 1992 data show that all but one method do very well. All but one of the r^2 values are very high. For the method that did poorly, there are a couple possible explanations. It is the easiest method to use, because it does not require shoaling the wave data, but uses only deep-water values and ignores the topography. Another possible explanation, as noted in the table's footnote, is that conservative data-acceptance criteria were applied, whereas all the other methods used all measured data.

In the methods that did well (explained a high fraction of the variance, as indicated by r^2), note that some represent *anti*-correlations, meaning they indicate the right variation, but the wrong longshore direction. In the preparation of this paper, considerable time was spent trying to find any errors in sign. But the signs reported in the table appear to be correct. In fact, it is easy to see by examining individual spectra, that the signs of the correlations are valid. For example, note the reversal in sign between Eq 4-47 and the other methods, for the very large transport rate during a storm, on 18 Jan 1992 (the bottom line in Table 3.) That method agrees with the measured transport direction, whereas the others do not. However, all agree that transport was very large. Thus the correlations agree with conclusions that can be reached by looking at individual data points in Tables 2 and 3.

The bottom half of Table 4 correlates the exact method with one of the approximate methods. Since we are no longer comparing to the measured transport, this allows us to use *all* the offshore wave data, increasing by two orders of magnitude the number of data points (and the sampling of different wave climates throughout the year.) In contrast to the short experiments, these large data sets *consistently* show the same results, no matter which year's data are applied. For the years shown, the r^2 is always about 0.40, so each method contains 40% of the variance of the other method. This low value is not encouraging, since it is the hope of engineers using the Shore Protection Manual that they will obtain roughly the same results, regardless of which method they use.

Modifications to the SPM transport equations may be extracted from Table 4. The slope m would be a modification to the coefficient K (Eq. 1) via K = 0.7 m (since 0.7 was our K value used in this rms-wave-height data set). For example, Eq. 6 performs well in the Jan 92 data set, so a new K could be K = 0.7 m = 0.7(0.6668) = 0.47, *provided* a y-intercept were also added to the equation. So one might compute I from the original formula, and then $I_{new} = mI_{old} + b$, and in our example b is negative.

Conclusions

The method of computing radiation stress is clearly of first-order importance, as illustrated by the disrepancy in output from the five methods examined.

Predicting transport by shoaling the radiation stress sometimes works very well in predicting transport, and at other times does quite poorly. The possible reasons for this are numerous, and we can only speculate. The wave gage could have been malfunctioning during one of the experiments. But since there are means for testing the reasonableness of the data, it is more likely that sometimes there are processes operating in the surfzone not represented by offshore waves, but at other times these processes are small (e.g., wind, river flow rates, river silt load, etc.).

Not shoaling the energy over the topography (just using the deep-water values directly) may worsen the predictive capabilities. Evidence the poor performance of Eq 4-45 (our Eq 4).

To obtain accurate estimates of sediment transport, one must do something more than place wave gages offshore. Measuring the transport directly is preferred, but this is tedious and expensive. The different methods of measuring a transport rate, such as tracers, electronic sensors, or extensive beach profiling, all have the same order of magnitude in cost. Spending time and money on means to reliably obtain directional wave data very close to the breakpoint would seem a worthwhile effort. The shoaling process is likely to represent a large portion of the accumulated error in the radiation-stress method.

Individual transport estimates cannot be reliably performed. Although certain methods produce reliable results *over many occurrences*, use of an individual wave spectrum to estimate sediment transport can result in huge error, frequently even predicting the wrong direction of longshore transport.

In another study, the main factor not included in the SPM equations that was found to improve *local* estimates of transport, was inclusion of a sediment threshold-of-motion criterion (White, 1987; White, 1989). "Local" refers to predictions and measurements at essentially one point in the horizontal, as opposed to the "global" methods tested in this paper. In comparing predictions of different local transport theories with transport measured by sand tracer, it was found that agreement on direction of transport improved from 70% to 100% of the experiments, once a threshold criterion was added to the theory. It would be interesting to see if this were also true of the "global" equations tested in this paper.

Table 2: Measured and Computed Longshore Transport Rates: July 1991

All transport values are total I_l in Newtons per second.
Positive transport is upcoast (roughly ENE) on heading 65 degrees geographic.

Date	Measured	Exact SPM	Approximate SPM Methods			
and	Longshore	Method				
Time	Surfzone	SPM	SPM	SPM	SPM	SPM
	Transport	Eq 4-40	Eq 4-44	Eq 4-45**	Eq 4-46	Eq 4-47
	Eq. (3)	(Eqs 1,2)	(our Eq 3)	(our Eq 4)	(our Eq 5)	(our Eq 6)
7/16/91 1100	91.5	-87.602	-597.910	-184.696	-402.412	-352.414
7/16/91 1400	17.4	5.557	-56.196	7.908	25.528	9.355
7/16/91 1700	-24.7	519.603	-24799.531	0.000	2386.853	-9238.986
7/17/91 0800	-9.0	3193.869	-79733.180	16971.643	14671.381	80159.672
7/17/91 1100	-8.7	-1490.971	75106.180	0.000	-6848.935	255138.078
7/17/91 1400	-5.8	2272.286	-88223.719	0.000	10437.991	-58378.953
7/18/91 0800	77.9	17.452	-168.193	0.000	55.347	-28.154
7/18/91 1100	91.2	-5.039	-369.507	0.000	-16.030	29.335
7/18/91 1400	14.6	-45.809	-93.181	0.000	-144.886	63.901
7/18/91 1700	18.8	-14.103	80.534	-28.691	-44.555	-26.928
7/18/91 2000	16.9	105.486	-680.172	135.104	332.024	1095.635
7/19/91 0800	281.2	-37.843	-47.146	-12.202	-119.570	-41.433
7/19/91 1100	267.7	-17.466	178.226	-44.099	-55.244	-49.373
7/19/91 1400	189.3	-40.244	-56.797	-110.643	-127.448	-220.015
7/20/91 0800	7.1	45.239	34.388	2.880	182.178	5.852
7/20/91 1100	34.7	-115.315	155.732	-20.051	-384.388	-52.606
7/20/91 1400	-140.9	-28.258	-76.787	-32.335	-89.106	-82.062
7/20/91 1700	392.8	37.447	-96.373	0.000	118.169	-56.893
7/21/91 0800	-187.7	-78.058	2.156	-2.934	-452.588	-7.262
7/21/91 0800*	-88.7	-78.058	2.156	-2.934	-452.588	-7.262
7/21/91 1100	11.8	-18.194	-20.979	-27.497	-57.423	-104.496
7/21/91 1100*	-97.7	-18.194	-20.979	-27.497	-57.423	-104.496
7/21/91 1100*	-171.0	-18.194	-20.979	-27.497	-57.423	-104.496
7/21/91 1700	-48.8	-17.595	99.275	0.000	-55.483	218.513
7/21/91 1700*	-36.5	-17.595	99.275	0.000	-55.483	218.513
7/22/91 0500	-143.4	-14.858	80.358	0.000	-46.850	169.555

*: Some days had multiple estimates of measured transport that corresponded to one offshore spectrum.

**: For low waves and very large wave angles, King set transport to zero in his method using Eq 4 (SPM Eq 4-45).

The computed transports are reported with far more significant digits than the method justifies, in order to retain digits until the rounding of the final result.

Table 3: Measured and Computed Longshore Transport Rates: January 1992

All transport values are total I_l in Newtons per second.
Positive transport is upcoast (roughly ENE) on heading 65 degrees geographic.

Date and Time	Measured Longshore Surfzone Transport Eq. (3)	Exact SPM Method	Approximate SPM Methods			
		SPM Eq 4-40 (Eqs 1,2)	SPM Eq 4-44 (our Eq 3)	SPM Eq 4-45** (our Eq 4)	SPM Eq 4-46 (our Eq 5)	SPM Eq 4-47 (our Eq 6)
1/10/92 1500	-675.0	-0.000	-0.000	0.000	-0.000	-0.000
1/10/92 1800	-733.5	0.082	0.020	0.000	0.613	-0.001
1/11/92 0900	-297.0	0.329	0.111	0.000	2.453	-0.004
1/11/92 1800	-189.0	0.072	-0.011	0.000	0.486	0.001
1/11/92 1800*	-436.5	0.072	-0.011	0.000	0.486	0.001
1/11/92 1800*	-423.0	0.072	-0.011	0.000	0.486	0.001
1/12/92 1200	-2116.0	-0.000	0.000	0.000	0.000	0.000
1/13/92 1200	166.5	-0.000	0.000	0.000	0.000	0.000
1/13/92 1500	188.7	0.069	-0.004	0.000	0.586	-0.001
1/14/92 0900	0.0	-0.000	0.000	0.000	0.000	0.000
1/14/92 1200	0.0	-0.000	0.000	0.000	0.000	0.000
1/14/92 1500	0.0	0.044	0.020	0.000	0.260	-0.001
1/14/92 1800	0.0	-0.000	0.000	0.000	0.000	0.000
1/15/92 0900	0.0	0.082	0.011	0.000	0.613	0.000
1/16/92 1500	31.5	60.529	73.570	0.000	279.402	-102.966
1/16/92 1800	115.5	26.672	-157.781	36.289	123.713	20.788
1/17/92 1200	-472.5	30.006	-112.689	39.340	135.807	60.029
1/17/92 1200*	-337.5	30.006	-112.689	39.340	135.807	60.029
1/17/92 1200*	-891.0	30.006	-112.689	39.340	135.807	60.029
1/17/92 1500	-1251.0	205.225	-446.378	388.386	947.329	2530.908
1/17/92 1500*	-990.0	205.225	-446.378	388.386	947.329	2530.908
1/17/92 1800	-1125.0	517.482	783.706	1252.541	2411.821	2213.608
1/18/92 0900	-9976.0	1020.884	11451.572	0.000	4597.314	-12620.669
1/18/92 0900*	-9444.8	1020.884	11451.572	0.000	4597.314	-12620.669

*: Some days had multiple estimates of measured transport that corresponded to one offshore spectrum.

**: For low waves and very large wave angles, King set transport to zero in his method using Eq 4 (SPM Eq 4-45).

The computed transports are reported with far more significant digits than the method justifies, in order to retain digits until the rounding of the final result.

Table 4: Correlation of Radiation-Stress and Direct Transport Methods

Method being correlated with measured transport	μ Mean (N/s)	σ Standard Deviation	m Slope of Regression	b Intercept (N/s)	r Corr. Coef.	r^2
	July 1991 (number of spectra, n = 26)					
Measured transport	21.156	136.057				
Exact Eqs 1,2 predict	155.905	815.274	-0.0064684	22.164	-0.03876	0.00150
Approximate methods:						
Eq 3 predicts	-4585.514	27631.621	0.0001806	21.984	0.03667	0.00134
Eq 4 predicts	638.325	3267.050	-0.0019586	22.406	-0.04703	0.00221
Eq 5 predicts	720.832	3742.993	-0.0013555	22.133	-0.03729	0.00139
Eq 6 predicts	10317.407	52714.162	-0.0001128	22.320	-0.04372	0.00191
	January 1992 (number of spectra, n = 24)					
Measured transport	-1202.3	2622.1				
Exact Eqs 1,2 predict	131.156	290.880	-8.4357	-95.919	-0.9358	0.8757
Approximate methods:						
Eq 3 predicts	935.915	3191.167	-0.8049	-451.961	-0.9797	0.9597
Eq 4 predicts	90.984	264.404	0.1688	-1217.674	0.0170	0.0003
Eq 5 predicts	596.568	1314.813	-1.8587	-93.502	-0.9320	0.8686
Eq 6 predicts	-744.500	3688.519	0.6668	-705.921	0.9328	0.8702
	All days Dec 90 thru July 91, 8 times per day (number of spectra, n = 1823)					
Exact Eqs 1,2:	-108.054	615.681				
Approx. Eq 4:	-135.514	1224.382				
Exact Eqs 1,2 predict results of approximate Eq 4			1.2017	14.8267	0.6043	0.3652
	All days Jan 92 thru Dec 92, 8 times per day (number of spectra, n = 2009)					
Exact Eqs 1,2:	-41.7032	216.9353				
Approx. Eq 4:	-75.7956	304.8631				
Exact Eqs 1,2 predict results of approximate Eq 4			0.9434	-0.4755	0.6743	0.4547

For low waves and very large wave angles, King set transport to zero in his method using Eq 4 (SPM 4-45).

The computed transports are reported with far more significant digits than the method justifies, in order to retain digits until the rounding of the final result.

Acknowledgments

The considerable efforts in obtaining the large field data set at Colorado River were performed by the capable staff of the Prototype Measurement and Analysis Branch of CERC, including Bill Grogg, Doug Lee, Rhonda Lofton, Bill Kucharski, Chuck Mayers, Debbie Shafer, and Kerry Taylor. The data-collection systems were designed and built by Ralph Ankeny, Bill Grogg, Gary Howell, and J. Rosati. The analysis of the surfzone time-series data and computation of measured transport were completed by Joon Rhee. The computations of transport potential using deep-water methods (SPM Eq. 4-45) were provided by David King. All other transport computations, including the extensive work in shoaling the wave data, were performed by Rhonda Lofton. Without her considerable efforts in data analysis, this paper would not have been possible.

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