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# Beach Profile Changes under Sea Level Rise in Laboratory Flume Experiments at Different Scale

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**ABSTRACT**

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Laboratory wave flume experiments have been used to provide improved understanding of beach profile evolution under different wave and water level conditions. However, the understanding of the processes involved in the evolution of beach profile under Sea Level Rise (SLR) toward equilibrium is unclear. Two similar, but distorted experiments were performed at large and medium scale in order to study the qualitative morphological changes involved in beach profile evolution under SLR. Both experiments showed similar beach profile evolution. The profile change predicted by the Profile Translation Model (PTM) and the Bruun Rule underestimated the observed reatreat in both experiments. The length of the active beach profile increased under SLR. For the large scale experiment, the reflection coefficient of the beach decreased while the vertical runup increased significantly. The beachface changed faster than the outer surf zone, making the beach more dissipative.

**ADDITIONAL INDEX WORDS:** *Sea Level Rise, Flume, Scale, Morphodynamic, Equilibrium*.

## INTRODUCTION

Physical models are useful tools for investigating beach profile evolution under controlled conditions. During the last few decades, many experiments have been undertaken to investigate beach and dune response to erosive and accretive waves. These experiments have mainly been undertaken in small and medium scale laboratory flumes due to the small number of large-scale flumes available around the world. Atkinson *et al.* (2018) and Beuzen *et al.* (2018) investigated beach profile response to erosive waves and a rising water level to investigate the effect of sea level rise on engineered and non-engineered coastlines. While these studies provided important insights into beach profile evolution under rising water levels, the likely presence of scale effects means that the direct application of these insights to prototype scale is not entirely clear. Limited examples of large-scale flume experiments studying profile evolution for varying hydrodynamic conditions exist. For example, Vellinga (1982) and Kraus and Larson (1988) undertook large scale laboratory experiments to investigate beach profile evolution under erosive conditions and changing water levels, however neither study investigated the evolution of beach profiles approaching equilibrium for a rising water level.

### Background

The concept of beach profile at equilibrium was first presented in Johnson (1919), as the profile that would naturally develop to a stable state under constant forcing conditions - *i.e.* no significant change in the profile evolution with time. Bruun (1954) extended this concept to define an equilibrium (average) beach profile shape with the equation:

$$h = Ax^{2/3} \tag{1}$$

where $h$ is the water depth, $x$ is the cross-shore location and $A$ is a scaling parameter controlled by the sedimentology and wave climate (Bruun, 1954; Dean, 1977). Equation (1) and the concept of beach profile equilibrium form the basis of the well-known Bruun rule (Bruun, 1962) for predicting beach recession with Sea Level Rise (SLR):

$$R = \frac{L}{B+h} S \tag{2}$$

where $R$ is the shoreline recession (m), $L$ is the length of the active profile (m), $B$ is the berm height taken from the still water level to the top of the berm (m), $h$ is the depth of closure (m) and $S$ is the total sea level rise. This equation is based on a number of assumptions, including that the profile before and after SLR is at equilibrium. Although equation (1) is a simple and intuitive way to represent a beach profile at equilibrium, it has been argued that the equilibrium profile shape (Equation 1) is not representative of natural beach profiles as it does not include any of the perturbations observed in nature, such as a bar, trough or berm, and was rarely observed in the field (Bruun, 1983; Rosati *et al.*, 2013). Furthermore, a true equilibrium condition is unlikely to ever be attained in nature due to constant changes in hydrodynamics and sediment availability. Therefore, the Bruun rule (Equation 2) cannot be expected to work perfectly, and is unlikely to be representative of all morphodynamic processes which drive coastal retreat.

Atkinson *et al.* (2018) performed a comparison of the existing methods to predict shoreline retreat and the evolution of beach profiles at quasi-equilibrium under rising water levels, including the Bruun Rule (Equation 2) and the Rosati *et al.* (2013) modified version of the Bruun Rule, including onshore sediment transport. A Profile Translation Model (PTM) was also developed to predict the evolution of beach profiles of arbitrary shape under water level rise. This method uses an actual measured profile and assumes it is near equilibrium, and then translates it upward by the value of water level rise, and landward until the erosion and deposition volumes match. As a result, onshore sediment transport and deposition over beach berms is taken into account automatically, in contrast to the modified version of Rosati *et al.* (2013) where this has to be estimated or based on measurement. The PTM provided similar predictions to those of the other methods tested, with the predicted shoreline retreat being within 30% of the observed retreat, but with the additional advantage that profile perturbations like bars and berms could be maintained through the evolution process.

None of the approaches discussed above have been tested using results from a large-scale laboratory experiment. In general, previous work has focused on understanding the profile evolution caused by water level changes, from one quasi-equilibrium beach profile to another. As discussed above, the maintenance of a constant beach profile shape is one of the crucial assumptions of the Bruun Rule and its derivatives. Beach profiles do typically have seasonal characteristics and shapes around which they fluctuate, which could be considered as a long-term quasi-equilibrium state. However, at shorter time scales, rapid water level fluctuations (*e.g.* storm surge) typically allow insufficient time for a new equilibrium beach profile to develop. Therefore, the Bruun rule and its derivatives may not apply in this context, and the processes involved in the evolution of a beach profile under water level changes before reaching a complete new equilibrium may differ significantly from these rules.

## METHODS

Two comparable laboratory flume experiments were completed to investigate the effect of a rising sea level on a sand beach profile at different scales. The experimental procedure for both experiments involved running a constant irregular wave condition and incrementally raising the water level , with the aim of reshaping the beach to a state of quasi-equilibirum at each water level. At each water level, the testing was divided into a series of "runs" varying in duration from 20 minutes to 3 hours. The beach profile was measured at the end of each run. A complete descriptions of the methodology used in this study is described in Bayle *et al.* (in review, a).

### Experiment descriptions

A prototype-scale experiment (DynaRev) was undertaken in the Groβer WellenKanal, GWK large scale wave flume, located at the Forschungszentrum Kuste (FZK Coastal Research Centre) in Hannover, Germany (hereafter the GWK experiment). A complete description of the experiment and further results are presented in Bayle *et al.* (in review, b). The flume is 309 m long, 7 m deep and 5 m wide. Reflected waves and low frequency resonance are damped at the paddle using Automatic Reflection Compensation (ARC). The beach profile was measured after each test using a mechanical profiler which consists of a roller attached to a mobile trolley running along the flume side walls. The coordinate system is defined as follows: the cross-shore position, $x$ has its origin at the wave paddle and is positive toward the beach; the vertical elevation, $z$ is positive upward the concrete bottom of the flume.

A scaled model experiment was performed in the University of New South Wales (UNSW) flume located at the Water Research Laboratory (WRL), Sydney, Australia (hereafter the UNSW experiment). The complete experimental description and results can be found in Beuzen *et al.* (2018). This flume is 44 m long, 1.6 m deep and 1.2 m wide. It uses a piston-type wave paddle backed with specialised foam blocks to damp wave reflections. Beach profiles were measured using a laser measurement system. This system consists of an array of five SICK DT50-P111 class 2 laser distance sensors mounted above the flume on a trolley rolling on the flume side wall. The final measured profile is an average of the five cross-shore profiles obtained. The coordinate system is defined as follows: the cross-shore position, $x$ has its origin at the bottom of the beach profile and is positive toward the beach; the vertical elevation, $z$ is positive upward the bottom of the flume.

Table 1. *General test conditions, characteristics and water level rise information for GWK and UNSW experiment* .

| | $H_s$ (m) | $T_p$ (s) | Slope | Sand $d_{50}$ | Water level (m) | Time at each water level (h) |
|---|---|---|---|---|---|---|
| GWK | 0.8 | 6 | 1:15 | 0.33 | 4.5 | 20 |
| | | | | | 4.6 | 7 |
| | | | | | 4.7 | 7 |
| | | | | | 4.8 | 7 |
| | | | | | 4.9 | 14 |
| UNSW | 0.15 | 1.25 | 1:10 | 0.35 | 1 | 7.67 |
| | | | | | 1.015 | 4.67 |
| | | | | | 1.030 | 3 |
| | | | | | 1.045 | 3 |
| | | | | | 1.060 | 3 |
| | | | | | 1.075 | 12.67 |

Both experiments started with a planar sandy beach profile. The sand in each experiment was similar in size and was non-cohesive in all cases (Table 1). Irregular time series of waves (JONSWAP spectrum) were generated based on the significant wave height and the peak period presented in Table 1. Both experiments used a series of incremental water level rise (four steps of 0.1 m for GWK and five steps of 0.015 m for UNSW) giving a total rise of 0.4 m and 0.075 m respectively. In both cases, the total water level rise was 50% of the significant wave height. The run times at each water level differed between the experiments, and are shown in Table 1.

Beyond the scale of each flume experiment, a few additional differences remained between them. GWK had a gentler initial slope (1:15) than UNSW (1:10). The initial profile was reshaped under 20 hours for GWK and only 7.67 hours for UNSW. Finally, the profile evolution was surveyed at irregular and different time steps for each experiment.

As detailed in Bayle *et al.* (in review,a), GWK and UNSW are fully distorted relative to each other in terms of Froude scaling, physical geometry, wave steepness, Dean number and Iribarren number. However, the values of the Iribarren and Dean numbers are characteristic of erosive conditions in both cases, hence an erosive profile is expected to develop making the profiles suitable for morphological comparison (Vellinga, 1982; Van Rijn *et al.*, 2011; Baldock *et al.*, 2011; Atkinson *et al.*, 2018).

**Assessment of Equilibrium**

Laboratory studies have demonstrated that complete, stable equilibrium is not easily achieved in a wave flume for sandy beaches forced by erosive random waves (*e.g.* Moore, 1982; Rector, 1954). However, the rate of morphological change can be observed to decrease over time. When this rate is small and reaches a certain threshold of change, the profile state is defined as 'quasi-equilibrium' (*e.g.* Baldock *et al.*, 2017; Beuzen *et al.*, 2018; Atkinson *et al.*, 2018).

Following the approach of Beuzen *et al.* (2018), equilibrium was assessed based on the evolution of three morphological indicators: shoreline position; the sediment transport rate; and the bar crest position. The shoreline position was defined as the intersection of the still water level with the beach profile. The bar crest position was determined as the location of maximum elevation of the offshore bar. The bar height was calculated by subtracting the initial planar bed elevation at the crest position from the bar crest elevation. The absolute sediment flux ($q_{abs}$) ($m^3/m$) was defined at each time interval as the sum of the absolute value of the local sediment transport across the profile relative to the initial planar profile:

$$q_{abs} = \int_{-\infty}^{\infty} \left| \int_{x0}^{x} \Delta z(x)\, dx \right| dx \tag{3}$$

where $x_0$ is the landward location of no profile change (*i.e.*, $q(x_0) = 0$), $\Delta z$ is the observed change in bed elevation (m) between the profile and the initial planar profile at location $x$, and $dx$ is the cross-shore increment.

The rate of change of these morphological parameters is expected to reduce through time for both experiments toward quasi-equilibrium conditions. The degree to which equilibrium was attained is expressed as the ratio of the rate of change during the final run and the initial rate of change (first run, 20 minute duration) for each parameter expressed as a percentage.

## RESULTS

The profiles analysed in this section were measured at the end of testing at each water level increment as detailed in Table 1.

**Observed beach profile evolution**

Fig. 1 shows the profiles at the end of testing at each water level for the GWK and UNSW experiments. Despite obvious differences in profile shape, similar and comparable qualitative behaviour was observed in both experiments. The shoreline was eroded as the berm retreated and increased in volume, and the bar moved landward and upward as the water level was increased. In both cases, the length of the profile, calculated from the bar crest to the shoreline, increases with water level rise. From the end of the initial water level to the end of the final water level, the profile length increases by 40 cm (from 2.65 m to 3.05 m) for UNSW (15% longer), and by 7.1 m (from 28.6 m to 35.7 m) for GWK (25% longer). Therefore, it appears that the profiles became more dissipative as the water level was raised, with the shoreline retreating faster than the bar. This behaviour was also observed in Atkinson *et al.* (2018). The berm height (from the still water level to the top of the berm, as defined in the Brunn rule) also increases in both experiments, by 2 cm and 4.5 cm for GWK and UNSW respectively. On the other hand, the berm height calculated by subtracting the initial planar bed elevation at the berm position from the berm crest elevation remains constant throughout both experiments, suggesting it is approximately self-similar at each water level. As a consequence, the inner surf zone becomes wider, and wave energy is dissipated over a larger area.

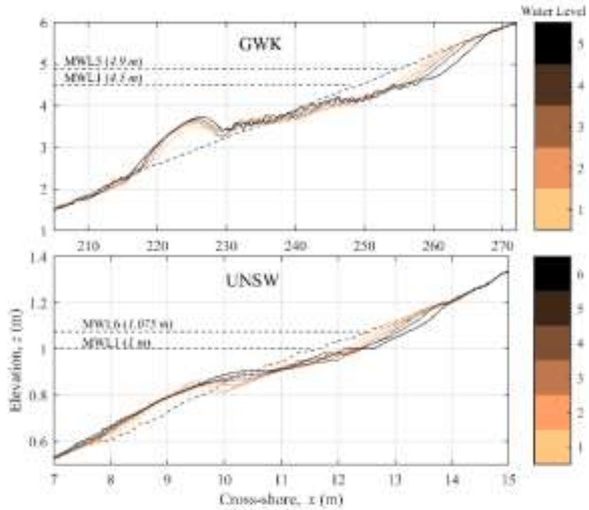


Figure 1. Beach profile evolution under water level rise for GWK (top panel) and UNSW (bottom panel). The dashed black profile represents the initial planar slope. The final profile for each water level is represented by a colour, from light copper to black. The horizontal dashed lines represent the initial and final water level (see Table 1 for more details).

**Beach profile equilibrium**

The rate of change of each of the parameters presented in the 'Assessment of equilibrium' section was calculated for the last run and compared to the rate of change during the first run (first 20 minutes), at the initial and final water levels for both experiments. The last profile in each experiment was measured at a different relative time toward equilibrium because the testing time allocated for each water level was different in the two expriments. Nevertheless, the rate of change reduced with time for all parameters in both experiments. They were both closer to equilibrium at the end of the initial water level. However, they appeared further from this theoretical equilibrium for the final water level case. For both cases, GWK appears to be further from equilibrium than UNSW. It is evident that the absolute sediment transport rate reduces at a slower rate than the other indicators examined here. This may be expected since it is an integrated indicator of change across the entire profile, and even at a state of equilibrium, significant sediment transport will occur under energetic wave action. However, the time-averaged net rate would be expected to approach zero given sufficient time (theoretical equilibrium beach profile).

Table 2. *Ratio of the rate of change during the final run and the initial rate of change (first run, first 20 minutes) expressed as a percentage for the shoreline position, sediment transport rate and bar crest position: final rate of change*100 / initial rate of change. Values are shown for both the initial and final water levels.*

| | Initial water level | | | Final water level | | |
|---|---|---|---|---|---|---|
| | Shoreline (%) | $q_{abs}$ (%) | Bar (%) | Shoreline (%) | $q_{abs}$ (%) | Bar (%) |
| GWK | 15 | 17 | 11 | 11 | 42 | 33 |
| UNSW | 4 | 5.5 | 0.7 | 1.4 | 15.4 | 5.5 |

**Profile translation model predictions**

Fig. 2 shows the application of the Profile Translation Model developed by Atkinson *et al.* (2018) to the GWK and UNSW profiles. For both experiments, the observed shoreline retreat (7.90 m for GWK and 1.06 m for UNSW) was greater than predicted by the PTM (5.95 m for GWK and 0.74 m for UNSW), and also more than the Brunn rule (5.89 m for GWK and 0.76 m for UNSW) and the Rosati *et al.* (2013) modified version of the Bruun rule (5.91 m for GWK and 0.77 m for UNSW). On the other hand, the bar retreated less than predicted by the PTM in both experiments. This observation can be at least partly explained by the increase in the profile length with water level rise discussed in the 'Observed beach profile evolution' section.

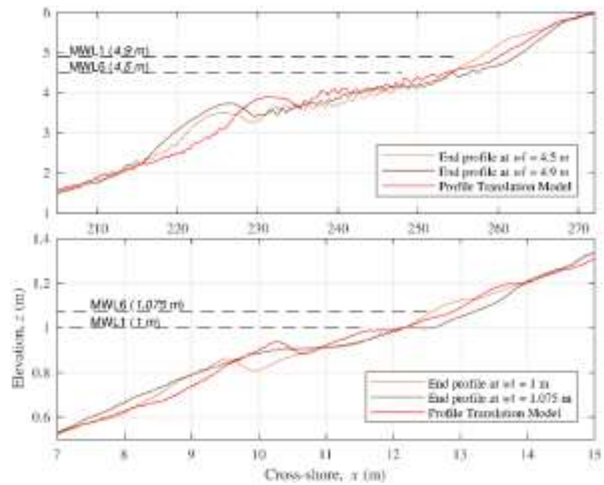


Figure 2. Comparison of the real beach profile evolution and profiles predicted by the Profile Translation Model (PTM), for GWK (top panel) and UNSW (bottom panel). Profile at the end of the initial water level is shown in light copper and profile at the end of the final water level in black. The red line represents the theoretical final profile under water level change obtained by translating the profile at the end of the initial water level (light copper) using the Profile Translation Model (PTM).

## DISCUSSION

The shoreline retreat observed in the two distorted experiments under water level increase (Fig. 2) differed significantly from the predictions of the PTM, Bruun rule and the Rosati rule, with both receeding more than predicted (obvserved in Atkinson *et al.*, 2018). Referring to Equation 2, the length of the profile $L$ is increasing at a greater rate than the berm height $B$ (almost neglictable) and the depth of closure $h$, and hence a larger recession is observed. It is also observed that the theoretical end profile given by the PTM did not represent the shape of the entire length of the final active profile. This can be explained by a combination of factors.

Firstly, the profile at the end of the first water level was not at equilibrium in both experiments, though the UNSW profile was closer to equilibrium. Therefore, the bar would be expected to move further offshore (mainly for GWK, Table 2) and the shoreline to retreat further (for both GWK and UNSW, Table 2) if sufficient run time was possible. The profile would have then been longer before raising the water level, and the translated profile could be expected to better match the PTM prediction.

The second factor is that Table 2 suggests that the shoreline was closer to equilibrium at the end of testing at the final water level than for the initial, whereas the bar was further from equilibrium (different state of equilibrium for the different indicators). The bar clearly showed a landward and upward movement from its previous position. Therefore the bar may be expected to move landward given additional time, while the shoreline was likely to remain stable. This process would eventually shorten the profile length as equilibrium was approached. GWK was further from equilibrium for both water levels, and lengthened by 25% under Sea Level Rise (SLR); UNSW was closer to equilibrium for both water levels, and lengthened by 15% under SLR. This may be explained by the fact that it is easier and faster to erode the beach face than it is to fully redistribute the sand in the surf zone, thus landward and upward movement of the bar is slower than shoreline erosion.

However, as previously noted, equilibrium is difficult to attain in both the laboratory and nature, and therefore, a beach profile will likely respond to a rise in water level, both on short (storm surge) and long (SLR) timescales in an out of equilibrium state.

Fig. 3 shows that as the length of GWK beach profile increased under SLR, the coefficient of reflection decreased. The profile was therefore less reflective, and so by definition, more dissipative. On the other hand, the wave runup increased significantly with SLR. Note that the experiment was designed so that the incident significant wave height at the wave paddle remained constant at all water levels. Therefore, the beach received more energy as the coefficient of reflection reduced with rising water level, and this can at least partly explain the increase in runup height. The runup increase can also be caused by the fact that the SLR is increasing relatively faster than the bar crest elevation. Thus, the depth above the bar increases and so the energy dissipated above the bar is likely lower. Under relatively rapid SLR (*e.g.* storm surge), beach profile is likely to reshape in a similar manner to the profiles in GWK and UNSW, leading to more dissipative profile shape and increased runup height, hence potential coastal erosion threat. This short term behaviour could change the assessment of coastal erosion under rapid sea level rise, hence the coastal management shceme used.

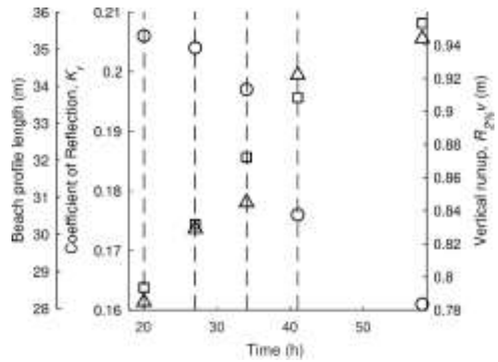


Figure 3. Coefficient of reflection $K_r$ (circles), vertical runup $R_{2\%}v$ (triangles) and length of the beach profile (squares) at the end of each water level test for GWK only (see Table 1). The vertical dashed lines show the times at which sea level was raised. The first 20 hours corresponding to beach profile development from the initial planar slope are not shown, meaning the time starts at 20 hours. The reflection coefficient and runup were calculated over the last 2 hours of waves at each water level. The length of the profile was calculated from the bar crest to the shoreline.

## CONCLUSIONS

Two distorted laboratory flume experiments at different scale were used to study beach morphological changes under water level rise. On the basis of these experiments, the overall behaviour of the profiles was similar at both scales suggesting that it is reasonable to undertake SLR experiments at small/medium scale in future. They showed similar shoreline retreat which exceeded the predictions of the PTM and the Bruun rule. The length of the active beach profile increased over the course of water level rise for both GWK and UNSW, causing the profile to become more dissipative. This is explained by the fact that the experiments may not have allowed sufficient time for equilibrium to be attained. Nevertheless, this behavior is likely to occur during short term SLR (*e.g.* storm surge).

The observed morphology changes meant that for GWK, the reflection coefficient of the beach decreased while the vertical runup and the length of the profile increased significantly as the water level was increased. The beachface was observed to change faster than the outer surf zone, leading to increased wave runup with water level rise, and hence increased coastal threat. It would be valuable to extend this work with additional test cases in order to confirm this short term behaviour and account for its contribution to coastal erosion through coastal management plan.

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