Sediment Transport in Low-Energy Rip Current Systems

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ABSTRACT


Sediment transport in rip currents is described based on field observations made at Palm Beach, NSW, Australia in April and June, 1994. Direct measurements of sediment transport using streamer traps mounted on portable racks were made in three low-energy rip currents. Time-averaged sediment flux was found to increase with increasing rip current velocity ($u_i$) and decreasing depth suggesting that maximum transport is associated with the fastest flowing rips at low tide. Sediment grain size exhibited a significant fining upwards trend in the rip channel flow with up to 50% of the sediments transported in the bottom 10% of flow. Gross sediment transport rates were found to be strongly related to $u_i^2$. Examination of the Shields parameter ($\theta$) indicated that waves are more important than currents in the entrainment of sediments, but that currents are responsible for subsequent transport of the sediments. Using a Bagnold-type approach as a conceptual basis, net transport in the feeder channel was found to be inhibited at all times during a tidal cycle, whereas offshore transport in the rip-neck occurred at all times. The relative roles of waves and currents in rip sediment transport therefore contributes to the infilling of the feeder channels and incision of the rip-neck channel observed during an almost complete cycle of low-energy intermediate beach state evolution as described by the model of Wright and Short (1984).

ADDITIONAL INDEX WORDS: Rip currents, sediment transport, coastal morphodynamics.

INTRODUCTION

Rip currents have long been recognised as a major mechanism for offshore sediment transport (Shepard et al., 1941; Wright and Short, 1984; Short, 1985; Smith and Largier, 1995). However, recent studies of offshore transport both within and outside the surf zone, have dealt almost exclusively with oscillatory motions (e.g. Jaffe et al., 1984; Hanes and Huntley, 1986; Nielsen, 1992), lower frequency oscillations (e.g. Huntley and Hanes, 1987; Osborne and Greenwood, 1992a,b), far-infragravity frequencies (Aagaard and Greenwood, 1995), and bed return flow or undertow (e.g. Greenwood and Osborne; 1990, Russell et al., 1991; Masselink and Black, 1995) as mechanisms for offshore sediment transport. In fact, very few direct measurements of sediment transport processes in rips exist (Cook, 1970; Kraus et al., 1989; Rosati et al., 1990; Shen, 1996; Aagaard et al., 1997) with most studies being limited to analysis of sedimentary structures and bedforms (e.g. Davidson-Arnott and Greenwood, 1976; Greenwood and Davidson-Arnott, 1979; Short, 1984; Gruszczynski et al., 1993; Sherman et al., 1993). The lack of field data is not surprising given the difficulty of deploying instruments in an environment which is both transient in space and time and commonly attains current velocities greater than 1 ms$^{-1}$ (Wright and Short, 1984; Gruszczynski et al., 1993; Short and Hogan, 1994).

Very little is therefore known about sediment transport processes in rips or the role played by rips in the bulk transport and distribution of surf zone sediments. Rip currents are an inherent component of intermediate beach states in the morphodynamic model described by Wright and Short (1984), particularly during conditions of decreasing wave energy, when rip channels become increasingly topographically arrested in position as the beach experiences overall accretion. Patterns of sediment transport in rips are of direct importance to the morphodynamics of intermediate beaches as it is these patterns which may act to both maintain and constrain the morphological evolution and the overall erosional/accretional state of the beach system. Greenwood and Davidson-Arnott (1979) suggested an equilibrium model for crescentic bars, in which landward sediment flux across the bar crest and longshore movement in the trough is balanced by seaward transport in rip currents. According to Short (1985), the export of sediment from rips in an accretionary beach cycle is likely to be exceeded by the import of sediment from bars which may actually act to infill the rip. Bowman et al. (1988) however, suggested that the rip-neck in low-energy conditions is continuously degradational and of sufficient energy to inhibit infilling. Unfortunately, there is no quantitative information available to examine sediment exchange within evolving rip systems and most existing studies reveal little about the nature of basic sediment transport processes and patterns operating within rip channels.

This paper describes results obtained from two separate
field experiments involving both the morphodynamic evolution of a rip current under conditions of decreasing energy and simultaneous measurements of sediment transport in three low-energy rip currents. The aims of this paper are: (1) to describe characteristics of basic sediment transport processes occurring in low-energy rip currents; (2) to assess the relative roles of waves and steady currents on sediment transport in rip currents; and (3) to relate these transport characteristics to commonly observed aspects of morphological change associated with low-energy beach state evolution.

FIELD SITE

The field experiments were conducted at Palm Beach, New South Wales, Australia (Figure 1) from 18–24 April, 1994 (PB1) and 18–20 June, 1994 (PB2). Palm Beach experiences a highly variable wind-wave climate superimposed on persistent moderate-to high-energy south-easterly swell (Short and Trenaman, 1992) with modal wave heights and wave periods of 1.6 m and 10 s respectively. The semi-diurnal tidal regime is micro-tidal and mean spring tide range is 1.6 m (Wright et al., 1980).

The experimental site is situated towards the southern end of the 2.3 km long beach and faces north-east (Figure 1) such that the southern headland gives moderate protection from southerly winds and modifies dominant incident waves from the south-east through refraction. The headlands compartmentalise the beach thus limiting the present-day supply of sand since there is virtually no littoral transport of sand between beaches in the region (Wright et al., 1980; Short and Wright, 1981). The beach and nearshore zone can be divided into a moderately steep subaerial beach (tan $\beta = 0.033 - 0.056$), a steep swash zone (tan $\beta = 0.1$); and a relatively gentle surf zone (tan $\beta = 0.017 - 0.024$). Beach and inshore sediments are composed of predominantly well-rounded, well-sorted, and negatively skewed medium sized quartz sands, with a shell content of approximately 30% and a median grain diameters of slightly less than 0.35 mm.

The modal topography of the beach is transverse-bar and rip (Short, 1993) and this was true of conditions during PB2 with three closely spaced rip currents located within the study area. The PB1 experiment encompassed an almost complete cycle of low-energy beach state evolution following a storm event with the nearshore system evolving from a long shore bar and rip morphology with two distinct feeder channels, through a sequence of stages, to an incipient low tide terrace state (Short, 1979; Wright and Short, 1984). Planform configurations of the bar and rip systems are shown in Figure 2 and Figure 3.

METHODOLOGY

During the experiments, data were collected on beach and surf-zone morphology, nearshore water surface elevation, current velocity, and sediment transport. Nearshore morphology and topographic change were surveyed daily at low tide along nine (PB1) and seven (PB2) cross-shore transects established at 25 m intervals along the beach. Water surface elevations and longshore and cross-shore current velocities were observed using 5 strain gauge pressure sensors and 9 bi-directional, ducted flow meters respectively. The sensors were mounted in various combinations on weighted, portable pods designed for use in the surf zone. Summaries of daily pod locations, referred to as Pods 1 through 5 (P1–P5), relative to components of the rip system are shown in Figure 2 and Figure 3. In general, pressure sensors and flow meters were mounted at 0.1 m and 0.3, 0.7, and 1.0 m above the bed respectively. A full description of the pressure sensor and flow meter deployments is given by Brander (1997).

All sensors were hardwired to a shore-based mobile laboratory where data was collected at a sampling frequency of 2 Hz for 34 minutes with runs separated by varying intervals. Data collection periods were dependant on the timing of the daily low tide and varied from 4–8 hours each day during the experiments. Readings from the pressure sensors were converted to water-surface elevation using Nielsen’s (1989) method of local approximations. Flow-meter data were corrected for frequency-response characteristics using the techniques of Nielsen and Cowell (1981). Estimates of root-mean-square wave height ($H_{rms}$) were obtained using the standard deviation ($\sigma$) of the pressure sensor records: $H_{rms} = 2.8\sigma$ (CERC, 1984).

The offshore sediment transport rate in rip channels was measured using vertical arrays of streamer sediment traps attached to portable racks. Three racks and twenty streamer traps were made for the experiment based on the design used and described by Kraus (1987) and Rosati and Kraus (1989). Each streamer trap consisted of a nozzle mouth, projecting 0.025 m up-current, with an opening 0.1 m wide by 0.025 cm high and a 1.5 m long sand collection component made of 100 $\mu$m polyester mono-filament cloth. The configuration of the streamer traps on the racks was consistent throughout the sediment sampling runs with traps deployed at 0.04, 0.1, 0.22, 0.28, 0.4, 0.58, and 0.82 m above the bottom of the rack assembly.

The three sediment traps were only available for PB2 and were deployed next to each pod in the rip-necks shown in Figure 3 for 20 minute intervals coinciding with data collection runs and a total of 11 deployments were made over the three day period. The racks were always located approximately 0.5 m to the south and slightly landward of the instrument stations to avoid flow disturbance and potential scouring and bed disturbance induced by the pod bases. The elevation of the lowest streamer trap nozzle was measured by the trap operator at the beginning and end of each transport run. Sediment samples taken from the beachface, swash zone, bar crest, longshore and rip current channels, and instrument sites were washed, oven-dried, and weighed. Grain size and sediment fall velocity analyses were performed on samples using a settling tube.

Calculations of time-averaged sediment flux ($\bar{Q}$) and total transport rate ($i$) follow the methodology described by Rosati and Kraus (1989). The dry weight of sand collected in streamer k is $S(k)$. The index $k$ increases from $k = 1$ at the bottom streamer to $k = n$, where $n$ is the total number of streamers in a particular trap. Streamer width is $\Delta w$ streamer height is $\Delta h$, and the sampling interval is $\Delta t$. If these quantities are used, the flux of sediment at streamer $k$, $\bar{Q}(k)$,
in units of weight per unit area and unit time, can be calculated as:

$$Q(k) = \frac{S(k)}{\Delta h \Delta w \Delta t}$$  \hspace{1cm} (1)

The flux between neighbouring streamers, $Q_n(k)$, can be estimated by linear interpolation between adjacent measured fluxes:

$$Q_n(k) = 0.5[Q(k) + Q(k + 1)]$$  \hspace{1cm} (2)

The flux density for a trap $i$ in units of sand weight per unit width of trap per unit time can be calculated using previously defined quantities and the distance between nozzles, $\Delta \alpha(k)$, as follows:

$$i = \Delta h \sum_{k=1}^{n} Q(k) + \sum_{k=1}^{n} \Delta \alpha(k) Q_n(k)$$  \hspace{1cm} (3)

in which $n$ is the total number of streamers on the trap. The first summation term represents the actual measured fluxes and the second summation term represents the interpolated fluxes between nozzles (Rosati and Kraus, 1989).

**BASIC CHARACTERISTICS OF SEDIMENT TRANSPORT IN RIPS**

No attempt is made in this study to distinguish between the contributions of bedload and suspended load transport. Although the design of the traps is such that if the bottom nozzle is resting at the bed it will collect sediments moving along as both bedload and suspended load, this study restricts analysis to aspects of suspended load transport for two reasons: (1) all measurements were obtained at elevations greater than 0.04 m, where streamer traps can only collect sediment moving in suspension, or intermittent suspension (2) the bottom nozzle was observed at, or below, bed level on only several occasions and due to potential errors incurred during the placement and removal of the trap apparatus in these circumstances, these streamer trap measurements are not included in this study.

**Sediment Entrainment**

Understanding the nature of sediment transport rates and patterns in rips is made complicated by the need to consider the combined effects of oscillatory waves and steady currents over a range of spatial and temporal scales. Since the amount of sediment transported in suspension in the rip is ultimately related to shear stresses exerted on the bed by both wave orbital motions and steady currents, the total skin friction Shields parameter (Shields, 1936) for combined wave and currents can be used as a surrogate criterion for predicting sediment entrainment:

$$\theta_s = \frac{\tau_s}{\rho g (s - 1) \bar{y} D}$$  \hspace{1cm} (4)
with \( s = (\rho_s - \rho)/\rho \), where \( \rho_s \) is the density of sea-water and \( \rho \) is sediment density, \( g \) is gravitational acceleration, \( D \) is mean grain size, and \( \tau_b \) is the bed shear stress, which under combined waves and currents can be expressed as (Beach and Sternberg, 1992):

\[
\tau_b = \rho (u_{bc}^2 + u_{bc}^w)
\]

Computation of the time-averaged shear velocity \( (u_a) \) followed that outlined by Nielsen (1992) in which friction factors based on Van Rijn (1990) and Swart (1974) were used for currents \( (u_{ac}) \) and waves respectively \( (u_{aw}) \). More complex calculations of shear stresses under the combined action of waves and currents have been proposed by Grant and Madsen (1979), but results using their approach were only 10–15% higher than those obtained using Eq. 5.

The relative contributions of bottom shear stresses exerted by waves and currents on sediment entrainment in the feeder and rip channels during PB1 are incorporated in Figures 4a and 4b which illustrate values of \( \theta_t \) and the component due to waves \( (\theta_w) \) and steady currents \( (\theta_c) \) alone. As expected, \( \theta_t \) was always in excess of 0.05, the value at which beach sand starts to move in water (Nielsen, 1992), indicating that sediment entrainment was omniscient in the feeder and rip channels. Significantly however, \( \theta_t \) was always considerably less than \( \theta_w \). This difference can be attributed to the fact that values of \( u_{ac} \) were typically four times greater than \( u_{aw} \). In some cases, particularly in the feeders (Figure 4b), \( \theta_t \) did not exceed the threshold for initiation of sediment motion. Similar results were found for PB2 except that values \( \theta_t, \theta_w, \) and \( \theta_c \) were approximately 20% lower. The total Shields parameter also exhibited a temporal pattern which was dependant upon location in the rip system with \( \theta_t \) in the rip-neck and northern feeder decreasing and increasing towards high tide respectively (Figure 4c). The opposite was true around low tide, with \( \theta_t \) being maximised in the rip-neck, but negligible in the northern feeder (Figure 4d). This pattern was consistent for each day of concurrent measurements of the rip-neck and northern feeder during PB1. It should be acknowledged, however, that Figure 4 is oversimplified in that wave and current contributions cannot be considered separately and superimposed (Grant and Madsen, 1979). Non-linear interactions exist between waves and currents and the sediment transport under their combined action is likely to differ from the sum of the individual contributions (Beach and Sternberg, 1992).
Vertical Distribution of Sediment Flux

All vertical distributions of sediment flux in the rip-neck, irrespective of location and time, exhibited an exponential decrease in \( \langle Q \rangle \) away from the bed, the magnitude of which was strongly influenced by the velocity of rip flow. In general, sediment fluxes close to the bed averaging 8 kg m\(^{-2}\) min\(^{-1}\), but ranged up to 44 kg m\(^{-2}\) min\(^{-1}\) during periods of strongest flow. The results are comparable to those measured by Kraus et al., (1989) in a rip channel having similar flow velocities (\( \approx 0.40 \) ms\(^{-1}\)) and in longshore currents with breaking wave heights approximately twice that recorded during PB2. Figure 5a illustrates the variation in vertical profiles of \( \langle Q \rangle \) for concurrent deployment of sediment traps in all three rip channels on 18/6/94. Mean flows of similar magnitude (\( \approx 0.52 \) ms\(^{-1}\)) occurred in both the southern and middle rips and both exhibit similar sediment flux distributions. The northern rip, however, was characterised by much smaller sediment fluxes in association with mean flows of only 0.14 ms\(^{-1}\). The observed reduction in sediment flux with decreasing flow velocity was characteristic of all the sediment trap deployments.

The influence of \( \bar{u} \) on \( \langle Q \rangle \) is also illustrated in Figure 5b, which shows that sediment flux in the southern rip on 19/6/94 increased at all elevations above the bed between Run 4 and Run 5 when \( \bar{u} \) increased from 0.23 to 0.46 ms\(^{-1}\), and then decreased dramatically from Run 5 to Run 7 when \( \bar{u} \) decreased to 0.06 ms\(^{-1}\). Sediment flux also appeared to exhibit distinct velocity-dependent spatial patterns within the middle rip-neck channel on 20/6/94 with a progressive offshore increase in \( \langle Q \rangle \) from the landward trap to the seaward trap (Figure 5c) associated with corresponding increases in \( \bar{u} \), from 0.31 to 0.35 to 0.51 ms\(^{-1}\).

The vertical variation of sediment flux through the water column was examined further by dividing individual streamer fluxes by the total sediment flux of the entire trap for each
Vertical Distribution of Grain Size

Grain-size analyses were performed on retained dried samples from the streamer traps and the least square regression fit ($R^2 = 0.8$) shown in Figure 7, which is significant at the
95% confidence level, illustrates that mean grain size of transported sediments in rip channel flow decreases with height above the bed such that:

\[ D = 0.32z/h + 2.1 \]  \hspace{1cm} (6)

where \( D \) is mean grain size in \( \phi \) units and \( z/h \) is the relative depth. These results suggest that the majority of sediment transported in the rip \((z/h < 0.1)\) consisted of material \(<2.0 \phi \) \((0.25 \text{ mm})\), whereas sediments transported at relative depths greater than 0.1 are finer than \(2.0 \phi \). Examination of vertical grain size profiles for individual sediment trap runs showed that there were no significant temporal or spatial deviations from this relationship despite changes in water depth and flow velocity. Standard deviations of the dried sediment samples were similar, ranging from 0.3–0.4\( \phi \), indicating well-sorted sediment samples. Although not shown on Figure 7, two samples were obtained from streamer traps whose nozzles were half-buried and the sediments at the bed were much coarser, with mean grain sizes of approximately 1.75\( \phi \) \((0.3 \text{ mm})\). Figure 7 also plots sediment samples obtained at \(z/h > 1.0\), which shows that there is sometimes a small offshore flux above the mean water level. A similar result was found in longshore currents by Kraus and Dean (1987), who attributed it to sediment transported during super-elevation of the water surface.

Although other field investigations have reported a slight decrease in mean grain size with elevation (Fairchild, 1977; Kana, 1979; Nielsen, 1983; Kraus and Dean, 1987; Osborne, 1990; Shen, 1996), the relationship expressed by Eq. 6 is considered reliable because of the large volumes of trapped sand available for analysis. The fining upwards trend suggests that sediment re-suspension in low-energy rip-neck channels may be dominated by a diffusive-type process (Vongsisessomjai, 1986; Deigaard et al., 1986; Nielsen, 1992). Unfortunately, direct measurements of bedforms during the experiment were restricted to those made by trap operators. They observed megaripples with spacings \((\lambda)\) of 0.8–2 m and heights \((\eta)\) ranging from 0.08–0.2 m with corresponding steepness \((\eta/\lambda)\) values of 0.1–0.13. There is no regular vortex shedding associated with such megaripples, but large sand plumes can be ejected up to heights of 1 m above the bed due to complex instabilities around the bedform (Nielsen, 1992).

**Total Transport Rates**

The total transport rate \(i_i\) for the trap deployments, calculated using Eq. 3, averaged approximately 3 kgm\(^{-1}\) with a maximum rate of almost 10 kgm\(^{-1}\). Given the dependence of \((Q)\) on \(u_r\), it is not surprising that the greatest transport rates were associated with the strongest flow velocities. In fact, Figure 8a shows that a strong functional relationship \((R^2 = 0.83)\), significant at the 99% confidence level, exists between \(i_i\) and \(u_r\), such that \(i_i\) is predicted by a linear least squares regression of the form:

\[ i_i = 27.6u_r^{0.8} + 0.92 \]  \hspace{1cm} (7)

This relationship indicates that sediment transport in low-energy rips increases exponentially with increasing flow velocity. Taking into account tidal modulation of rip velocity however, total transport within the rip would be expected to decrease towards high tide. Although no trap deployments were made at high tide, the time series shown in Figure 8b suggest that \(i_i\) at high tide is likely to be negligible as \(u_r\) approaches 0 m s\(^{-1}\). A similar result was reported by Aagaard et al. (1997), who measured small amounts of onshore directed transport in a rip channel at high tide and attributed this to weak onshore directed mean flows and/or oscillatory incident waves. Breaking wave heights measured during PB2 were small \((<0.6 \text{ m})\), but it is apparent from Figure 8b that \(H_b\) did increase towards high tide and that maximum transport rates in the rip channel occurred when \(H_b\) was reduced.

**DISCUSSION**

Although the modelling of sediment transport in rip currents is beyond the scope of this paper, several results provide evidence to suggest that a Bagnold-type approach may be suitable. Bagnold’s (1963) model involved predictions of total load sediment transport for oscillatory motion with a superimposed current. Conceptually, the model is based on the idea that waves act to entrain sediments while a steady current of arbitrary strength transports the sediments away. This scenario is supported by the data in this study. First, Figure 4 illustrated that the total Shields component due to waves was much more important in entraining sediments than that due to currents. Second, Figure 9 indicates that the transport rate in rip channels is correlated much better with \(\theta_v\) than \(\theta_s\). Whereas \(i_i\) increases in a linear fashion with greater values of \(\theta_v\), there is no relationship whatsoever with \(\theta_s\). A similar result was found under combined waves and currents by Beach and Sternberg (1992) who reported that the current contribution to their measured longshore sediment flux was approximately 1.7 times that of the wave contribution.

Sediment transport in rips is extremely complex however, and requires an understanding of the morphodynamic relationships operating within low-energy rip systems. In particular, three factors should be considered: i) recent studies by Brander (1997) and Aagaard et al., (1997) have shown that a distinct tidal modulation of rip velocity exists, with maximum rip flows occurring at low tide and minima at high tide; ii) this study has shown that the sediment transport rate increases with increasing mean rip velocity; and iii) low-energy intermediate beach state evolution, from a longshore bar-trough and rip state through to a transverse bar and rip state, is characterised by an overall increase in rip current velocity (Brander, 1997; Wright and Short, 1984). These findings imply that sediment transport in rip current channels is maximised at low tide and increases through the course of low-energy beach and rip state evolution.

The different roles of waves and currents on sediment transport in low-energy rip currents does, in fact, provide a partial explanation for the patterns of morphological evolution observed during PB1 (Figure 2). Sediment entrainment in the feeder channel is minimised at low tide (Figure 4d) largely due to enhanced wave breaking and dissipation across
Figure 8. a) Total sediment transport rate \(i_t\) as a function of mean rip-neck velocity \(u_n\). Data values represent all of the sediment trap runs made during PB2. The regression line corresponds to a linear function \(R^2 = 0.83\) of the form: \(i_t = 27.6u_n + 0.92\); and b) The variation of total sediment transport rate \(i_t\), mean rip-neck flow velocity \(u_n\), and wave height \(H_{\text{rms}}\) with changing water depth for all sediment trap runs during PB2. The time axis is converted to hours relative to low tide and linear least squares regression lines are used to illustrate trends.

The nearshore bars inhibiting wave motions in the feeder channel, thereby reducing values of \(\theta_n\). Despite stronger flow velocities in the feeder at low tide due to tidal modulation, the potential for overall transport is nevertheless inhibited by the lack of sediments entrained. At high tide, wave dissipation is reduced, waves propagate across the feeder channel, and values of \(\theta_n\) (Figure 4c) are maximised. However, flow velocities in the feeder are minimised at high tide and were on the order of 0.1 m s\(^{-1}\) in this study. Therefore, net transport would again be inhibited.

Entrainment in the rip-neck is markedly different than in the feeder with \(\theta_n\) maximised at low tide and minimised at high tide (Figure 4c, d). Since flow velocities are also maximised at low tide, net offshore transport of sediments in the rip-neck channel would be extremely large. Although the flow decreases towards high tide, velocities in the rip-neck are still relatively strong (\(=0.4\) m s\(^{-1}\)) and despite smaller values of \(\theta_n\), net offshore transport would still be significant. Therefore, transport in the rip-neck occurs at all times during the tidal cycle.
Given that net transport out of the feeders was inhibited at all times and net offshore transport in the rip-neck was promoted at all times, it is not surprising that the feeder channels were characterised by overall infilling and the rip-neck by overall incision during the morphological evolution observed during PB1 (Figure 2). These patterns are best illustrated in Figure 10, which shows the net surf zone bed elevation change between longshore bar, feeder and rip morphology on 18/4/96 (Figure 2a) and transverse bar and rip morphology on 23/4/94 (Figure 2f). Both the infilling of the northern feeder and the erosion of the rip-neck channel are clearly indicated and BRANDER (1997) found that accelerated rip-neck channel incision coincided with an overall increase in $u_0$, from 0.4 ms$^{-1}$ to 0.6 ms$^{-1}$ at the onset of transverse bar and rip morphology. This observation is supported by the dependence of sediment transport rate on rip current velocity found in this study (Figure 8a). The rip-neck channel would only start to infill once $\theta_c$ became significantly reduced. During low-energy rip evolution, this would most likely occur during low-tide terrace and rip morphology where dissipation of waves across the transverse bars is dominant throughout the surf zone. In fact, the period between 23/4 and 24/4/94 was characterised by infilling of the rip channel as the system attained incipient low-tide terrace and rip morphology (Figure 2f).

Although WRIGHT (1987) suggests that use of the Bagnold approach within the surf zone is convenient, but an oversimplification of a more complex system, it nevertheless provides a sound conceptual basis describing sediment transport in low-energy rip currents. Analyses using the Shields parameter as a surrogate for the amounts of sediment entrained support this concept quantitatively and the strong dependence of $i_e$ on $u_0$, found in this study (Eq. 7) provides additional quantitative justification since BAGNOLD'S (1965, 1966) unidirectional sediment transport model related both bedload and suspended load transport to $u^3$.

**SUMMARY AND CONCLUSIONS**

The results of this study have added significantly to our knowledge of basic sediment transport characteristics operating within low-energy rip current channels. Time-averaged sediment flux was found to increase with increasing current velocity and decreasing depth suggesting that maximum
transport is associated with the fastest flowing rips at low tide. Sediment flux was also found to increase offshore in the rip channel and of the sediments transported in the rip channel, 50% were transported very close to the bed with the grain size of the material fining upwards in the flow. Total sediment transport rates were a direct function of \( \dot{u}^2 \), suggesting that a Bagnold-type approach may be suitable for modelling of unidirectional transport in rips. This was supported by the finding that wave motions are more important in entraining sediments than steady currents, but that transport in the rip is driven by the currents. The relative roles of waves and currents in rip sediment transport also provide a conceptual explanation for infilling of the feeder channel and incision of the rip-neck channel observed during a sequence of low-energy beach state evolution. The nature of this study is, however, unique in the literature and further research is clearly needed to both verify and expand upon the findings presented in this paper.

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