PHYSICAL MODELLING OF THE EFFECT OF STORM SEQUENCES ON BEACH PROFILE EVOLUTION AND BEACH EROSION

Uriah Gravois, Tom E. Baldock, Sean Hsieh, Carlos Gomez, David P. Callaghan
School of Civil Engineering
University of Queensland, St Lucia, QLD
u.gravois@uq.edu.au

Abstract

Physical model tests to investigate the effect of storm sequencing on beach profile evolution are reported. The experiments are performed at medium scale for random waves on two different profiles, representing a mildly sloping beach and the same beach with sub-ariel nourishment. High resolution laser profiling is used to calculate sub-aerial and sub-aqueous sediment transport patterns and volumes. Sequences of two storms where the larger event occurs first, and *vice versa*, are simulated. The results indicate a complex behaviour. In some tests beach profiles at the end of forward and reverse sequences are similar, and in other cases not. Likewise, the effect of sequencing on the net offshore transport is variable. Reasons for this are discussed.

1. Introduction

It has long been recognised that storms may arrive in sequences but models for beach profile evolution do not yet demonstrate consistent skill in this regard. This study aims to complement the shoreline translation modelling being undertaken in the Bushfire and Natural Hazards CRC Project "Resilience to clustered disaster events at the coast: storm surge".

Beaches undergo continuous cyclic evolution in the form of erosion and accretion processes, and the beach profile at any given instant has an effect on the impact of subsequent storms. A morphological storm cluster occurs when the beach is unable to recover from a storm event before the next one commences. This needs to be distinguished from storm clustering in the wave climate. The erosive potential of a storm is determined by multiple environmental parameters such as wave height, preceding beach morphology, sediment size or variations in water level due to storm surge and tide.

Usually, the largest measured historical event is applied as a reference to assess beach erosion for design purposes. This method tends to overlook the effects of storm clusters, which can be more erosive than isolated large events (Callaghan et al., 2008). In some instances, the cumulative impact of smaller storms may outweigh the erosion potential of a single much larger storm. While it is clear that design of coastal protection, setback lines etc, should consider storm clustering, a precise definition of how the storm sequences should be combined has not been found (Coco et al., 2014). Morton (2002) suggests that the sequencing or chronology might be a critical factor in determining the erosive potential of a storm cluster. The cumulative effect of storms is also important and has been investigated recently by a number of model and field studies (Dissanayake et al., 2015; Karunarathna, et al., 2014; Splinter et al., 2015). The expected behaviour is a dependent both on the wave conditions and the antecedent beach morphology (e.g. Yates et al., 2009; Splinter et al., 2015) and the subsequent active beach profile after the wave conditions change (Baldock et al., 2016).

This paper presents results of new laboratory experiments to assess the importance of sequencing of storm events on beach profile response and the net bulk sediment transport. Physical modelling was deemed the most appropriate tool to investigate this phenomenon. Field studies require extensive and detailed data collection, and nature rarely allows the study of different chronological combinations of similar storm events with similar initial conditions. The paper is organised as follows. Section 2 outlines the methodology, including scaling issues, sediment transport calculations and wave conditions. Results are presented in section 3. A discussion of the implications and conclusions follow in sections 4 and 5.

2. Methodology

Physical modelling was performed to investigate the morphological response of beaches to sequences of storms. Experiments were performed at medium scale using random waves, with wave periods of 1-2s and significant wave heights, H_s, of 0.08-0.15m. The sand grain size was 0.3mm. The storm sequences comprised of two events or storms with different H_s, different or similar wave period, but the same duration. The smaller storm occurs first in a forward sequence, and *vice versa* in a reverse sequence. The initial beach profile is the same at the outset of each sequence.

Beach profiles were measured using a laser profiler capable of measuring the complete sub-aqueous profile from above the water surface, in addition to the sub-ariel profile (Atkinson and Baldock, 2016). The measurement accuracy is of order ±2mm with data obtained at a resolution of 1mm in the vertical and 1mm in the horizontal. The system resolves ripples to high accuracy. The complete profiler comprises of 8 lasers mounted across and above the flume, which yields 8 profiles, at a cross-flume spacing of order 0.2m. In combination, the 8 profile lines and high spatial resolution of each profile greatly improves the accuracy of the overall sediment transport calculations from the sediment continuity equation. Profile shown are the mean of the eight profile lines.

The initial beach profile varied between experiments. Series 1 comprised of experiments with an initial plane slope for all experiments of 1:15. In series 2, the beach around and above the still water line was modified to 1:4, simulating a beach scarp or upper beach nourishment project. The beach is manually reshaped after each sequence and compared to the desired initial profile using the laser profiling system such that discrepancies in elevation are kept to less than 1.5cm. Experiments are run when the water level of the reservoir located behind the beach matches the water level of the tank (0.6m). The wave gauges are calibrated before each storm event. Active wave absorption is used for all tests.

Scaling

The model beach used in the experiments does not represent a scaled version of a particular natural beach. However, the main objective is to attain similarity between sediment transport dynamics in the model and in nature. To distinguish different tests, the dimensionless effective relative fall speed parameter (Gourlay, 1968) is used $\Omega = \frac{H_s}{\omega T_p}$, where H_s is the significant wave height, T_p is the peak wave period and ω is the fall velocity of the sediment. The Gourlay number or variants also provides a means to distinguish between erosion and accretion (Gourlay, 1968, Wright et al., 1985) and it includes the wave period, which has a critical influence in beach evolution. It is therefore a suitable descriptor of the nearshore wave and sediment conditions for these particular experiments.

In the present experiments the length scale is approximately N=1/30, decided upon mainly due to wave maker constraints, wave data from the East Australian coast, a storm wave height threshold and previous experiments in the same flume. The prototype storm wave height threshold which is exceeded approximately 5% of the time is 3 metres, which will correspond to 0.1 metres in the laboratory experiments. Assuming equal sediment density between model and prototype the model will represent a natural beach with sediment fall velocity of 0.21m/s, or an approximate sediment size of d_{50}=1.5mm. Alternatively, adopting Hattori and Kawamata's (1980) modification to the Gourlay number, through the addition of the beach slope in the numerator, and assuming an equivalent sediment size in model and prototype, the slope in the laboratory would be representative of a 1:65 natural beach slope, which is a little gentler than typical beach slopes along the East Australian coast. The morphological features observed throughout these experiments match the typical storm profiles observed in nature and similar scales match well with larger scale physical model tests (Baldock et al., 2011). The scaling method is therefore deemed appropriate to study the influence in beach profile of altering the order of successive storm events.

Sediment Transport calculations

The local total sediment transport rate (bed load and suspended load) between any two time periods (interval Δt) is determined from

$$q(x_i) = q(x_{i-1}) + \int_{x_{i-1}}^{x_i} N \frac{\Delta z}{\Delta t} dx \quad (1)$$

where positive values of q (m^2/s) represent onshore transport. x_i is the cross-shore location, Δz is the change in bed elevation (m), Δt is the time difference, and N is the solid fraction, taken as 0.6. Assuming no net transport past the run-up limit, x_{max}, and the depth of closure x_{min}, any remaining closure error after averaging over all 8 profile lines is distributed uniformly along the beach profile. The bulk net cross-shore sediment transport across the whole profile between any two time periods is determined from integrating the local transport volume along the profile (Baldock *et al.*, 2011)

$$Q = \Delta t \int_{x_{min}}^{x_{max}} q\,(x) dx \quad (2)$$

over the same closure limits. Q represents the net bulk sediment transport (m^3 per unit width of flume) moved either shoreward (positive) or offshore (negative), and has previously been adopted to categorise overall beach response as erosive (Q<0), accretionary (Q>0) or stable (Q≈0). Q may be divided into a sub-aerial and sub-aqueous component with different choices of the limits in (2). The total bulk net transport is also equivalent to the change in the 1st moment of area of the beach profile between two time intervals, but the latter cannot be divided into different sub-aerial or sub-aqueous components, and does not yield the local transport in (1).

Experimental wave conditions

In both series of tests a range of wave conditions were utilised to simulate different idealised and scaled natural storm sequences. The idealised sequences comprised of two storms, run in forward and reverse order, with the beach reshaped to the initial condition between the two experiments. The duration of the storms and the number of repeats of the storms within the sequence varied. Typically, each storm duration was 4 hours in the model, which, according to Froude scaling corresponds to approximately 1 day (22 hours) in the prototype. Complete forward and reverse sequences are denoted by the notation AB, BA, with each letter denoting a duration of four hours in the model. The results here are part of a larger series of tests, and the numbering is maintained, so tests here are not always numbered sequentially.

Exp.	Event/ Storm	$H_s\ (m)$	$T_p\ (s)$	Ω	Storm	$H_s\ (m)$	$T_p\ (s)$	Ω	Beach face
1	**D**	0.08	1.5	1.37	**B**	0.15	1.5	2.56	Plane
2	**A**	0.12	1.5	2.05	**B**	0.15	1.5	2.56	Plane
3	**C**	0.1	1	2.56	**B**	0.15	1.5	2.56	Plane
7	**A**	0.12	1.5	2.05	**B**	0.15	1.5	2.56	Berm
8	**A**	0.12	1.5	2.05	**B**	0.15	1.5	2.56	Berm

Table 1. Model scale wave data. Event D is not a storm in the chosen classification. Storm B remains constant throughout all experiments. Experiments 7 and 8 have a different upper beach profile (nourished profile) compared to experiments 1-3. All tests are 4 hours duration.

3. Results

Experiment 1.

In experiment 1 Storm B corresponds to a prototype wave height of 4.5m, while event D corresponds to a prototype wave height of 2.4m, which, despite being a considerable wave size, is below the adopted storm threshold (and is therefore classified as an event instead of a storm). Figure 1 illustrates the profile evolution for each test in the forward and reverse sequences respectively. Event D develops a berm-bar profile, for which the bulk transport is onshore (figure 2). Storm B develops a strongly erosive profile with a breaker bar, but also forms a berm on the upper beach face, resulting in the bulk transport being offshore, but relatively small magnitude. Running the same incident wave conditions in reverse order yields different results. It appears that event D preceding storm B has a minimal influence on the development of the storm (B) profile during the forward sequence, although the preceding event actually increases the bulk net transport during storm B compared to that for storm B commencing from a plane profile. The profiles at the end of each sequence differ in terms of bar position and berm location, but the local transport is quite similar (figure 2) and the final bulk sediment transport (figure 3) is almost the same for sequence DB and sequence BD, and there is an overall net onshore movement of sediment.

Experiment 2

In Experiment 2 there is an increase in wave height for the smaller wave condition, from 0.08m to 0.12m (denoted storm A). The prototype wave height for event A is now 3.6m, and hence it is now classified as a storm. Using the forward sequence (figure 4) as a guide, a logical prediction for the reverse sequence would be initial erosion caused by storm B followed by accretion caused by storm A. However, with storm A following storm B more erosion occurs (figure 4), and the bar developed by storm B displaces further offshore. It is clear that storm A has kept eroding the beach, thus, erosion is larger than expected. In the forward sequence of Experiment 2, storm A creates a bar that is then ignored by storm B, which erodes the profile to the same extent as for storm B from an initial planar slope. In this case then, a small storm following a large storm continues erosion below the water line, moving the bar offshore, but also builds a higher berm. The net effect is only a minor difference in the bulk transport.

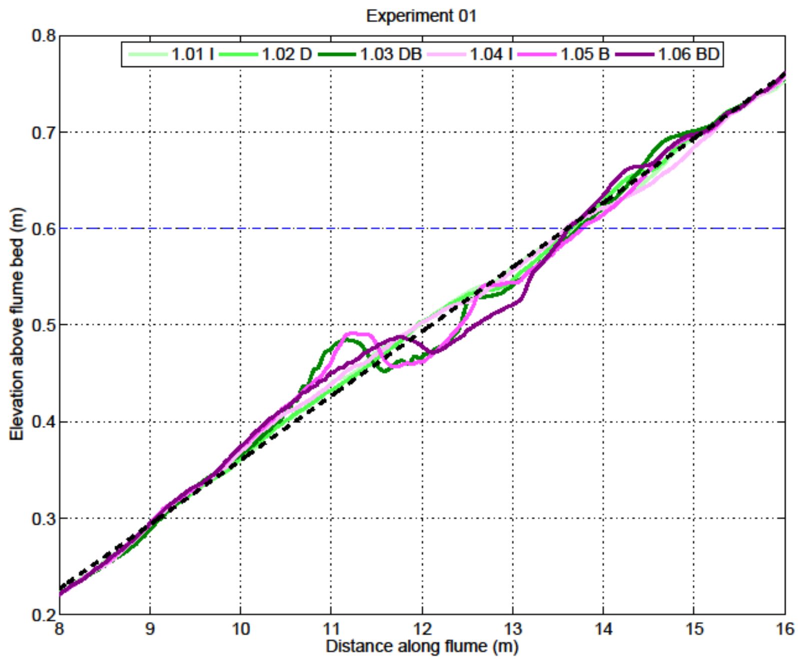

Figure 1. Experiment 1 forward (DB) and reverse sequence (BD). I indicates the initial profile for each sequence.

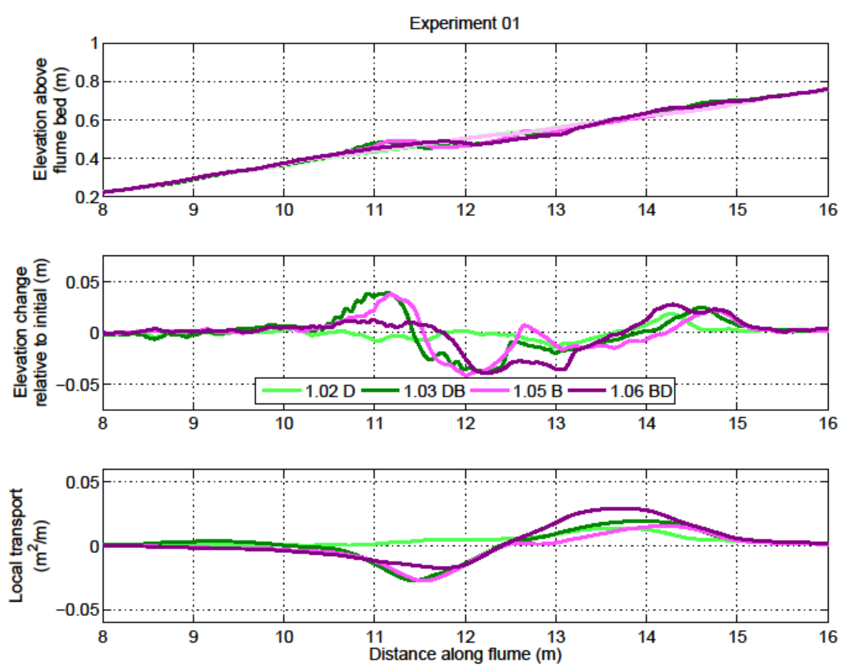

Figure 2. Profiles, bed elevation changes and local net sediment transport (equation 1) for Experiment 1.

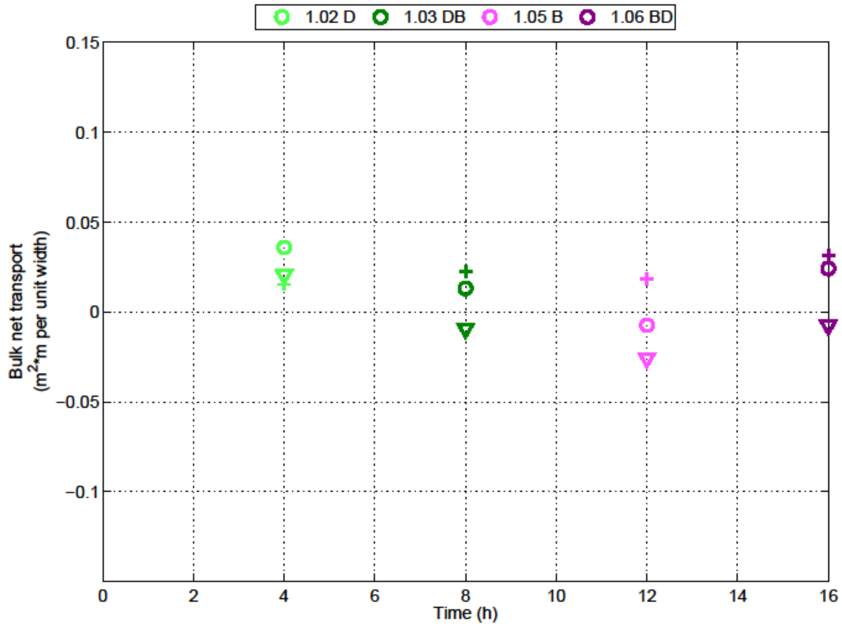

Figure 3. Bulk transport (equation 2) for Experiment 1. Note that the beach is reshaped to the initial plane state after the forward sequence (DB). Circles, total transport; triangles, sub-aqueous transport (below SWL); cross, sub-aerial transport.

Experiment 3

In this case the Gourlay number for both storms is the same, however, the wave power of storm B is more than triple that of storm C. Equivalent Gourlay numbers should yield profiles with similar shapes and morphological features according to Wright et al. (1985), which is consistent with the data. The reverse sequence of Experiment 3 displays similar behavior to that of Experiment 1. Storm C produces net onshore transport and storm B is erosive. The bar has begun to dissipate and the inner step is being displaced onshore. The difference in bulk transport with respect to Experiment 1 is visible in the transport calculations for the last storms of each sequence. Storm B in isolation produces more offshore transport and erosion than sequence CB (figure 7 & 8).

Experiment 7

Experiment 7 has the same two storms as experiment 2, but a steep 1:4 upper beach was shaped from the still water line landward, with the initial profile further seaward remaining at 1:15 plane slope. This might represent, for example, a beach nourishment. It is observed that in the reverse sequence, BA, storm A flattens the bar created by the initial larger storm and moves it onshore, indicating slight accretion. In the forward sequence, Storm B further erodes the beach after the initial smaller storm. The final results of both sequences have similar beach profiles. However, the bar-trough created by the AB sequence erodes more, leaving the inner step further offshore. It is noted that storm B in isolation produces a strong breaker bar, but also onshore transport on the berm, a result of overtopping. The bulk transport between each sequence is quite different, despite similarities in the profiles.

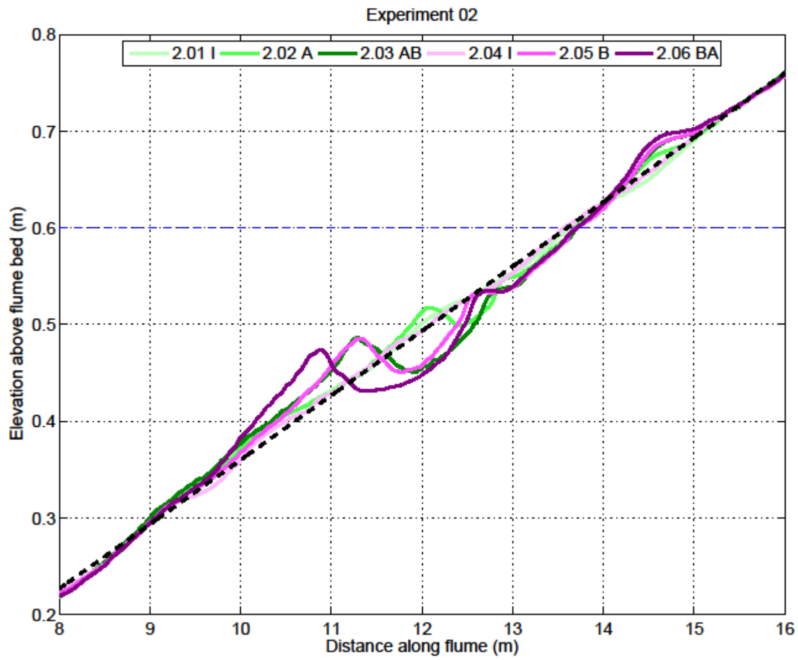

Figure 4. Experiment 2 forward (AB) and reverse sequence (BA). I indicates the initial profile for each sequence.

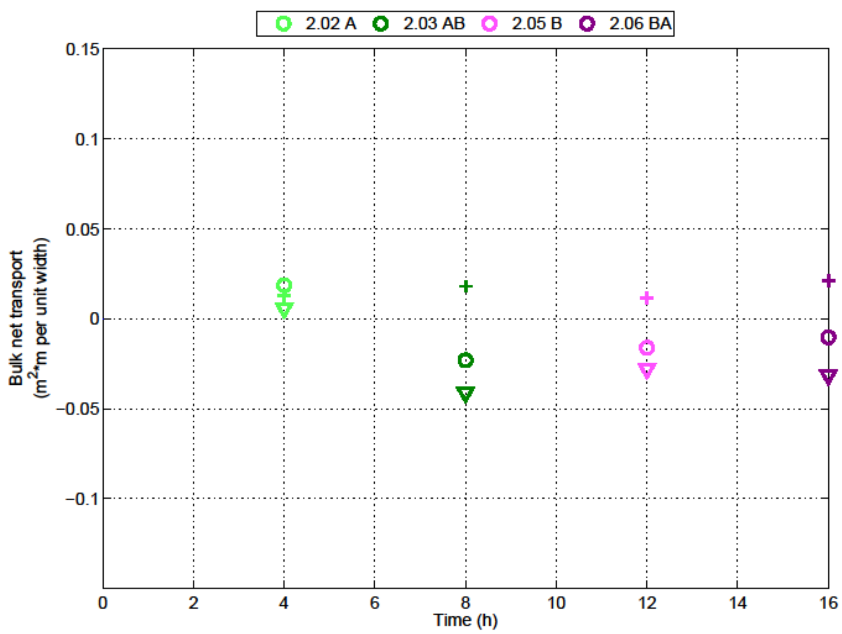

Figure 5. Bulk transport (equation 2) for Experiment 2. Note that the beach is reshaped to the initial plane state after the forward sequence (AB). Circles, total transport; triangles, sub-aqueous transport (below SWL); cross, sub-aerial transport.

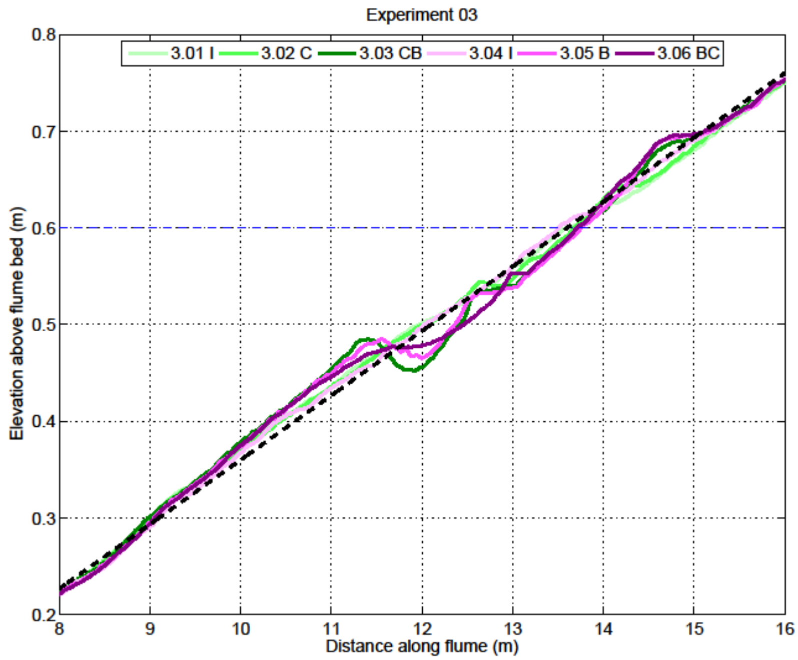

Figure 6. Experiment 3 forward (CB) and reverse sequence (BC). I indicates the initial profile for each sequence.

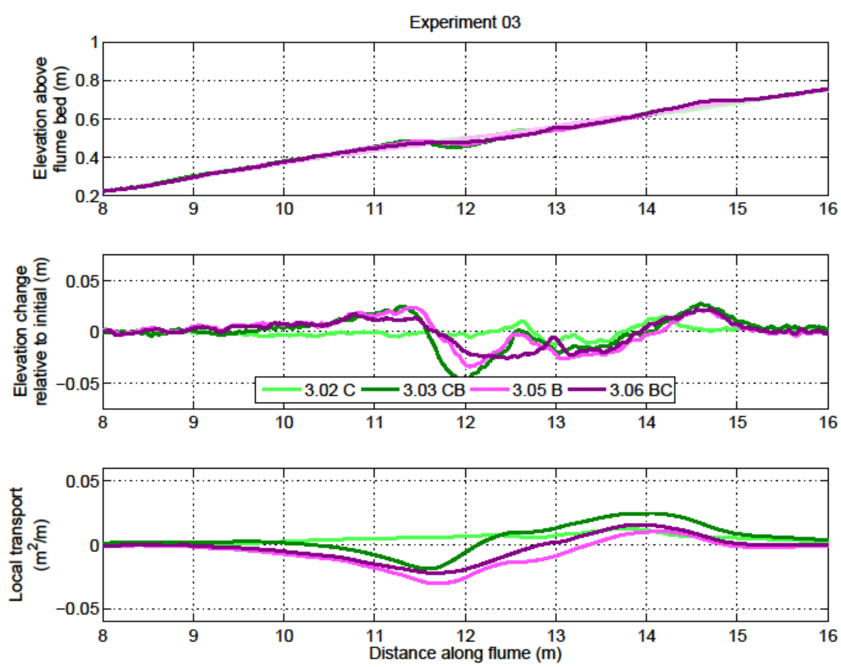

Figure 7. Profiles, bed elevation changes and local net sediment transport (equation 1) for Experiment 3.

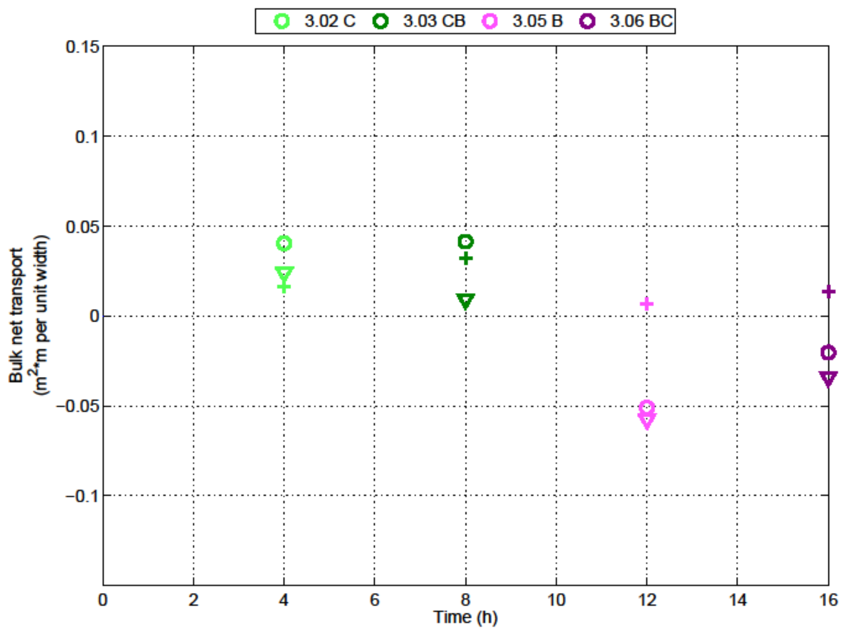

Figure 7. Bulk transport (equation 2) for Experiment 3. Note that the beach is reshaped to the initial plane state after the forward sequence (CB).

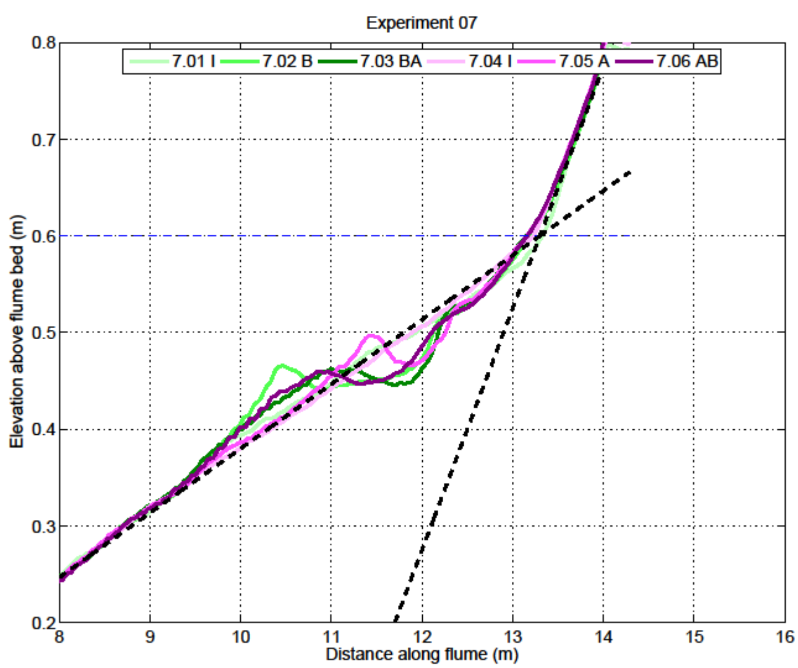

Figure 8. Experiment 7 forward (AB) and reverse sequence (BA). I indicates the initial profile for each sequence. Note change in upper beach profile and legend is in reverse order.

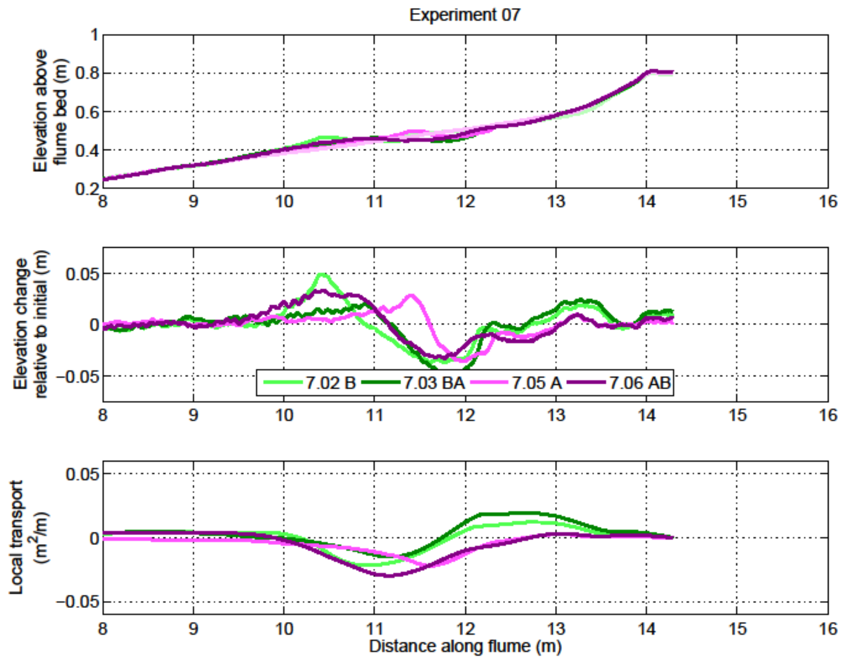

Figure 9. Profiles, bed elevation changes and local net sediment transport (equation 1) for Experiment 7.

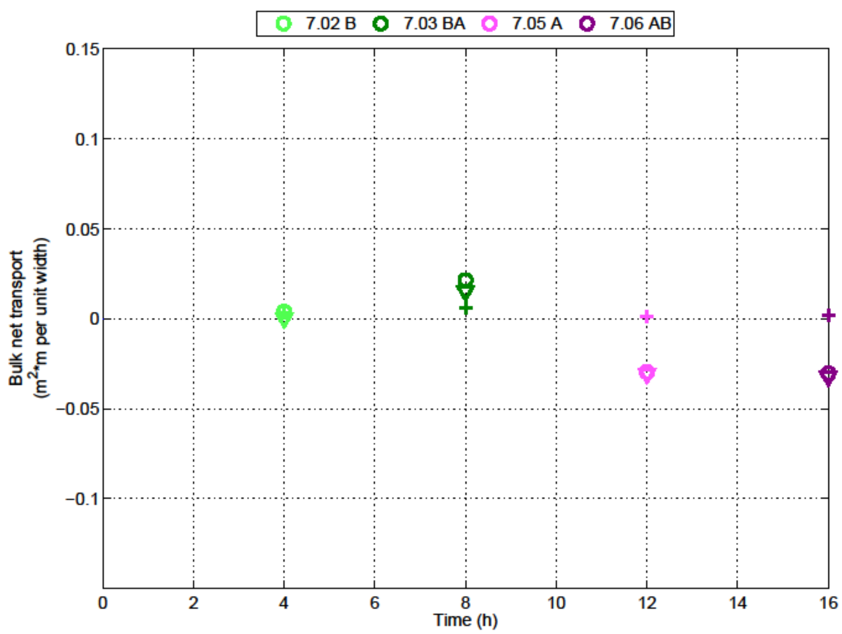

Figure 10. Bulk transport (equation 2) for Experiment 7. Note that the beach is reshaped to the initial plane state after the forward sequence (AB). Circles, total transport; triangles, sub-aqueous transport (below SWL); cross, sub-aerial transport.

Experiment 8

Experiment 8 was similar to experiment 7, with the exception that the steep upper beach profile extended below the still water line, representing a nourishment lower on the profile or a storm surge. This results in much stronger erosion over the whole profile (figure 11), with net offshore transport everywhere. The bulk transport is therefore much greater in magnitude, and offshore for all tests in the sequence (figure 12). Despite quite different final profiles for each sequence, the bulk transport is quite similar. In this case sub-aqueous transport dominates over sub-aerial transport, despite the steep upper beach.

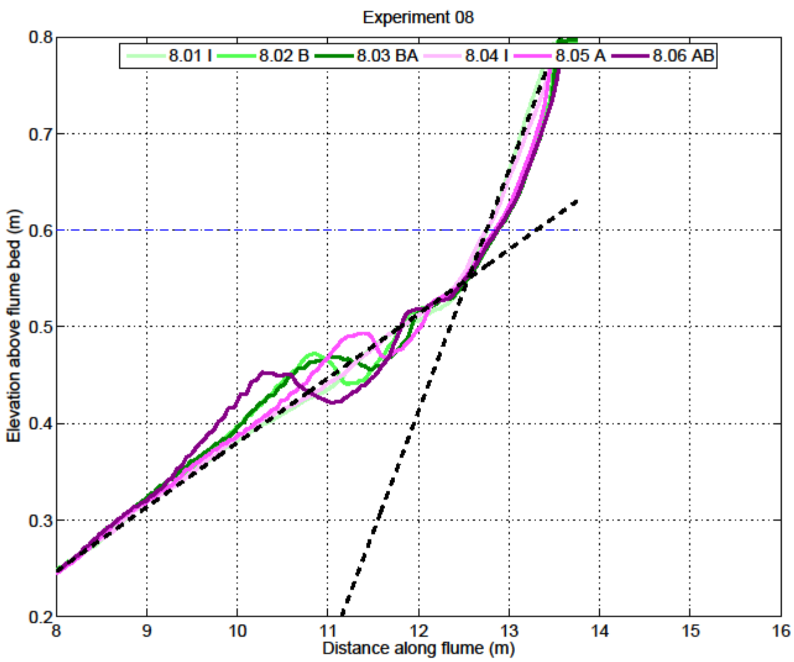

Figure 11. Experiment 8 forward (AB) and reverse sequence (BA). I indicates the initial profile for each sequence. Note change in upper beach profile and legend is in reverse order.

4. Analysis and Implications

The conventional equilibrium beach profile concepts and classical beach state models provide a range of options for beach evolution under sequences of events, depending on the antecedent conditions and if the beach has evolved to an equilibrium or not during the event. It is the subsequent active beach profile following a change in wave conditions that then determines how the beach evolves (Baldock et al., 2016). Depending on this subsequent active profile, the new wave conditions may fall on either side of the equilibrium beach state curve defined by Wright et al. (1985). Consequently, it is possible to approach the equilibrium state from either side, giving the possibility of both erosion or accretion with a reduction in wave height. These data give either option, i.e. a larger storm followed by a small storm can result in a larger offshore bar (and further offshore) than the reverse (experiment 2), and *vice versa* (experiment 8). Further, a single storm can generate the largest breaker bar in the sequence (experiment 7). The net bulk transport is generally not dissimilar for forward and reverse sequences, despite profile differences. Three experiments (1,2,8) show no significant difference in the bulk transport for different sequences, two experiments show contrasting behaviour, with a smaller event following a larger event giving most net offshore transport (3) and *vice versa* (7). The growth of beach berms influences the net bulk transport magnitudes and directions and illustrates the importance of tide/surge level in controlling the net offshore movement of sand.

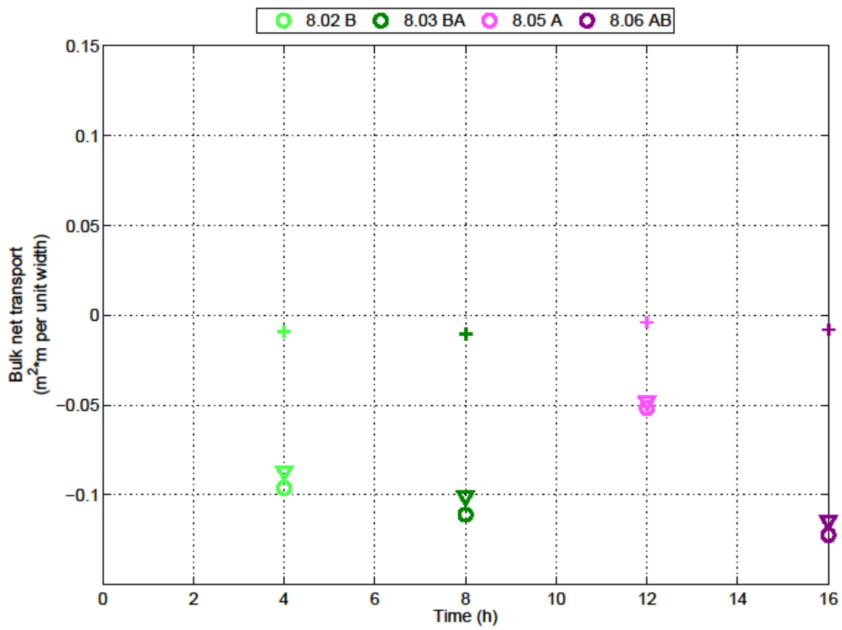

Figure 12. Bulk transport (equation 2) for Experiment 8. Note that the beach is reshaped to the initial plane state after the forward sequence (AB). Circles, total transport; triangles, sub-aqueous transport (below SWL); cross, sub-aerial transport.

5. Conclusions

Physical model tests on the infleunce of storm sequencing on beach profile evolution show a complex behaviour. In some cases most erosion occurs for a large storm following a small storm, but the opposite also occurs. Further work is needed to resolve the reasons for this, which is dependent on the antecedent conditions and the subsequent active beach profile.

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