Armour Layer Development and Destruction: An Investigation into the Effectiveness of Beach Raking

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ABSTRACT: This study aims to determine the effectiveness of a novel river management initiative, termed *beach raking*. *Beach raking* is a process which involves the manual breakup of the armour layer on the surface of river beaches, using a tractor, and custom-built 'ripping' blades. There is anecdotal evidence to suggest this process allows the smaller, more frequent flood events, to entrain sediment which would normally be protected by the armour layer. A laboratory study, based at The University of Auckland, was conducted to quantify the effectiveness of this process. Gravel-bed topography data were obtained using an acoustic depth profiler. Topography measurements, at a resolution of 1 x 1.225mm mapped the bed surface, and provided bed elevation data for the purposes of statistical characterisation. The armoured, raked and post-flooded bed surfaces were characterised in accordance with Goring et al. (1998), Aberle and Nikora (2006) and Coleman et al. (2011), to describe surface response to flow and relative bed composition. The sediment, which was eroded from each bed, was collected post flooding, and was subsequently weighed and graded. The response of each bed to flood could be compared through the interpretation of changes to bed-elevation statistics, and confirmed via comparison of the eroded masses and grain size distributions. Armoured beds developed during this study can be described through the increase of standard deviation, and skewness with increasing armouring flow rate. The increase in standard deviation represents greater variation of the bed surface, due to the relative protrusion of the larger grains (representative of bed roughness). The increase in skewness can be attributed to the accumulation of coarse grains on the bed surface, while smaller grains fill the interstitial spaces between, creating a bed which is stable, and resistant to movement. Once raking had destroyed the armour layer, the raked beds where characterised by larger standard deviation and a negative shift in skewness. The larger standard deviation is a representation of the inherent vertical variation introduced to the bed surface, through the crests and furrows of the raking. The skewness shifting negative is an important development in this study. It illustrated that the process of raking destroying the armour layer can be characterised through changes in statistics. Therefore, characterisation of the final raked bed surface will give an accurate indication of the effect of subjecting a raked bed to flooding, The raked bed showed a significant change in surface character, and a greater mass of eroded material. The raked bed eroded between 30 and 40% more material than the non-raked bed, and the d_{50} of the eroded material from the raked bed was consistently higher. The raked bed surface appears to coarsen beyond the level that could be achieved though the armouring flow rate alone, due to the successive removal of fine material from the surface. This study illustrates that the process of breaking the armour layer on a gravel-bed surface, allows for sediment movement to occur across a bed which previously would have remained stable.

KEY WORDS: Sediment Transport, Beach Raking, New Zealand, Statistical Characterisation, River Management.

1 INTRODUCTION

The process by which gravel bed-rivers develop a coarse surface layer is termed armouring (Parker 1982, Chin 1985). Riverbeds are composed mainly of non-uniform sediments, which as well as being the basis of the armouring phenomena, are also the source of variability within rivers at the basin, reach and grain scales. If the flow conditions are such that selective sediment movement occurs, and all bed particles are not in motion (entrained by the flow), an armour layer will develop on the bed surface. This armour layer will consist of coarser grains than the parent bed material, which are unable to be entrained by the flow. An armour layer acts to increase the resistance of the bed particles to further movement due to inundation by flood flow, and the increased stresses and velocities which accompany increased flow and rising water levels. It also protects the parent bed material, which is inherently finer than the coarse armour layer, and thus more susceptible to movement.

The desire to exert control over an extremely un-predictable and variable process such as river erosion and aggradation has led the Hawkes Bay Regional Council, New Zealand to develop its *beach raking* program. This process involves the manual break-up of the armour layer on the surface of the river beaches, and the reintroduction of the subsurface sediment by a tractor and trailer unit and large metal 'ripping blades' (Figure 1). Theoretically, this aids sediment movement by reducing the gravel's resistance to movement due to inundation and the forces which arise due to the increased water levels during flood. This process is unique to the Hawkes Bay, New Zealand and it is unknown whether this process is undertaken in any other country. As this process is novel, there is limited understanding or research regarding the processes at work, and the overall effectiveness of the *beach raking* programme. Quantitative data analysis to support anecdotal evidence qualifying *beach raking* as a council procedure for aiding sediment movement and flood control is needed to justify this procedure.

Figure 1 Tractor and trailer unit raking a beach on the Waipawa River in the Hawkes Bay (left); The 'ripping blades' used to break the armour layer (right).

The Hawkes Bay Regional Council states that *beach raking* aims to aid gravel movement, remove vegetation and act as a flood control measure. It is thought that the process of breaking of the coarse armour layer, which is present in most gravel-bed river channels, and the reintroduction of fine subsurface material into the surface layer, will achieve these objectives. The gravel beaches alongside the river are relatively stable and resistant to flow induced erosion. During flood, the water rises over these beaches, slowly at first, causing only the finer particles to be entrained by the flow. If the flood is significant, larger gravels, cobbles and even boulders may be entrained. However, the smaller, more regular floods are only capable of moving the finer fraction of the sediment. This causes the larger particles which remain to form a coarse surface layer, or armour layer. It is this armour layer, which is far more stable than the original gravel beaches of mixed sized particles, and thus the remaining sediment is more resistant to movement caused by small flood flow rates.

Controlling this sediment movement is important for river maintenance, flood control and sediment budgeting. Of particular importance in this study are the implications relating the control of sediment movement and subsequent gravel extraction on the rivers in the Hawkes Bay. Gravel extraction is an essential and lucrative industry for both the contractors undertaking the work and the Regional Council. The gravel, which is removed from the rivers, is used for many applications, including to construction fill, the production of concrete, decorative stone, or crushed to be used as roading aggregate.

Scope

This study aims to analyse the effectiveness of the *beach raking* process, and determine whether a raked gravel-bed is more susceptible to erosion than an armoured bed. This will be investigated via a laboratory study where a model will be developed to mimic field conditions including sediment size, flow rate, depth of raking, separation between raking lines and flow depth. The effects of armouring and flood flow rates over a raked and a non-raked gravel-bed will be tested.

Analysis will consist of the interpretation of bed topography data with respect to:

- Trends in erosion and deposition on the raked and non-raked beds.
- Statistical analysis and interpretation of the 1st to 3rd order statistical moments.

As well as sediment analysis, including:

- Collection of the eroded mass from the raked and non-raked beds.
- Particle size distribution of the underlying parent bed material, with respect to the size distributions from the eroded material.

2 STUDY METHODOLOGY

The aim of the present study is to investigate the effectiveness of the *beach raking* process, or the manual breakup of the armour layer in gravel-bed rivers. Due to various environmental constraints and uncontrollable natural phenomena, this study is best performed in a laboratory environment. Here, variables can be controlled, manipulated and scaled, to accurately represent processes which are occurring in the field. This laboratory investigation aimed to prove whether the *beach raking* procedure acts to promote sediment movement in a gravel-bed river. This sediment movement can be represented by an excessive change in bed elevation through erosion and aggradation, or as a change in bed surface structure. This was done by quantifying the differences in response between an armoured bed, and a raked bed in a controlled laboratory flume with simulated armouring and flood flow rates. The study used acoustic bed profilers to map surface topography post armouring and flood flow rates, to determine relative changes occurring to the beds. The data collected via these topography measurements form the basis of the Digital Elevation Models (DEM's), Probability Distribution Functions (PDF's) and statistical analysis.

2.1 Laboratory Flume

The flume used for the experiments was 14.8m long, 2.4m wide, with a maximum allowable flow depth of 0.37m. The maximum flow rate which could be generated in this flume is 273 l/s. This flume has a 2.6m long, 2.2m wide and 0.4m deep sediment recess set into the flume floor. This is located 7m downstream of the flume inlet to allow for a fully developed boundary layer to form, and to protect against significant scouring at the upstream limit of the sediment recess. This sediment recess was suited for an investigation into the comparative erosion of two gravel-bed surfaces. For the purpose of this study, the sediment recess was divided into 4 sections. The two upstream sections were manually filled with gravel, and the two downstream sections are used to collect the eroded sediment from the surface upstream. Measurement equipment was installed on an automated carriage above the sediment recess to measure the bed topography.

2.2 Materials

The sediment used in this study was well graded river gravel from the Tukituki River in the Hawkes Bay with a d_{50} of 7.8mm. The sediment which was placed in the flume had all been sieved to a maximum size of 25mm, this sieving process also acted to re-mix the sediment to a well graded mixture. The gravel beds were created by placing the graded sediment into the sediment recess, starting at the downstream limit, being careful not to segregate or preferentially distribute the mixture.

2.3 Experimental Methodology

The primary objective of the experiments was to isolate the raking procedure to see its effects on an armoured bed. This was done through the investigation of the process by which armour layers form and the difference in response between a raked and a non-raked bed. Below is a summary of how the experiments were prepared, carried out and concluded.

The sediment, which was used in this study, was placed in the flume sediment recesses, and manually screeded to the level of the false floor, using the screeding tool. Sediment had been sieved to a maximum size of 25mm and a d_{50} of 7.8mm. The bed was lightly compacted after screeding to ensure it held together during the initial topography measurement, and to protect against preferential entrainment of particles, which are slightly more exposed to the flow. The sediment trap was cleared to remove any gravel, which had been accumulated during the previous experiment or during the bed construction.

A negligible flow rate was run to inundate the beds while the acoustic depth profiler mapped the screeded bed. This allows for erosion and aggradation to be seen relative to the initial flat bed surface. Also, it allowed for the initial bed to be compared with the subsequent armoured surface, to determine the degree of armouring. This inundation during the screeded measurement allowed the gravel bed to be fully saturated, and removed the trapped air from within the gravel beds (Chin 1985), before it was subjected to the armouring flow rate, mimicking real gravel-bed river behaviour more accurately.

After the screeded bed topography measurement, the flow rate was increased to the armouring flow rate and the surface was allowed to armour at a constant discharge. The duration of the armouring was 24 hours, and at this point sediment movement appeared to become negligible. This armouring flow rate was determined through entrainment or theoretical threshold of motion calculations and was verified by observation of sediment movement and subsequent statistical characterisation.

The flume was then drained overnight so that the bed surface was dry before being subjected to raking. The sediment recess on the true left of the flume was then raked using the specially developed raking tool. After raking, the beds were inundated, while the armoured and raked bed surfaces were profiled. This should theoretically show the flat coarse armoured bed on one side of the flume, with the variable crests and furrows of the raked bed on the other. Care was taken to flood the bed slowly, whenever starting the measurement flow rate. It was essential to preserve the topography of the beds, particularly the raking crests and furrows, which were to be captured by the bed profile.

Following the measurement of the armoured and raked beds, the beds were then flooded for 24 hours as in accordance with Aberle and Nikora (2006). This duration was appropriate as any representative changes to the bed surfaces would have occurred within this time. After 24 hours the flow was reduced to the measurement flow rate, and the final bed surface was mapped using the bed profiler.

The water was drained from the flume, and the sediment traps were carefully emptied and the eroded material was weighed and subsequently sieved to show the grain size distribution of the eroded material.

2.4 Analytical Methodology

The interpretation of the bed topography data with physical evidence from the sediment analysis will lead to a conclusion regarding the effectiveness of *beach raking*.

The bed surface was treated as a random field of bed elevations z(x,y), where z is the bed elevation at point x, y (transverse and longitudinal to flow). This approach allows for the high accuracy application of traditional statistical order moments of mean, standard deviation, skewness and kurtosis, to describe and characterise bed roughness and structure. In the current study, statistical characterisation will be used to indicate gravel-bed armouring as described in Aberle and Nikora (2006). Investigation into the use of statistics to describe the action of the raking breaking apart the armour layer on the bed surface will be explored. Subsequently, the influence the raking procedure has on bed-surface changes due to flooding can be observed via changes to the statistical order moments. The comparison of the response of an armoured bed, with a bed which had been subjected to raking, will give an indication of the effectiveness of the raking at promoting sediment movement. The conclusions drawn from the random-field approach determining the effectiveness of gravel-bed raking will be confirmed by aspects of traditional sediment analysis.

Statistical characterisation has successfully been used to interpret alluvial beds (Coleman et al. 2011), and to measure apparent armouring effects on gravel beds (Aberle and Nikora 2006). In this study, the use of the parameters outlined in this section will be investigated to describe the response of an armoured gravel bed to raking. As standard deviation can be used to describe gravel-bed roughness, and there are links between armour layer development and relative skewness values, it is thought that armour layer destruction could be characterised by these parameters also. The response of the raked gravel bed to flooding can also be described by the same statistics, and compared with those from a non-raked bed. The statistical characterisation of the gravel-bed topography data, aligned with physical evidence from the eroded sediment, will constitute the analysis for each experiment.

3 RESULTS AND DISCUSSION

The results depicted in this section are from an experiment where the bed was armoured with a high flow rate, to provide a stable and coarse armour layer with a high degree of armouring. Subsequently, raking destroyed one side of the bed, which was then flooded with a low flow rate. If raking does increase the propensity for particles within a gravel bed to be entrained by the flow rate, this low flow rate should be able to entrain the finer fraction of the bed which is exposed during raking, while the non-raked be should remain stable.

3.1 Contour Plots

In Figures 2 and 3 the raking lines can be seen prominently after the post-armouring measurement. Post flood flow rate, there is still some evidence of the raking lines remaining on the raked bed (Figure 2), this is to be expected as the flow rate was not designed to be large enough to completely flatten and re-armour the bed. It was designed to entrain the finer grains, which were reintroduced to the bed surface from the subsurface material. The non-raked bed appears to have changed very little (Figure 3), with only a slight reduction in the variation of elevations. It appears to have flattened and subsequently re-stabilised due to the lower flood flow rate. This is associated with local grain movement, in an act to re-stabilise the bed and is not representative of sediment being entrained and eroded.

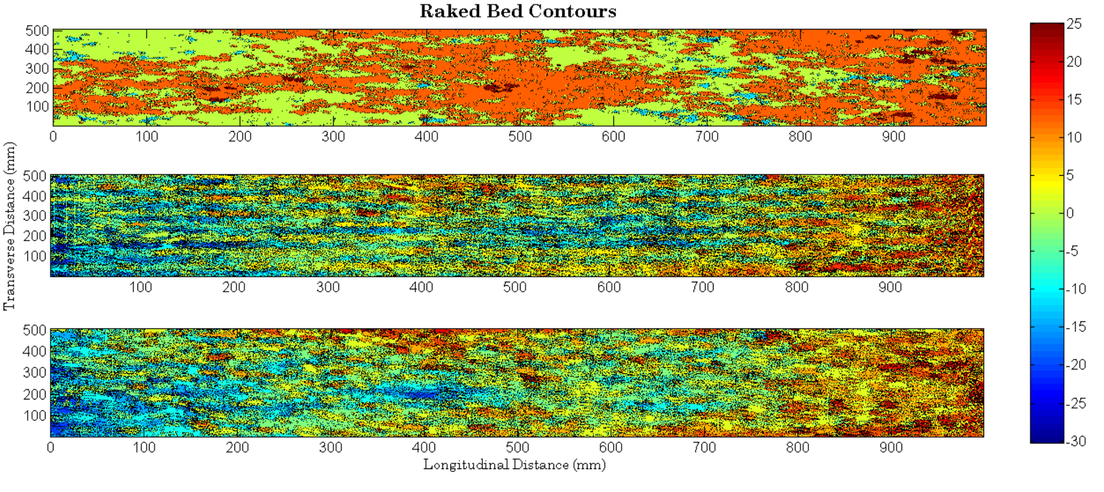

Figure 2 Raked bed contours (units in mm) – screeded (top), raked (middle) and flooded bed (bottom)

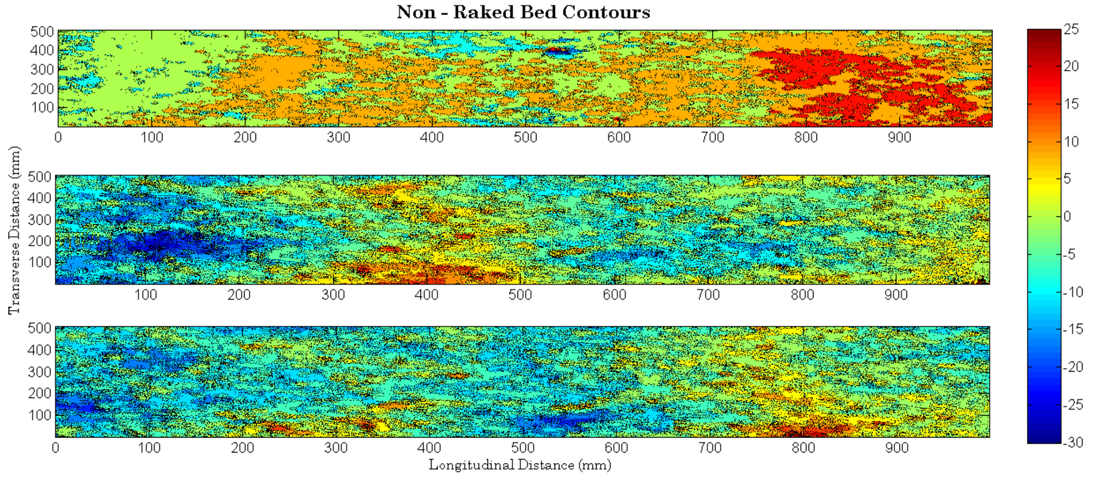

Figure 3 Non-raked bed contours (units in mm) – screeded (top), armoured (middle) and flooded bed (bottom)

3.2 Cross Sections

Figures 4 and 5 both show that there appears to be a considerable amount of erosion at the upstream end of the measurement window during the armouring phase, with subsequent deposition at the downstream end. Variability in the bed elevation, induced by the raking, can be seen in the raked-bed cross sections, however the upstream end of the non-raked bed also exhibits considerable variation.

The post-flood cross sections of the raked bed are at consistently higher elevations than the post-armouring cross sections. This is indicative sediment movement into the system from upstream.

The levels of the non-raked bed remained particularly stable, especially in the downstream section. This was expected, as the lower flood flow rate should not have been able to entrain many of the particles on the bed surface. There is some evidence of deposition on the surface, however this appears to be a result of the bed re-stabilising itself after an extensive and destructive armouring flow rate.

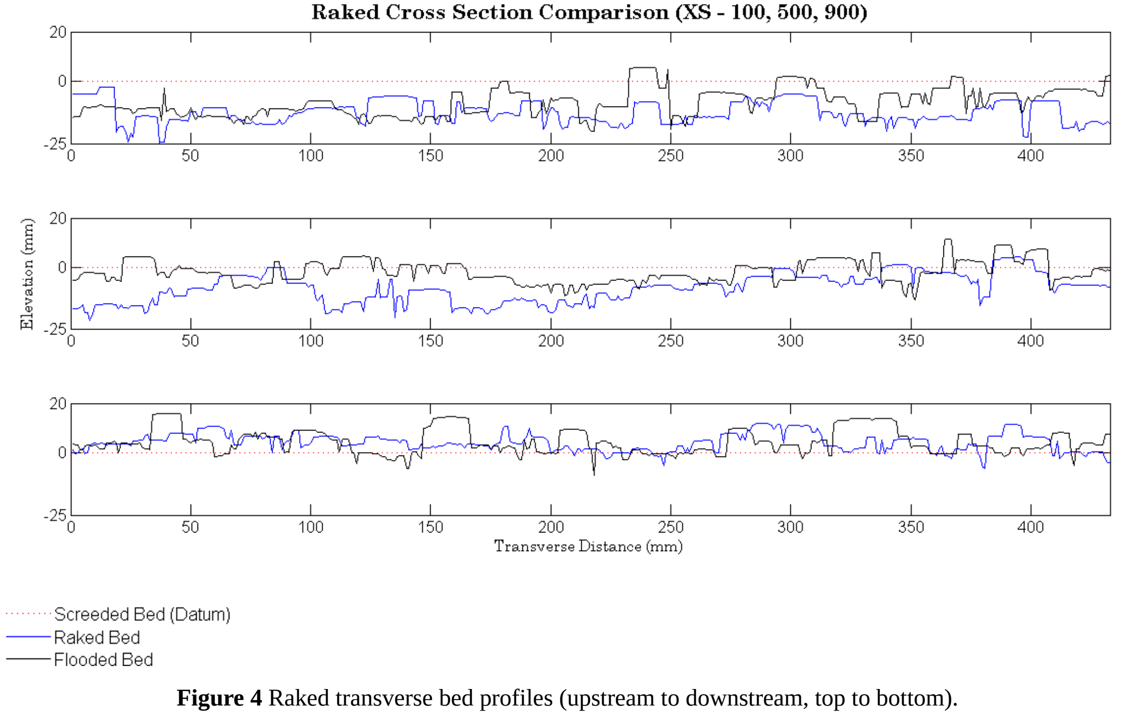

Figure 4 Raked transverse bed profiles (upstream to downstream, top to bottom).

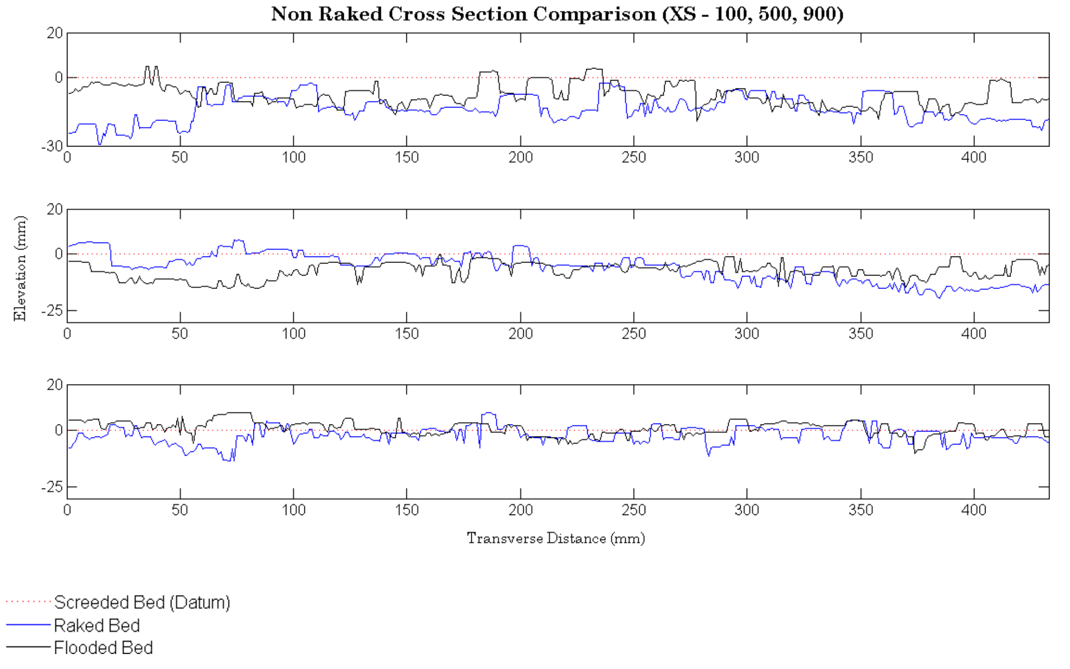

Figure 5 Non-raked transverse bed profiles (upstream to downstream, top to bottom).

3.3 Statistics

Table 1 shows the statistical order moments of mean, standard deviation and skewness for selected cross sections. The decrease in mean bed elevation for both beds is consistent with considerable sediment movement due to a high armouring flow rate. The raked-bed elevation is slightly raised overall, due to the influence of the raking on the bed surface. Both beds also show an increase in mean bed elevation post flood, however the raked bed increases significantly more than the non-raked bed. This greater change in bed elevation implies a far greater propensity for sediment movement on this bed.

Post armouring, both standard deviations increase significantly, with the non-raked bed having a slightly lower value than that of the raked bed. This is consistent with other raked beds, as the raking introduces an inherent variation into the gravel surface.

Table 1 Statistical order moments of mean, standard deviation and skewness for selected cross sections

	Mean [mm]		**Standard Deviation [mm]**		**Skewness [-]**	
Bed Measurement	Raked Bed	Non-Raked Bed	Raked Bed	Non-Raked Bed	Raked Bed	Non-Raked Bed
_screeded	0	0	0.002	0.003	-0.7	-0.9
_armoured	-1.9	-2.4	7.6	6.6	-0.2	-0.03
_flooded	0.2	-2.1	6.8	6.4	0.3	0.2

Post flooding, the standard deviations of both beds decrease. The lower flood flow rate, which has been employed, was designed to entrain the finer sediment exposed by the raking. It appears that this lower flow rate has effectively done this, and as a result has flattened the raking lines. Both post flood standard deviations are lower than the post armouring values, albeit the non-raked beds values are very similar, indicating an apparent stability. However, there is still evidence to suggest that the undulations introduced by the raking remain on the bed surface, as the final standard deviation of the raked bed is higher than that of the non-raked bed.

The skewness of the non-raked bed is sufficiently higher than that of the raked bed, indicative of a coarsened surface. The post raking bed is far more negatively skewed than the armoured bed, which is indicative of the broken armour layer on the bed surface. However, interestingly the non-raked bed does not exhibit a positive skewness, which is commonly associated with an armoured bed. Post flooding, the skewness of both beds shifts positive, indicating an even coarser final bed surface. This is expected for the raked bed, where the fines have been stripped twice from the bed surface, and apparent excessive coarsening takes place. This excessive armouring has been proposed as an outcome of flooding a bed which has been subjected to raking. The non-raked bed also shows a shift towards positive skewness, which in itself is not surprising, however this bed should have remained stable over this low flow rate.

3.4 Probability Density Functions

The water worked beds (post armouring and flooding) display far shallower and wider PDF's than the screeded beds (Figure 6). The reorganisation of particles results in a more variable bed surface and thus, a shallower PDF. Post armouring, the raked bed exhibits a slightly right skewed curve, where as the non-raked beds curve is slightly left skewed. As previously established, raking reduces the compaction of the bed, and creates crests higher than the comparative armoured bed surface, this increase in bed elevation is the reason for the slight shift to the right. Post flooding this curve shifts slightly back left, signifying erosion of the bed surface. Interestingly the curve becomes slightly steeper, which could indicate the bed leveling and stabilising after the flood flow rate.

The non-raked bed shifts very little post flood. This suggests that the bed is relatively stable under this flow rate, which is a positive outcome. The steepness of the curve increases slightly, which could again represent the bed reorganising itself and becoming more uniform in general.

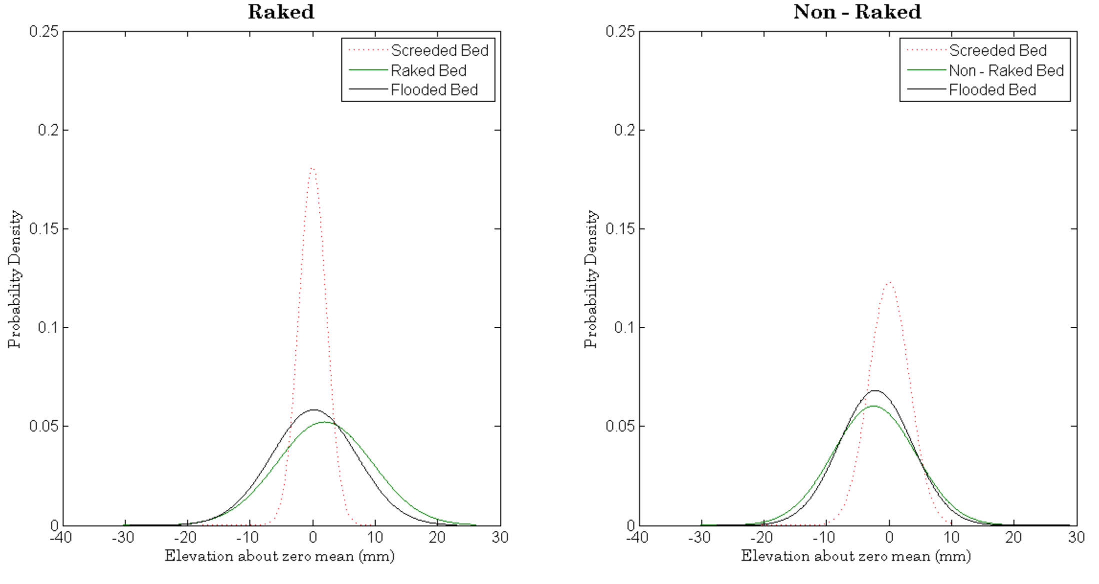

Figure 6 Probability density functions showing the distribution of the bed elevations relative to a zero datum.

3.5 Sediment Analysis

There was considerably more eroded material collected from the raked bed than the non-raked bed in this experiment (Table 2). The material, which was collected from the raked bed, also had a significantly larger mean grain size (d_{50}). Figure 7 shows the grain size distributions.

Table 2 Mass of eroded material from the raked and non-raked beds

Bed	Eroded Mass (g)	d_{50} (mm)
Raked	2110.3	7.47
Non-Raked	655.5	5.27

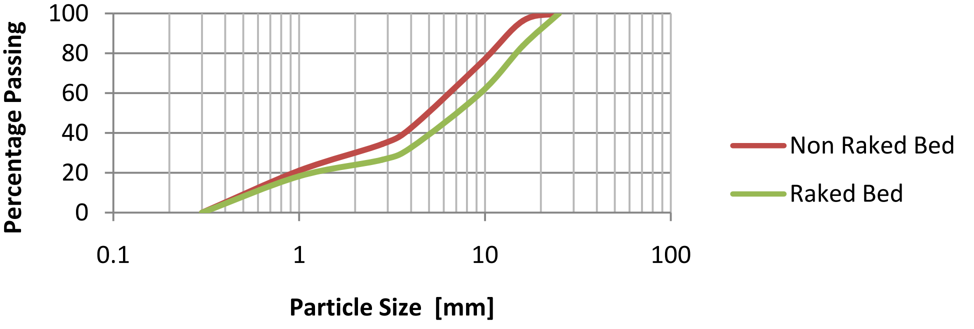

Figure 7 PSD of the materials eroded during the flood phase of the experiment.

3.6 Discussions

The ability to create a stable armour layer was essential for determining the response of a raked bed as compared to an armoured bed post flooding. If the bed was not properly armoured, or at least coarsened, the flood flow rate would act to destroy both beds uniformly and no conclusions could be drawn. To investigate the cause of gravel-bed armouring was one of the objectives of this investigation.

When comparing the raked bed with the naturally coarser non-raked bed, certain differences in statistics are representative of the breakup of the armour layer, and the introduction of innate randomness due to the raking. It appears that the actual process of raking the armour layer changes the character of the bed significantly, thus a differing response to flood flow rates is expected. The ability to characterise the physical breakup of the armour layer through statistical analysis is a significant result for this study.

Raking physically breaks the coarse armour layer, which covers the bed of parent material. This inherently reduces the overall compaction of the bed which can be seen as an increase in bed elevation when compared to a non-raked bed. This reduction in compaction reduces the magnitude of the interparticle friction forces holding a given particle into the bed, thus reducing the forces needed to entrain it. As the whole bed is experiencing this reduction of friction force, inherently the bed is easier to erode. Theoretically, this could lead to the coarse particles being able to embed more readily into the less dense surface, which after an extended duration could create an even more stable armour layer. The raking also acts to re-introduce the fine portion of the parent bed material back into the exposed surface. This fine portion would have been eroded during the armouring flow rate and its subsequent re-introduction to the surface reduces the apparent coarseness of the gravel bed. It is this finer sediment, which will theoretically be entrained during the subsequent flood event, leading to a decrease in bed elevation, and general sediment movement downstream.

Statistical characterisation illustrates the difference in nature of a raked bed as opposed to a bed which is left armoured. The action of raking the bed caused the mean bed elevation of the bed post raking to be consistently higher than that of the non-raked bed. The standard deviation of the raked bed is significantly higher than that of the non-raked bed, due to the variation introduced by the raking (i.e. troughs and furrows, as well as general randomness). The skewness is considerably lower for a raked bed (usually negative), which is significant as positive skewness is commonly associated with a stable armour layer.

It was seen during this experiment that the mean bed elevation within the measurement window finished at a higher level than that of the screeded bed. The only explanation for this is that the sediment eroded at the upstream limit of the sediment recess is being deposited within the measurement window. As the effectiveness of *beach raking* relates to the overall ability to entrain sediment from the bed, it can therefore be assumed, that any significant change in bed elevation (albeit positive or negatively shifted about the datum) is perceived to represent a greater propensity for erosion.

This study sees the non-raked bed remain stable during the flood flow rate, where the raked bed erodes. This was confirmed by the masses of eroded material, where the raked bed eroded a larger quantity of sediment with a coarser d_{50}, and by statistical characterisation which showed the non-raked bed remained stable with respect to roughness parameters and the raked bed was greatly affected by the flood flow rate and altered characteristics considerably.

4 CONCLUSIONS

4.1 Primary Conclusions

At the beginning of this study, the primary objective was to determine whether a raked gravel bed is more susceptible to erosion than an armoured bed. From the interpretation of the data collected during the laboratory study, the following conclusions can be drawn to meet the objectives outlined above.

- Armoured beds, which have been raked, show greater signs of sediment movement than armoured beds, which are left non-raked.
    - Changes in mean bed elevation of a raked bed are larger than changes in mean bed elevation of a non-raked bed.
    - Raked beds characterisation via 1^{st} – 3^{rd} order statistics suggest a raked beds response to flow is more significant than a non-raked beds response.
- Raked beds tend to erode more material during flooding than a non-raked bed
    - The eroded material from a raked bed is consistently coarser than the material eroded from a non-raked bed.

4.2 Further Conclusions

- Raking will actively alter the armoured bed surface by:
    - Breaking the armour layer of coarse particles on the bed surface
    - Re-introducing the sub-surface fine grains to the exposed surface
    - Reducing the compaction of the bed. Thus, elevating the bed level and reducing the interparticle forces keeping individual particles attached to the bed.
- Flooding a raked bed, as compared to a non-raked bed, will result in:
    - Preferential entrainment of the exposed fine grains on the surface of the raked bed
    - Secondary entrainment of the larger grains which would normally be embedded in the armour layer
    - A greater mass of eroded material collected from the raked bed
    - A coarser sediment grading of eroded material from the raked bed
    - A coarser final bed surface than should be able to form at the given flow rate on the raked bed (especially under sediment starvation).

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