Rip Currents and Their Causes

by

Robert A. Dalrymple[1]

Introduction

"The outworn dogmas of science seem to be particularly concentrated in the discussions of the ocean in geology books". Beginning with this controversial statement, F. P. Shepard in 1936 tried to lay to rest the concept of the undertow, which had been debated in the pages of Science for over a decade. At the same time, he introduced the term, rip current, to describe the rapidly seaward-flowing currents, which were well-known to lifeguards at that time, as these currents were responsible for carrying swimmers offshore at frightening speeds.

Subsequent studies by Shepard and his colleagues (Shepard, Emery and LaFond, 1941; Shepard and Inman, 1950a, 1950b) showed that rip currents (1) are caused by longshore variations in incident wave height, (2) are often periodic in both time and in the longshore direction and (3) increase in velocity with increasing wave height. The major reason put forth to explain the variation in wave height was the convergence or divergence of wave rays over offshore bottom topography (such as submarine canyons) or the forced wave height variability caused by coastal structures, such as jetties.

McKenzie (1958) and Cooke (1970) in their studies corroborated the findings of the Scripps Institution of Oceanography researchers and also pointed out the persistence of rip currents (once high energy waves in a storm had caused rip channels to be cut into the bottom) after the storm had abated. In fact it appears that on coastlines which are affected by major storms which build offshore bars, that the nearshore circulation may be dominated by the storm-induced bottom topography for long afterwards.

The researchers up to the late 1960's who attempted to theoretically model rip currents knew the importance of longshore wave height variability and the wave-induced set-up in the formation of rip currents, but it was not until Longuet-Higgins and Stewart (e.g., 1964) codified the wave momentum flux tensor that great strides were made in providing models for rip currents.

This paper is intended to categorize and review the more recent theories for rip current generation and to discuss a simple model for rip currents on barred coastlines.

[1]Associate Professor, Department of Civil Engineering, University of Delaware, Newark, Delaware, U.S.A. 19711

Theoretical Approaches

The various mechanisms proposed to date to explain rip currents can be conveniently placed into two categories: (1) wave interaction and (2) structural interaction. The distinction between the two is that the first category mechanisms can occur on uniformly planar beaches (having no longshore variability), while the second group cannot. Table I lists the categories and the candidate theories within each.

Table I. Rip Current Mechanisms

Wave Interaction Models	Primary Investigators
Incident-edge wave	
Synchronous	Bowen (1969), Bowen and Inman (1969)
Infra-gravity	Sasaki (1975)
Intersecting wave trains	Dalrymple (1975)
Wave-Current Interaction	LeBlond and Tang (1974), Dalrymple and Lozano (1978)
Structural Interaction	
Bottom Topography	Bowen (1969), Noda (1974)
Coastal Boundaries	
Breakwaters	Liu and Mei (1976)
Islands	Mei and Angelides (1977)
Barred Coastlines	Dalrymple, Dean and Stern (1976)

Wave Interaction Models - The first theory in this category is the incident/edge wave interaction model proposed by Bowen (1970), Bowen and Inman (1970) and independenly by Harris (1967). This model requires the intersection of synchronous edge waves (traveling along the shore) and the incident wave field to provide the longshore variability of wave heights. The synchronous edge wave forces a nearshore circulation with a longshore periodicity, L_r, equal to the edge wavelength, L_e,

$$L_r = L_e = L_o \sin\{(2n + 1)\beta\} \tag{1}$$

where $L_o = gT^2/(2\pi)$, the deep water wavelength, g the acceleration of gravity, β is the beach slope and n is the offshore mode number of the edge wave. Clearly the rip current spacing depends strongly on the incident wave period. (Surprisingly, some of Harris' laboratory experiments (Mark II) show no period effects). The length of the rip spacing has a maximum of L_o, for the case of very steep beaches and/or high mode edge waves. Often, however, for many beaches, such as Silver Strand (see Bowen and Inman (1970)) and the East coast of the U.S., L_r exceeds L_o, or else very high mode numbers are required for Eq. (1), Tait (1970). The origin of synchronous edge waves could be reflection of the incident waves by a structure or headlands or through a nonlinear resonance, but Guza and Davis (1974), theoretically, and Guza and Inman (1975) and Harris (1967), experimentally, showed that the most likely resonant edge wave is the subharmonic edge wave, which does not produce rip currents. A further restriction on the model is that the shoreline must be reflective, requiring the waves to be non-breaking. Guza and Inman (1975) have proposed the requirement for the existence of edge waves as

$$\varepsilon = \frac{a_i \sigma^2}{g \tan^2\beta} = \left(\frac{2\pi H_o}{L_o \tan^2\beta}\right) \leq 2 \qquad (2)$$

Note that this parameter, ε, is directly relatable to the parameter proposed by Irribarren and Nogalles (see Battjes, 1974).

For surf zones, characterized as dissipative ($\varepsilon > 2$), which would have a significant width, Bowen and Inman hypothesized that longer period edge waves and surf beat could perhaps interact to cause the longer rip spacings, $L_r > L_o$. Sasaki (1975), noting that there is significant energy in the surf zone at low frequencies (Suhayda, 1975; Huntley, 1976) recommended an empirical equation for the case of infra-gravity waves

$$L_r = 1.27 \times 10^{-2}\ \varepsilon \qquad (3)$$

For cases other than those used by Sasaki, Bruno and Dalrymple (1978) found an apparent linear trend with ε, but for small ε. Additionally the slope of the line was different than that in Eq. 3.

Dalrymple (1975) and Dalrymple and Lanan (1976) generalized the edge/incident wave model to show that rip currents and beach cusps are produced by intersecting synchronous wave trains. The periodic spacing of the rip current is

$$L_r = \frac{L_o}{(\sin \Theta_o - \sin \zeta_o)}$$

where Θ_o, ζ_o are the deep water angles of incidence made between the wave rays and the beach normal. This model has no theoretical maximum for L_r but has a minimum spacing of $L_r = L_o/2$, thus there is a small region of overlap between the edge wave and the intersecting wave model. While it is clear that this model will generate rip currents when the incident wave field is reflected back on itself or when refraction or diffraction is strong, it is not known what percentage of the time this mechanism is valid on a plane beach when two different synchronous wave systems would have to be present.

A third class in the wave-interaction category is the wave-current interaction models, which have been stimulated by the observations of Arthur (1950, 1962), Harris (1967) and others that rip currents can cause strong refractive effects on the incident wave field.

The concept is that for normally incident waves, the basic state is one of uniform setup along the beach with no nearshore circulation; however, as the investigators of this class of models have discovered, there are other modes that are also possible, which do yield rip currents. LeBlond and Tang (1974) investigated the possibility that the interaction of the nearshore currents and the wave energy would cause a feedback mechanism and a preferential spacing for rip currents. Iwata (1976) used a similar approach; but, as pointed out recently by Dalrymple and Lozano (1978), these models did not predict rip current spacings. Mizaguchi (1976), unable to get rip currents with a fixed bottom friction, introduced an arbitrary variation in the friction coefficient and was able to predict rips; however, the assumed variability in f was somewhat arbitrary. Dalrymple and Lozano (1978) showed that only when the effects of incident wave refraction by the outgoing rip currents are included can a model similar to LeBlond and Tang's predict a rip current spacing. The non-dimensional rip current spacing, $\lambda X_b \equiv 2\pi X_b/L_r$, (where λ is the longshore wave number for the circulation and X_b is the surf zone width) is expressed as a function of the parameter A_D = (tan $\beta\kappa\pi/8f$) where κ is the breaking index, O(1), which relates the breaker height to the water depth and f is a Darcy-Weisbach (constant) friction coefficient. This result can be approximated as

$$\lambda X_b \cong \frac{1}{A_D} + 2.8 \qquad (4)$$

Note that this result yields an increase in L_r with wave height as X_b directly proportional to H_b, the breaking wave height. The solution obtained by Dalrymple and Lozano was for a beach characterized by a flat sloping surf zone bottom and a flat offshore; the discontinuity in slope at the breaker line caused the development of two circulation cells, one wholly contained within the surf zone and one which extends across the breaker line. Despite this, the results appear to follow the trend of LEO observations, taken by the Coastal Engineering Research Center, with a great deal of scatter (Bruno and Dalrymple, 1978).

A key assumption included in these theories is the manner in which energy dissipation is modelled in the surf zone at each order of the perturbation. For the above studies it was assumed that the form of energy dissipation corresponds to that necessary to give $H = \kappa d$ at the basic state (LeBlond and Tang, 1974), that the relationship between H and d is true for all order of perturbations (Dalrymple and Lozano, 1978) or there is no dissipation beyond the basic state (Iwata, 1976). Recently Miller and Barcilon (1978) have used a hydraulic jump analogy to develop a form for energy dissipation. Their results yield an approximate formula (for their B = 32 case)

$$\lambda X_b = 0.03/A_D + 0.6 \qquad (5)$$

This result is far smaller than most field observations. Until more studies are made for energy dissipation in the surf zone, no real progress can be made using these techniques.

Another problem that hampers this area of research is the inability to study the instability mechanisms; for example, a small perturbation in the basic state. Since the governing equations have been time averaged (over a wave period), only slowly evolving instabilities can possibly be studied. As yet, even this problem has not been solved.

Finally, Hino (1974) has proposed a model for coastal instability based on a feedback between the deforming bottom and the flow field. His model yields approximately a constant spacing

$$\lambda X_b \cong \pi/2 \tag{6}$$

Significant work still needs to be done in this area.

Boundary Interaction Models - This category of models probably accounts for the majority of rip currents observed on coastlines. As mentioned, the early researchers discerned that longshore variability in the bottom topography would cause rip currents to form. If the bottom variability is periodic in the longshore direction, then periodic nearshore circulation cells may form. The first theoretical model for this case was put forward by Bowen (1969). Numerical and analytical extensions of his work to various bottom bathymetries have verified the basic forcing of the nearshore circulation due to the bottom topography's effect on the wave field, e.g., Sonu (1972), Noda (1974), Noda et al. (1974), Birkemeier and Dalrymple (1974) and Mei and Liu (1975). All of these models have utilized linearized models in the sense that the wave field has been characterized by linear water wave theory and the mean equations for the nearshore currents do not include the convective acceleration terms.

In addition to bottom topography, the presence of man-made or natural lateral barriers influence the nearshore circulation also. Dalrymple, Eubanks and Birkemeier (1977) studied the circulation interior to rectangular basins, such as a harbor or, in particular, laboratory wave basins. Liu and Mei (1976) in a series of two papers examined the wave field and the nearshore circulation in the vicinity of breakwaters both shore-connected and detached. Mei and Angelides (1977) examined the wave-induced flow around a circular island, considering refractive effects alone. This problem of circulation around structures is still one that requires a significant amount of study, particularly in determining the wave field in the regions surrounding structures, that not only partially reflect and diffract the waves, but also serve as significant energy sinks. Laboratory studies of structures and the effect on the nearshore circulation have been conducted by Gourlay (1976).

The case of incident waves encountering longshore bars and the associated nearshore current field has been largely neglected in the literature. While the presence of rip channels in bars has been recognized in longshore current formulae, e.g. Inman and Bagnold (1963) and Bruun (1963), efforts to develop nearshore circulation models in this case are hampered by an inability to correctly predict the wave field over the longshore bar. Recently, Dalrymple, Dean and Stern (1977) indicated that, in addition to the usual continuity assumptions (that is, the mass transport of water over the bar must equal the flow in the rip current), wave reflection from the submerged sand bar provides an important forcing for the circulation system. Since that work has not been clearly expounded upon, a similar approach is presented here for normally incident waves on a bar.

Currents on a Barred Shoreline

The model primarily is presented to examine mean currents behind a longshore bar, including the effect of wave reflection from the bar. There are three equations necessary for the model. The first is the continuity equation, which relates the onshore flow over the bar to the increase in flow in the longshore trough, between the bar and the beach.

$$Uh_b = h_t w_t \frac{\partial V}{\partial y} \tag{7}$$

where U is the vertically and time-averaged in-flow, including the mass transport, h_b is the mean depth over the bar, h_t and w_t are the mean depth and the width of the trough, and V(y) is the cross-sectionally and time-averaged longshore current. Figure 1 illustrates the geometry. The second equation is the equation of motion within the trough.

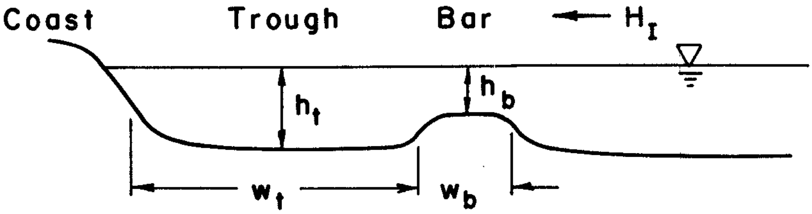
$$V \frac{\partial V}{\partial y} = -g \frac{\partial \bar{\eta}}{\partial y} - \frac{f_t U_{m_t} V}{4\pi h_t} \tag{8}$$

where $\bar{\eta}(y)$ is the mean water level within the trough measured from the still water level. The bottom friction term is of the form developed by Longuet-Higgins (1970) for weak currents (see Liu and Dalrymple, 1978, for a generalization for strong currents), U_{m_t} is the wave-induced water particle velocity over the trough.

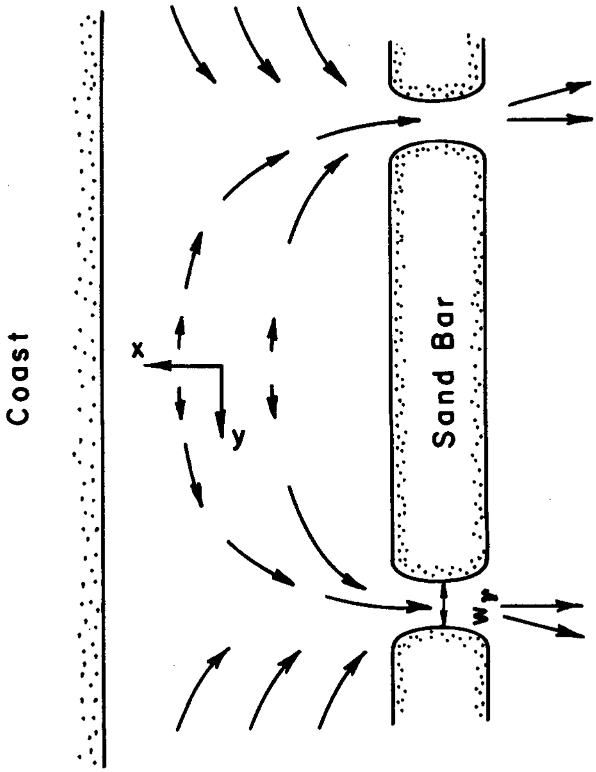
$$U_{m_t} \approx \frac{H_t \sqrt{gh_t}}{2\, h_t} \tag{9}$$

and f_t is the Darcy-Weisbach friction factor in the trough.

The final equation is the onshore/offshore momentum equation, which includes the mean excess momentum flux due to the presence of the waves (the radiation stresses), denoted S_{xx}, as well as the force exerted on the submerged bar by the waves. The basic premise here is that the portion of the incident wave reflected by the bar induces a force as its momentum flux has been reversed. This force is provided by the reaction force of the bar but also by a set-up of water inside the bar (Longuet-Higgins, 1967) or bottom friction across the bar. The set-up of water, which only exists where the bar is reflecting waves and which is much smaller where the rip channel exists, provides the longshore variation in water level to drive the longshore flow. Therefore, the force balance on each side of the bar is



ELEVATION



PLAN

Fig. 1

$$S_{xx,I} + S_{xx,R} + \frac{1}{2}\rho g h_t^2 - F = S_{xx,T} + \frac{1}{2}\rho g (h_t + \bar{\eta})^2 + \tau_b \omega_b \qquad (10)$$

where the subscripts on the radiation stresses denote incident, reflected and transmitted, F is the mean wave force on the bar and $\tau_b\omega_b$ is the shear force exerted on the bar.

If the longshore bar is uninterrupted by rip channels, then the set-up, $\bar{\eta}$, would be uniform in the longshore direction and will be denoted as $\bar{\eta}_p$, where the subscript p indicates the potential set-up. For this case the friction term would be absent (no flows over the bar) and F can be determined (Longuet-Higgins, 1976). If, on the other hand, rip channels exist and $\bar{\eta}$ is drawn down below the $\bar{\eta}_p$ level necessary to provide the force balance, then a shear stress is developed by an inflow across the bar. Therefore, if we define

$$\bar{\eta}_D = \bar{\eta}_p - \bar{\eta} \qquad (11)$$

where $\bar{\eta}_D$ is the deficit in the set-up between the maximum potential set-up and the actual set-up, η, and substituting into the previous equation, we have remaining,

$$\rho g h_t \bar{\eta}_D = \tau_b \omega_b \qquad (12a)$$

or

$$\rho g h_t \bar{\eta}_D = \frac{f_b U_{m_b}}{2\pi} (U - \tilde{u}) \omega_b \qquad (12b)$$

where the mean flow is reduced by mass transport velocity, $\tilde{u}$, which does not contribute to the bottom friction (Iwata, 1970).

Using the last equation and the continuity equation, $\bar{\eta}_D$ may be eliminated from the longshore equation of motion, with the assumption that the geometry is fixed and all second order terms may be neglected (including the convective acceleration terms), leaving

$$\frac{d^2V}{dy^2} - \gamma^2 V = 0 \qquad (13)$$

and

$$\gamma^2 = \left(\frac{f_t \, U_{m_t} \, h_b}{2 f_b \, U_{m_b} \, h_t \, \omega_b \omega_t}\right) \qquad (14)$$

A solution to this equation, which is zero at y = 0, the midpoint between two rip channels, is

$$V = V_m \frac{\sinh \gamma x}{\sinh\left(\frac{\gamma \ell}{2}\right)} \qquad (15)$$

where V_m is the maximum of V which is assumed to occur at $\ell/2$, the location of the rip channel. The distance ℓ is the longshore length of the bar.

The deficit, $\bar{\eta}_D$, can be found from the linearized Eq. (8), subject to the condition that $\bar{\eta}_D = 0$ at x = 0.

$$\bar{\eta}_D = \frac{f_t\, U_{m_t}\, V_m(\cosh \gamma x - 1)}{4\pi g h_t \gamma \sinh\left(\frac{\gamma \ell}{2}\right)} \tag{16}$$

and also, from the continuity equation,

$$U = \frac{\gamma h_t \omega_t\, V_m \cosh \gamma x}{h_b \sinh\left(\frac{\gamma \ell}{2}\right)} \tag{17}$$

The V_m can be found from the bottom stress, Eq. (12b), to yield

$$V_m = \left(\frac{h_b}{h_t \omega_t}\right)\frac{\tilde{u}}{\gamma} \sinh\left(\frac{\gamma \ell}{2}\right) \tag{18}$$

Thus

$$V = \frac{\tilde{u}\, h_b}{\gamma h_t \omega_t} \sinh \gamma y \tag{19}$$

For small y, the longshore current V can be approximated as

$$V = \frac{\tilde{u}\, h_b}{\omega_t h_t}\, y \tag{20}$$

which indicates initially the longshore current increases due to the inflow over the bar by mass transport. However, as the mean water level drops from its potential value at y = 0, the inflow U increases above the $\tilde{u}$ value.

$$U = \tilde{u} \cosh \gamma y \tag{21}$$

Further

$$\bar{\eta}_D = \frac{f_b\, \omega_b\, U_{m_b}\, \tilde{u}(\cosh \gamma y - 1)}{2\pi g h_t} \tag{22}$$

The flow out of the rip channel is

$$U_r = \frac{2V\, \omega_t h_t}{\omega_r h_r}$$

by continuity considerations, where the r subscripts refer to rip variables.

It is expected that the maximum upper limit for $\bar{\eta}_D$ is $\bar{\eta}_p$; that is, $\bar{\eta} = 0$, which would occur at $y = \ell/2$. With this upper limit, an estimate may be made for ℓ. For the case of no wave breaking over the bar, Longuet-Higgins (1965) showed

$$\eta_p = \frac{\alpha E}{\rho g h_t}$$

where $\alpha = (1 + K_r^2 - K_T^2)$, where K_r and K_T are the reflection and transmission coefficients. For other cases, where breaking occurs on the bar, $\bar{\eta}_p$ would be larger.

Since $\tilde{u} = E_b/(\rho C_b h_b)$ and $U_{m_b} = \kappa\sqrt{gh_b}/2$, we can write Eq. (22) as

$$\frac{2\pi g h_t \bar{\eta}_p}{f_b\ \omega_b\ U_{m_b}\ \tilde{u}} = \cosh\left(\frac{\gamma\ell}{2} - 1\right) = 2\ \sinh^2\left(\frac{\gamma\ell}{4}\right) \tag{23a}$$

or

$$\frac{\pi\alpha h_b}{f_b\ \omega_b\ \kappa\beta} = \sinh^2\ \frac{\gamma\ell}{4} \tag{23b}$$

where β relates E_b to $E_{incident}$.

Finally

$$\ell = \frac{4}{\gamma}\ \sinh^{-1}\left(\sqrt{F\ \frac{h_b}{\omega_b}}\right) \tag{24}$$

where F is a constant, of order (125).

$$F = \frac{\pi\alpha}{f_b\kappa\beta}$$

Now, h_b can be related to H_b by the breaking index κ and ω_b is presumed to be a fixed fraction of the wavelength $\omega_b \sim \mu L$, therefore

$$\ell = \frac{4}{\gamma}\ \sinh^{-1}\ \sqrt{\frac{F}{\mu\kappa}\left(\frac{H_b}{L}\right)}$$

Recall from Eq. (14)

$$\gamma = \sqrt{\frac{f_t}{2f_b}\ \frac{U_{m_t}}{U_{m_b}}\ \frac{h_b}{h_t}\ \frac{1}{\omega_b\omega_t}} \approx \varepsilon\ \frac{1}{L}$$

where $$\varepsilon = \left(\frac{f_t}{2f_b}\,\frac{\omega_b}{L}\,\frac{\omega_t}{L}\left(\frac{h_b}{h_t}\right)^{1/2}\right)^{1/2}$$

assumed to be a constant.

From the preceding results and assumptions, it is logical to expect the dimensionless rip spacing (ℓ/L) to be related to the wave steepness, H/L, with some effects due to sediment characteristics (f). It remains to be proven whether this is in fact true; however, laboratory experiments to date have shown (1) gaps in bars to produce longshore and rip currents and (2) there is a longshore gradient in water surface slope as predicted by the theory.

A significant assumption is the neglect of the convective acceleration terms which certainly play a role, particularly in the deceleration in the base of the rip current. Another critical assumption is the neglect of wave-current interaction which plays an important role in varying the wave direction offshore of the rip channel and in the longshore trough.

Conclusions and Recommendations

In the fifty years that rip currents have been the study of coastal engineers and scientists, numerous theories have been proposed to explain their occurrence. Most of these theories have appeared in the last ten years and yet, owe their origin to different mechanisms. These theories can be grouped into two broad generic categories, the wave-interaction models and the boundary interaction models. Of the various theories within each group, it is not yet entirely clear during which percentage of time they may occur for a particular coastal type or wave climate, if they occur at all. This question, which, of course, bears on the validity of the various theories, must be addressed by field observations of nearshore circulation for many coastal types. Some work has been undertaken in this area (Sonu, 1972, Fox and Davis, 1974 and Allender, *et al.* in this volume), yet more detailed and thorough studies remain to be conducted, to include all relevant variables and many coastal geometries.

Significant research needs to be conducted to provide a general model for the shoaling, refraction and diffraction of water waves, so as to provide a unifying basis on which a general model can be built.

Finally the hydrodynamics must be melded to the sediment transport, in order that the feedback mechanism of bottom topographic changes can be incorporated into the models. This development would provide the bridge between the two classifications of rip currents, thus allowing a model of the wave-interaction category to develop perturbations in a previously planar bottom, which would then force a reinforcing circulation of the boundary interaction type.

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