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Rain Waves vs Swash-Zone Ripple Marks: Why Are They Mutually Exclusive?[1]

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ABSTRACT

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Rain waves are well-organized, geometrically more-or-less perfect asymmetrical waves which are commonly found on smooth gently-sloping surfaces (such as sidewalks and streets) immediately after a rain. Swash-zone ripple marks are made by paired sets of hydraulic jumps on gently-sloping beaches during the arrival of medium-to-long period waves. These hydraulic jump sets are formed, and maintained, during the backwash, rather than during the swash, and therefore appear under conditions superficially similar to those responsible for rain waves: gentle slope, smooth or almost-smooth surface, and gravity flow. Yet the two are markedly different, and almost never co-exist. Rain waves form where discharge is steady and also large enough to produce above the wall layer a discontinuous sheet (moving ripples), but not large enough to close the gaps in the discontinuous sheet. The product of "water depth" and "velocity" (hv) has the smallest possible numerical value. Swash zone hydraulic jumps appear where the discharge is increasing (downslope) and also is too large for the sheet of moving water above the wall layer to break down into discontinuous strips (rain waves). The product "hv" is far above the minimum, perhaps by a factor of 5 to 10. Rain waves, as far as is known, do not deform the sand surface, and therefore do not leave recognizable marks on that surface. The paired hydraulic jumps, formed during the backwash, make (and maintain) swash zone ripple marks, bedding plane features so subtle that even specialists might fail to note them.

ADDITIONAL INDEX WORDS: *Backwash, beach, Froude number, hydraulic jump, rain wave, ripple mark, swash zone, wall layer.*

THE PROBLEM

The rain wave (MAYER, 1957; KOLOSEUS and DAVIDIAN, 1966) is a naturally occurring phenomenon, during sheet flow, on more-or-less smooth, gently sloping surfaces such as dirt roads and paved areas (sidewalks, streets, and parking lots). It has also been observed, in a few very wide, shallow streams, such as Médano Creek, in Great Sand Dunes National Monument, near Alamosa, Colorado, U.S.A. Rain waves have almost perfect and regular asymmetrical geometrical form and a steady velocity. They are not known to devleop on grass or other similarly rough surfaces.

Swash zone ripple marks (TANNER, 1977) are produced, naturally, in the backwash on certain beaches, where a system of paired hydraulic jumps creates, in the sand, long more-or-less parallel, more-or-less symmetrical ripple marks. Once the system has been created, the hydraulic jumps are fixed in position, even though water is flowing through them. Between swash and backwash, or after the tide has dropped significantly, the swash zone ripple marks are visible in the sand, although their relief is vanishingly small.

Both features can be seen in what appears to be a single environment: sheet flow, over rather smooth surfaces. Yet there are sharp differences. Rain waves *do* migrate, and do *not*, as far as is known, produce ripple marks. Swash zone hydraulic jumps do *not* migrate, and *do* form ripple marks. The problem that arises can be stated as follows: How is it that two different processes operate in this environment so that two different features are formed (rain waves; paired hydraulic jumps)?

It should be noted here that, until this project was undertaken, no hydraulic jumps had been seen in

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the presence of a well-developed set of rain waves, and rain waves had been noted only rarely in the swash zone. It is now possible to confirm this statement: There are only a few minor exceptions to the observation that the two do not form during the same study interval, at the same place. The exceptions are essentially insignificant, and one can say that the two are, for practical purposes, mutually exclusive.

Methodology and Observations

Natural Rain Waves

Natural rain waves were observed on sloping paved surfaces immediately after the rain stopped. They formed several meters (2 to 5) downslope from the source of water, and their presence depended on the rugosity of the surface. Where rugosity was too high, rain waves were not present. Instead, very irregular and chaotic waves were observed, disturbed by eddies and von Karman vortices derived from the irregularity of the surface.

On relatively smooth surfaces, long-crested, almost straight, asymmetric rain waves were formed, with a wavelength between 28 and 48 cm, period 0.8 to 1.5 sec. and wave height 1 mm to 1 cm.

In the accompanying table of data (Table 1), the letters a, b, c, and d, indicate the places of observation; the results vary because conditions are different for each observation; slope, roughness, and discharge vary from place to place, and, for the same place on two separate occasions, discharge was not the same.

The important conclusion is that Q/w, ***F*** and velocity have a narrow spread of values, that is, it is possible to define rain waves in terms of these parameters (Q = discharge, w = width, ***F*** = Froude number).

Rain Waves in Laboratory Experiments

Smooth Surface (rugosity was zero). Laboratory experiments were carried out on a varnished board, 1.70 x 0.30 m, with a source of water having adjustable discharge. Experiments were made under different conditions of slope and discharge. Observations indicated that in the first meter from the source, water flowed as a single lamina; then it started forming very irregular waves, that rapidly coalesced into parallel, short-crested, slightly curved rain waves, with a wavelength of 16-22 cm, period 0.3 to 0.5 seconds and wave height about 0.1 cm (Table 2).

Measurement of the velocity with a float was difficult: the very small depth caused the float to be stranded. The float was always carried away if located on the wave crest, which is in the deepest part of the water mass, but when the float got wet, it sank and dragged on the bed. For that reason, calculations of ***F*** and Q/w were always based on the wave front velocity.

Different values of Q/w for different observations, with the same slope, were caused by variations in the discharge, which was allowed to change between 85 and 200 cm^3 per sec.

Rough Surface. Observations were made on the same board but now covered with glued sand, to approach those conditions occurring on natural rough slopes.

First, the board was coated with medium sand in a layer about 2 to 3 sand grains thick. Despite many experiments, it was never possible to get rain waves, even with a lot of different conditions of discharge and slope. Roughness apparently was too large, so the medium sand was changed to a very fine sand. Again, rain waves were not formed. An additional observation was made by covering the glued sand with a layer of loose sand. Rain waves were not formed, but it was observed that despite the fact that water was running as a smooth layer, sand did not move, except where water became channeled. Additional experiments were run, with only the last

Table 1. Natural Rain Waves.

Slope	i	Q/w	h(cm) depth	V float cm/s	V wave cm/s	length cm	T Sec	Froude	Observations
a	8°	8.88	0.2	44.4		36	0.81	3.17	R.W.
	8°	24	0.4	60		46.8	0.78	3.03	R.W.
b	4°	30.3	0.5	60.6				2.74	†
	4°	65	1	65		48.7	0.75	2.08	R.W.
c	1°	2.38	0.1		23.8	36	1.5	2.41	R.W.
d	1°	6.36	0.2	31.8		28	0.9	2.27	R.W.
e	1°	2.62	0.1		26.2	32	1.2	1.87	R.W.
f	1°	6.46	0.2	32.3		29	0.9	2.31	R.W.

† No rainwaves; roughness too high.

Table 2. Rain Waves in Laboratory Experiments: Smooth Surface.

i	Q/w	h cm	V float cm/s	V wave cm/s	length cm	T sec	Froude No.
9°	5.6	0.1	54	56	16.8	0.3	5.6
8°	6.1	0.1	56	61	21.3	0.35	6.16
8°	5.5	0.1	55	55	16.5	0.3	5.55
8°	4.3	0.1	43			43	4.34
*8°	5	0.1		50	17.5	0.35	5.05
5°	5	0.1	45	50	20	0.4	5.05
5°	3.3	0.1	33	33	16.5	0.5	3.33
*4°	3.7			37.5	16.90	0.45	3.79
3°	2.8	0.1	28	28			2.83

30 cm of the board coated with sand, leaving the upper 1.40 m in its original smooth condition (without sand), to allow the rain waves to be formed before they reached the rough surface.

Rain waves were obsrved to form on the smooth surface (these data are included in Table 2 marked with an asterisk). When the waves reached the rough surface, a transition zone was observed where the water velocity decreased, producing on one hand a spilling of water over the sides of the board, but on the other hand, a slight increase in depth. These changes produced a decrease in the velocity of the wave front of about 12 to 14%. The wavelength remained constant whereas the wave period increased.

In the case indicated with an asterisk it was possible to make careful observations and to estimate the velocity in the wall layer, on the very surface where rain waves move (Tables 3 and 4). To do this a wax paper float was used at first; because it never got wet, it always floated on the water surface.

This experiment was totally successful only twice, and probably lacks great precision, but at least it gives an idea of the velocity in the wall layer.

Rain Waves on the Beach

Rain waves were observed on the beach only a few times, as very tiny ones in the upper swash zone, after the backwash had retreated almost completely seaward. They were seen only when the period of the incoming wave was large enough to let the backwash retreat down slope completely and leave the beach exposed for a relatively long period of time (during which rain waves developed), before the next swash advanced up the beach.

Rain waves were parallel, asymmetric, slightly convex downslope, with wavelength about 6 to 10 cm (increasing downslope), wave period about 0.4 to 0.8 seconds and wave height about 0.1 cm (Table 5). Although in the laboratory experiments they were observed to be formed after a certain distance (they needed several tens of centimeters to start forming), on the beach they formed almost immediately after the water movement started. They were followed by rhomboidal "ripple-mark" formation.

Characteristics of swash and backwash were also measured (Table 6). Cases indicated as (a) and (b) in the tables correspond to the same moment in time (Tables 5 and 6).

Table 3. Rain Wave in Laboratory Experiments: Rough Surface.

i	Q/w	h cm	V wave cm/s	Length cm	T Sec	Froude No.
8°	6.3	0.15	42	15.5	0.42	3.47
6°	5.6	0.15	37.5	17.3	0.46	3.09
4°	5	0.15	33.3	16.9	0.51	2.75

Table 4. Rain Waves in Laboratory Experiments: Rough Surface.

i	Q/w	h cm	V cm/s	V wave cm/s	V trough cm/s	Froude No.
4°	5	0.15		33.3		2.75
	2.14	0.1	21.4			2.16
	0.47	0.05			9.5	1.36

Table 5. Rain Wave on the Beach.

i	Q/w	h cm	V float cm/sec	V wave cm/sec	Length cm	T Sec	Froude No.	Wave Conditions H cm	Wave Conditions T Sec
(a) 7°	2.5	0.1		25	6-10	0.4	2.53	20	6-8
(b) 5°	1.12	0.1		11.7	6-10	0.8	1.18	10	1-1.5

Table 6. Characteristics of Swash and Backwash.

	Swash				Backwash				Wave Conditions	
i	Q/w	h cm	V float cm/s	Froude No.	Q/w	h cm	V float cm/s	Froude No.	T Sec	H cm
6°	568.8	7.9	72	0.82	325.5	4.2	77.5	1.3	1-2	
5°	175	2	87.7	1.98	89.3	1	89.3	2.85	3	40
5°	626	5	125	1.79	373	5	74.6	1.07	3	40
(b) 5°					60	1	60	1.92	1-1.5	10
(a) 7°	249	3	83	1.53	86	1	86	2.75	6-8	20

The Froude Number in the Swash Zone

Observations made by TANNER (1977) indicated that the Froude number was either larger or smaller than 1 for the swash process, in most cases being <1. For the backwash it was always >1 except over the swash zone ripple mark troughs, where it dropped below 1. Rain waves on sidewalks and streets, and also in laboratory experiments, had $F > 1$.

Observations made in the present study (Table 6) indicate that F was generally greater than 1, varying between 0.82 and 1.92 for the swash process, and always greater than 1, between 1.07 and 2.85, for the backwash. Except in one case, F in the backwash was always greater then F in the swash for the same set of observations, because of decreased water depth during the backwash with respect to the swash. This is due to the acceleration which occurs during the backwash, leading to a decrease in depth, contrary to the swash, which is decelerated.

Depth in the backwash is estimated to be about one half or one third less than in the swash. In the exceptional case (F was greater in the swash), water depth was the same for both processes and therefore the determinant factor was either the water velocity, or an error in measurement.

Rain waves on non-permeable outdoor surfaces (sidewalks, paved streets) as well as those observed in laboratory experiments, showed F values slightly higher than those showed by rain waves on beaches. Although the number of observations is not large enough to compare them, one difference should be established: rain wave history on the beach is discontinuous; that is, it depends on the amount of water left on the beach surface after the backwash. At a given point, the volume of water decreases as rain waves travel downslope, and these waves quickly disappear (when no more water is available). The history of natural rain waves or rain waves produced in laboratory experiments is continuous, because the water source is always delivering a constant discharge.

Roughness is the most important factor in regulating the characteristics of rain waves. Rain waves on rough surfaces showed values of F between 1.18 and 3.47, with a mode between 2 and 3. On the other hand, rain waves on smooth surfaces (board without sand), varied between 2.83 and over 6, that is, its average exceeds almost twice the average of F for rain waves on rough surfaces. The main reason for this is that the velocity on a rough surface decreases at a rate of about 10 to 20% with respect to the velocity on the smooth surface. Also, roughness produces an increase in the depth of the water.

Discharge

Discharge (Q) also reflects the different sets of conditions occurring in the swash zone. This parameter is better expressed as Q/w, to eliminate the influence of the width of the zone affected by that discharge. It is also easy to obtain and to compare with other readings.

In the swash zone, Q/w oscillated in a wide range between 60 and 625, but always the backwash showed lower values than the swash. Again, the important factor here is the depth of the lamina of water, which is smaller in the backwash than in the swash due to the process of acceleration (also percolation may be important).

Rain waves always had (except in two cases on a sidewalk), Q/w values smaller than 10, with the mode between 2 and 6 and average 4.4. That is, rain waves occur only when Q/w reaches minimum values.

The diagram (Figure 1) shows the ratio between ***F*** and Q/w. The general relationship, which is easier to see by plotting the mean values of both ***F*** and Q/w for the swash, backwash, and rain waves, is an inverse one. The figure also shows that rain waves occur only when Q/w is minimum, and swash and backwash processes occur well above this minimum. Backwash and rain waves are equal to each other only when the depth in the backwash is excessively low (<1 cm) and depth of the rain waves is large (>1 cm).

Actually, the curve should be asymptotic, with the highest values of Q/w (and hence the lowest values of ***F***), corresponding to river flows.

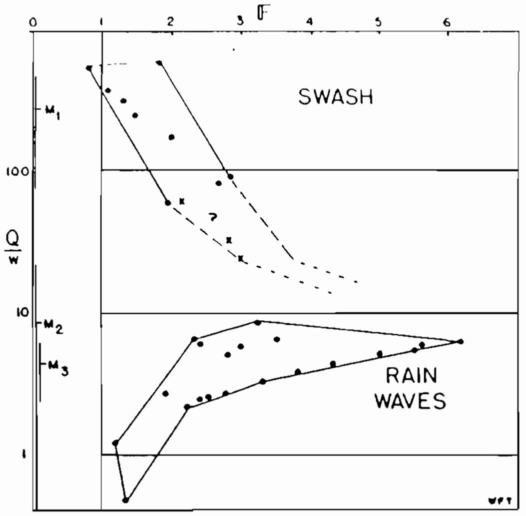

Figure 1. Plot of water discharge (per unit width) vs the Froude number, for experiments carried out specifically in preparation for the present paper. The dots in the upper part of the figure represent swash-zone events (*e.g.* back-wash ripple marks), and the dots in the lower part of the figure represent rain waves. The crosses are rain waves which plot close to the swash-zone field; because of their perhaps anomalous position, they are questioned. Mean values (M), plus-and-minus one standard deviation, are shown in the left part of the figure: M_1 refers to swash-zone events, and M_2 and M_3 refer to rain waves, with, and without, the three crosses. The separation of the number fields is statistically reasonably clear. Q/w equals the product hv (water depth times water velocity). Rain waves are seen to develop at minimum values of hv; it is reasoned, in the text, that even smaller values do not exist in nature. As the product hv increases, one passes from the rain-wave number field to the swash-zone number field, and then into ordinary water flow (Measure units are cm and sec.).

BACKGROUND

Observations by TANNER (1969, 1977) of natural and artificial rain waves, along with observation of the swash zone processes, mainly the variation in the Froude number, led to the problem of comparing the rain wave process with swash and backwash. The fact that on a single surface, the beach in this case, there is a sequence of swash-backwash (and rain waves, when they are present), implies a continuity of changing conditions producing this particular sequence of events. It is important to observe these conditions and to explain the change from one process to another.

Paired hydraulic jumps in the swash zone, and the ripple marks which they form, have been observed on many gently-sloping sand beaches in various parts of North and South America. They occur in sets up to, or more than, 50 in number, although commonly, only 5 ot 10 sets are present at any one moment. Each hydraulic jump marks the position of a change in flow regime from supercritical (Froude sense) to tranquil (or subcritical), or vice versa. Two adjacent hydraulic jumps, having supercritical flow in the space between them, stand over the ripple mark ridge. The latter is low and essentially symmetrical, having a ripple index (ripple spacing divided by crest height) generally in the range of 50 to 150, and in some instances as much as 400.

As the backwash flows down this beach slope, the Froude number decreases from a very high initial value, toward unity. If the beach slope is gentle, and if the wave period is long enough for one backwash to complete its flow before the next swash arrives, the Froude number drops below 1.0, and the hydraulic jump appears. The changes in water depth and velocity that are associated with the jump push the Froude number back above 1.0, and a second jump appears, facing in the opposite direction. These two hydraulic jumps make up the pair that scour a ripple mark trough. If the beach is gentle enough, and the wave period large enough, additional matched pairs may develop.

It is interesting to note that large numbers of paired jumps (*e.g.* 50 or so) have been noted on gently-sloping sand beaches along the Pacific coast, where wave periods may be quite large; intermediate numbers of paired jumps have been studied on the Atlantic coast, where wave periods are not so large; swash zone hydraulic jumps are relatively rare on the beaches of the Gulf of Mexico, where wave periods are commonly only 3 to 5 or 6 seconds; and this phenomenon has not been seen by us on lake beaches where the wave period is typically 1 to 3 seconds.

The data for the present report were obtained on beaches, on outdoor (non-permeable) surfaces such as sidewalks and streets, and in laboratory experiments on permeable and non-permeable surfaces.

Observations on beaches were carried out on Panacea Beach and at Alligator Point, south of Tallahassee, during high tide. These beaches are made of fine-grained sand, with slopes of about 5 degrees, and have low to medium wave energy levels. The high tide insures a greater energy level than average and hence a better observation of the swash and backwash processes. Measurements of velocity were made over a length of 50 cm, marked on the beach by two wood stakes or a wire rod that long. That length allows a relatively good measurement. Because of the variation of the velocity and depth in different parts of the beach for the same swash or backwash events, a length longer than that is not suitable for getting a representative value.

Observations of natural rain waves on concrete surfaces were made over a length of 2 or 3 meters. Flow in this case is constant; that is, there are no variations in water depth or velocity along the surface, so a longer length insures more precise measurements.

Laboratory experiments were made on a device described in the section "Methodology and Observations," and measurements were made over a length of 30 to 50 cm.

In every case, measurement of rain wave parameters was taken along a surface slope. In the swash zone, measurements of velocity and depth of swash and backwash, beach slope, and wave parameters were taken.

Measurements of velocity were made by using a hand chronometer. Six to twelve measurements in each observation were taken in order to provide a reasonably good mean value.

DISCUSSION

Rain waves are formed where the effective discharge (volume flow rate, divided by the width; Q/w = hv) has two important characteristics. (1) It is constant. (2) It falls within a range between two limits. (a) The lower limit is that Q/w below which only a stripped wall layer appears; that is, there is no excess water, above the wall layer, to form the rain waves. (b) The upper limit is not as sharply defined, but is that Q/w above which there is sufficient water on top of the wall layer to form a continuous moving sheet.

In other words, rain waves appear where the volume of water, on top of the wall layer, is adequate to produce a series of disconnected, moving ridges, but is not large enough to constitute a continuous sheet.

Because Q/w is constant, there is no change in the Froude number, and therefore no hydraulic jump. The rain waves slide over the underlying wall layer, pushing a small set of tiny shock waves ahead of each rain wave.

Swash zone hydraulic jumps are formed within the following limitations: (1) Water depth increases, downslope, during a single backwash event, so that the Froude number drops toward unity. (2) If the beach slope is gentle enough, and the wave period long enough to delay the subsequent incoming swash, ***F*** drops to below unity, thus starting the formation of one or more hydraulic jumps. The limits here are beach slope and time; where they are not restrictive, 50 or more such jumps may be formed. (3) Q/w increases systematically from the swash line to the toe of the beach (barring interruption by the next arriving swash), but rarely has values low enough for the water, on top of the wall layer, to shrink into a discontinuous sheet. This could occur only near the swash line, where ephemeral rain waves have been seen on a few occasions.

The swash itself almost always has Froude values less than unity, and therefore does not produce paired hydraulic jumps (or swash zone ripple marks). It flows over these ripple marks, but makes only minor modifications in them. It appears to be true that the transition from swash to backwash produces Q/w values down in the rain wave ranges; however, rain waves require a finite non-zero history, for organization purposes, commonly a few seconds, and this much time is generally not available. That is, flow conditions in the backwash change so rapidly that rain waves cannot develop very well.

The differences between rain waves and swash zone hydraulic jumps can be seen from a different point of view. Rain waves occur when Q/w is in that range where only a discontinuous sheet of flowing water is present. Except for time intervals that are too brief for rain waves to be organized, flow in the swash zone is always made up of a wall layer and an overlying sheet which is continuous across the zone. The combined sheets in the backwash, however, are nevertheless sufficiently thin that, under suitable conditions, the Froude number oscillates back and forth across the critical value of unity.

CONCLUSIONS

Natural rain waves form over smooth, gently-sloping surfaces (such as sidewalks), where the discharge is steady and large enough to produce both a wall layer and a discontinuous sheet (parallel moving ridges) above it, but not large enough to produce two continuous sheets.

Swash zone hydraulic jumps appear, in nature, over smooth gently-sloping surfaces (such as beaches) where Q/w is increasing, has values large enough to form a continuous sheet of flowing water on top of the wall layer, and has an uninterrupted history long enough for the dropping Froude number to fall below unity.

Rain waves may move across loose sand, but are not known to produce sedimentary features of any kind. Paired hydraulic jumps, in the backwash, create swash zone ripple marks, which have distinctive geometry (very high ripple indices). These ripple marks indicate a gentle beach slope (and hence medium to fine sand) and a fairly large wave period, such as would be expected on an open ocean.

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