# Waimakariri River bed sediment movement for ecological resetting

**NIWA Client Report: CHC2008-016**
**March 2008**

**NIWA Project: ECN08515**

# Waimakariri River bed sediment movement for ecological resetting

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*Prepared for*

Environment Canterbury

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# Executive Summary

Environment Canterbury (ECan) has requested NIWA to determine the flood flow at which the median flow river bed is disturbed sufficiently to reset the benthic ecology. The context is in relation to the application by Central Plains Water Enhancement Scheme (CPWES) to extract up to 40 $m^3s^{-1}$ from the Waimakariri River in addition to the ~22 $m^3s^{-1}$ that is already allocated for abstraction. A wider context is the need to review the allocation framework for the Waimakariri River.

The approach used was to measure the surface bed sediment size distribution in the median flow (93 $m^3s^{-1}$) bed and to use criteria from the literature as a basis for estimating the bed shear stress for surface flushing of fine particles and flushing of the armour layer. CPWES is expected to double the time the flow is maintained at about 41 $m^3s^{-1}$ so a similar exercise was also carried out for the bed inundated at that flow.

The surface bed material sampling found the median grain size to be 28 mm and this was consistent with published values.

Hydrodynamic models were run for flows over the range 93 $m^3s^{-1}$ to 768 $m^3s^{-1}$ for the median flow bed and 40 $m^3s^{-1}$ to 768 $m^3s^{-1}$ for the minimum flow bed. Considering the median flow bed, flows of 288 $m^3s^{-1}$ were sufficient to flush fine particles from 77% of the bed and to deep flush 55% of the bed. For the minimum flow bed, flows of 288 $m^3s^{-1}$ were sufficient to flush fine particles from 79% of the bed and to deep flush 58% of the bed. At these flows the main braids are almost completely flushed with most of the unflushed areas in patches in minor braids. These results give a minimum area for ecological resetting because the method predicts only vertical erosion and does not take into account areas of deposition and lateral erosion. Lateral erosion is a significant mechanism for bed movement in gravel bed braided rivers such as the Waimakariri River. However, in the context of ecological resetting lateral scour of the dry river bed is not relevant and areas of shallow deposition may be recolonised quicker than scoured areas because of recolonisation by the buried invertebrates.

Based on modelled velocity, long filamentous algae was scoured from 80% of the minimum flow bed at a flow of 82 $m^3s^{-1}$ and from 80% of the median flow bed at a flow of 130 $m^3s^{-1}$. Both short filamentous algae and diatoms would be removed from ~80 % of the bed by surface and deep flushing at a flow of 288 $m^3s^{-1}$ before being scoured by velocity alone.

Observations of river bed and benthic invertebrate presence/absence before and after a 542 $m^3s^{-1}$ flood confirmed the pattern of bed disturbance indicated by the modelled bed shear stress.

Hydrograph analysis shows that most inter-fresh durations for flows of 288 $m^3s^{-1}$ are short with a median duration of 14-16 days, but can be as long as 312-417 days depending on the abstraction regime, with the maximum duration increasing with size of take.

# 1. Introduction

Environment Canterbury wishes to determine the flood flow at which f the river bed occupied by the median flow is disturbed sufficiently to reset the benthic ecology. The context is in relation to the application by Central Plains Water Enhancement Scheme (CPWES) to extract up to 40 $m^3s^{-1}$ from the Waimakariri River in addition to the ~22 $m^3s^{-1}$ that is already allocated for abstraction. A wider context is the need to review the water allocation framework for the Waimakariri River.

The assumptions being made are that the productivity of the river is based on the area occupied by the median flow and that to maintain the health and productivity of the river the median flow bed needs to be disturbed periodically to remove excess periphyton growth and fine particles. Also of interest is the flow required to disturb the minimum flow bed, as irrigation abstraction will sometimes flat-line the river at the minimum flow.

Flushing flows have both a beneficial and detrimental effect on rivers. In the short-term, they result in a loss of productivity, but in the long-term biota benefit through the improvement in habitat quality. The detrimental effect of high flows on stream biota is largely a result of the high water velocities and bed sediment movement (Jowett & Richardson, 1989; Scrimgeour & Winterbourn 1989).

Traditionally the interest in flushing flows has been to control periphyton biomass and cover for maintaining aesthetic, recreational and biological values. In relation to the latter a particular interest is identifying the flow, or flow range, that will disturb the bed to such an extent that a substantial portion of the periphyton and invertebrates are lost from the reach due to abrasion and bed mobilisation. Traditionally the aim has been to preferentially flush invertebrates that tolerate high algal biomass and poor water quality and retain “clean water” taxa, such as mayfly and large caddis fly larvae, that tend to be larger, drift prone and better foods for fishes and birds. An additional, new, reason for identifying flows that flush and reset benthic invertebrate communities is related to predicting the effect of “flat lining” on invertebrate productivity. Flat lining is the extreme result of abstracting from flow recessions. Smaller allocation volumes have lesser effects on the hydrograph but still potentially erode productive invertebrate habitat during flow recessions. Currently a model is being developed by Cawthron Institute and NIWA to quantify the effects of abstraction over flow recessions on productive invertebrate habitat and relative biomass. Key parameters of the model include colonisation time and the magnitude of floods that meet predetermined thresholds for resetting invertebrate biomass. It is assumed that the later is related to the proportion of the bed that is mobilised.

The objective of this study was to determine the flood magnitude required to disturb the Waimakariri River bed sufficient to reset the benthic ecology of the river. The frequency of occurrence of such flows before and after abstraction can be assessed to determine the effect of the proposed CPW abstraction or proposed allocation frameworks on the frequency of disturbance.

The work is based on a 2D hydrodynamic model of a 3 km reach of the Waimakariri River at Crossbank. The model is based on topography captured by airborne laser survey and wet channel topography in February 2000 (Hicks et al 2008).

# 2. Approach

The approach was to:

- Collect surface bed material grain size data for representative riffles, runs, pools and bar surfaces.

- Use the above information to map grain size distributions in the median flow (93 $m^3s^{-1}$) channels of the existing Waimakariri River 2D hydrodynamic model.

- Use the existing 2D hydrodynamic model to calculate bed shear stress at a range of steady flows and hence the proportion of the median (or minimum) flow bed where the surface is flushed of fine material and where the bed is deep flushed (surface bed material moved). Model calculations of velocity and the proportion of the bed where certain velocity criteria were exceeded were used to determine periphyton scour.

- Determine the criteria for assessing the degree of flushing that is sufficient to reset the benthos.

- Use the criteria and extent of flushing to determine the critical flows.

# 3. Setting

This work was carried out on the Crossbank reach of the Waimakariri River primarily because of the existence of a 2D hydrodynamic model for the reach (Cornell and Connell 2001, Duncan 2001, Duncan et al.2003). Data from the model has been used to assess the relationship between flow and physical habitat for a number of riverbed animals and plants. The Crossbank reach is about 18 km from the mouth. According to Griffiths (1979) this location is about where the river changes from a degrading reach to an aggrading reach. The model domain has the low relative relief, multi-channel and low level armouring characteristics of an aggrading reach. Griffiths (1979) notes that the $d_{85}$ grain size (grain size for which 85% of a sample is smaller than) reduces more or less linearly from about 120 mm at the lower gorge to about 90 mm at Crossbank, from where it reduces at a faster linear rate to become about 20 mm just downstream of the Railway Bridge. Coincident with the different grain sizes are different bed slopes with steeper slopes upstream and shallower slopes down stream. Thus we are unsure whether or not the results of the modelling are transferable either upstream or down stream of Crossbank. However, as the grain size, bed slope and braiding intensity are more or less in equilibrium throughout the river it is likely that the results of this study also apply elsewhere on the river.

The other issue is that while the bulk bed material size distribution at any location is fairly constant with time the bed surface material size distribution will vary with time and space. Carson and Griffiths (1989) sampled the bed surface of 34 areas and obtained a strong mode for $d_{50}$ of 24-26 mm. Freshly deposited material ranged in $d_{50}$ from 12 mm to 36 mm, averaging 24 mm. Griffiths (1979) had earlier assessed a $d_{50}$ of 28 mm for the same reach. The difference between a $d_{50}$ of 24 mm and one of 28 mm may not seem significant but bed load yield over a 15 month period calculated by Carson and Griffiths (1989) varied by 33% depending on which median grain size was used.

# 4. Methods

## 4.1. Surface bed material sampling

The river bed surface was sampled using the Wolman (1954) principle. About 300 particles were measured along transects at each of 15 sites in an attempt to get a good measure of the larger particles at each site. Particles were taken from parallel transects 0.5 to 1 m apart and 30-50 m long at each site until 300 particles had been sampled. Particles for measurement were those under each 0.5 m mark of a tape stretched across each transect. In addition we measured the largest visibleparticle in the vicinity of the transects at each site. Most sampling sites were alongside the main channels when the discharge at the Old Highway Bridge recorder was ~34 $m^3s^{-1}$. The assumption being that at the median flow (96 $m^3s^{-1}$), or higher, most of the sampling sites would be under flowing water. Particles have lengths, breaths and heights commonly referred to as the x, y and z axes. The Wolman method essentially measures the y axis. The smallest category we used was for particles with a y-axis of <8 mm. Most of the particles in this category were silt or sand.

## 4.2. Flow modelling

The work is based on a 2D hydrodynamic model of a 3 km by 1 km reach at Crossbank on the Waimakariri River. The model is based on topography captured by digital photogrammetry and wet channel topography in February 2000 (Hicks et al 2008). The model is described by Beffa and Connell (2001) and Connell et al. (2001). The Waimakariri model assumes a fixed bed, has a fixed 2 m by 2 m square grid, and uniform hydraulic roughness. This is the same model and grid size as has been for instream habitat assessment in other studies e.g., Jowett et al. 2007. An earlier version of the model used a 2 m by 4 m rectangular grid. The smaller grid is better because it allows the model river bed to fit more closely to the digital terrain model on which it is based. Increased computer computational speed and larger memory allowed the grid size to be reduced.

The model was run at steady flows of 96 $m^3s^{-1}$ (median flow), 123 $m^3s^{-1}$ (3 times the minimum flow), 192 $m^3s^{-1}$, 288 $m^3s^{-1}$, 384 $m^3s^{-1}$, 480 $m^3s^{-1}$, 576 $m^3s^{-1}$, 672 $m^3s^{-1}$ and 768 $m^3s^{-1}$ (multiples of the median flow). Model runs were also available from previous studies for every 10 $m^3s^{-1}$ from 40 $m^3s^{-1}$ to 130 $m^3s^{-1}$.

## 4.3. Channel morphology mapping

The reason for channel morphology mapping is to relate the measured surface bed material grain size and its channel morphology to that of the model, e.g., if we find that particular morphologies have characteristic bed material sizes then we can assign appropriate critical bed shear stress (the minimum bed shear stress required to move a particle) values to each morphology in the model.

Two approaches were taken for channel morphology mapping:

- The approach of Jowett (1993) where either Froude number or depth to velocity ratio is used to classify flow into riffles, runs and pools. Froude number is a direct output of the 2 d modelling programme and a post processing programme can produce velocity to depth ratios for each model cell.

- The second approach was to stereoscopically view vertical aerial photographs of the modelled reach and to make a subjective assessment of the channel morphology based on the water colour and water surface appearance. e.g., flat surface for pools, wavy surface for runs and a broken water surface for riffles and the underlying topography.

The two approaches were compared. This involved a comparison of the results from the classification of the modelled flow of 96 $m^3s^{-1}$ with the flow on the day of aerial photography of 74 $m^3s^{-1}$.

To classify the channel morphology we preferred to use the depth to velocity ratio rather than Froude number because we believe the former is more robust over a range of river sizes. The Waimakariri River with its median flow of 96 $m^3s^{-1}$ is much larger than the river that Jowett used (9.2-23 $m^3s^{-1}$) to determine the classification criteria.

## 4.4. Criteria for bed movement

A key decision for this work was to determine the critical dimensionless bed shear stress (i.e., when bed particles just begin to move). We considered that this relatively low threshold for bed movement should be sufficient for our modelling aim because a flood can be expected to last for at least 12 hours and so even if only a few particles are in motion at any one time much of the bed is likely to have moved over this period.

Disturbance criteria were taken from Milhous (1998), who suggested that a dimensionless shear stress of 0.021 is sufficient to flush fine sediment deposits but not disturb the armour layer. Armour disturbance was assumed to begin when the dimensionless shear stress exceeded 0.035 (Milhous 1998; Jowett 2006). The criteria Milhous used to determine the flushing flow were the cross-section median surface grain size, cross-section averaged hydraulic parameters and the need to exceed threshold critical shear stress in 19 out of 20 cross-sections. His study river had a mean flow of 73 $m^3s^{-1}$ which is similar to the flow of interest in the Waimakariri River. Using cross-section averaged values will take into account the lower shear stress areas near banks. In this application we use model cell values rather than cross-section averaged values of bed shear stress that include low bed shear stress bank and shallow bar areas and thus the criteria to exceed threshold critical shear stress in 95% of cross-sections may need to be relaxed. In our model bed shear stress varied from 0 $Nm^{-2}$ to >59 $Nm^{-2}$ at median flow.

## 4.5. Determination of the area of the bed in motion

A mask of the median flow (96 $m^3s^{-1}$) channel configuration was laid over modelled bed shear stress for a range of flows and the portion of the bed under the mask that exceeded the critical bed shear stress for both surface flushing of fines and disturbance of the armour layer ($d_{50}$ of reach averaged bed material) was determined.

The area of the bed at the minimum flow (flow below which irrigation abstractions must cease) of 41 $m^3s^{-1}$ is also relevant. The river will be held at this flow or lower for prolonged periods under the proposed Central Plains Water Enhancement Scheme and it would be of interest to determine the flow at which most of the minimum flow bed area and benthos is disturbed. So the same bed disturbance analysis was undertaken for this flow as was done for the median flow.

## 4.6. Determination of the critical flow for ecological resetting

There are a number of issues to be resolved:

- The base flow against which the criteria will be judged (median flow, minimum flow or some other flow),
- The relevance of the minor channels flowing at the base flow,
- Whether to use the percentage area affected by surface flushing or deep flushing,
- How much flushing is enough to reset benthic ecology?

The base flow could be any flow judged to be relevant. In this case we have used both the median flow and the minimum flow. Other flows, such as the minimum flow for any new abstraction, could also be analysed.

While it is relevant to determine the extent of bed disturbance of all braids at the minimum flow because they provide useful habitat for a long period, the extent of disturbance of median flow minor braids may be less critical, as some are likely to dry up as flows fall below median flow.

While it is clear that the area of deep flushing would certainly amount to a resetting of the habitat for invertebrates, there are arguments to say that surface flushing would also result in resetting as the moving fines would abrade the periphyton and deprive the invertebrates of a food source. When there is surface flushing there is also a portion of the bed that is deep flushed. In addition to the areas of vertical erosion identified by flushing, there are also portions of the bed that are scoured by lateral erosion and subject to deposition. The area of lateral erosion of the dry bed may not be relevant to ecological resetting even though it does provide new habitat, but the areas of deposition may be quickly recolonised by invertebrates moving up through the loose gravel from the surface that was previously the bed.

How much flushing is enough? Following the arguments above, one might conclude in relation to the median flow channel that flushing of most of the main braids is all that is required, while for the minimum flow channels all the channels needs to be flushed. Jowett et al. (2008) say that “flushing flow or channel maintenance flows cause movement over part of the stream bed only (except in uniform channels with uniform substrate). Sediment transport occurs at practically all flows and as the flow increases the amount and size of sediment transported increases. Some areas of the stream bed will resist movement more than others, so that the area of a stream bed that is disturbed by high flows gradually increases as the flow increases. A suitable flushing flow might be the flow that flushes 80% of the river bed that is submerged at base flow. The area that is to be flushed is an arbitrary decision that must be made when deciding on a flow”.

Sagar (1986) studied the effects of floods on the invertebrate fauna of the Rakaia River. Generally, invertebrate abundance was inversely related to antecedent discharges. Invertebrate abundance decreased at mean daily flows greater than 400 $m^3s^{-1}$ and lowest densities were recorded following floods in excess of about 550 $m^3s^{-1}$. These flows correspond to ~2.5 and ~3.5 times the Rakaia River at Gorge median flow of 161 $m^3s^{-1}$.

Biggs and Close (1989) studied periphyton in relation to flows and nutrients and the study rivers included the alps fed Rangitata, Rakaia and Waimakariri Rivers. A flood of 311 $m^3s^{-1}$ (~ 3 times the median flow) scoured away filamentous algae and their general conclusion was that flows 5-6 times the preceding base flow were required to scour periphyton in alps fed rivers. They report a study by Irvine and Henriques (1984) in the Hawea River where a flow change of 1.8 times the preceding base flow caused major periphyton scouring. This was consistent with the data of Biggs (1982) that found flow thresholds for periphyton scour at 1.5 and ~5 times the preceding flow. They postulated that the first peak was associated with progressive tearing out of the surface mat and the second with the initiation of bed load movement and associated physical abrasion of the tightly bound cells.

The study of Irvine and Henriques (1984) focused on the effect of increased flows on invertebrates. They found that invertebrates associated with the periphyton were contained in the scoured material, but benthic invertebrates numbers were not increased in the drift even with flows 7 times the previous steady flow of 15 $m^3s^{-1}$. This is consistent with the bed being stable as would be expected in controlled lake-fed river that experienced floods up to 240 $m^3s^{-1}$.

Clausen and Biggs (1977) studied the relationships between benthic biota and hydrological indices in New Zealand rivers. They found that the flood frequency statistic FRE3, that is defined as the annual number of flood peaks (as mean daily values) greater than three times median flow, was the most useful *overall* (their emphasis) flow variable in New Zealand streams. They found that periphyton biomass decreased with increasing FRE3, whereas invertebrate density had an increasing curvilinear relationship peaking at values of FRE3 of 10-15 floods per year. It was clear that FRE3 was not a threshold above which periphyton or invertebrates did not survive. Inspection of their data set reveals that most of their study rivers were small (median of the median flows was 18 $m^3s^{-1}$) and probably single thread. Also they showed the mean cross-section velocity of large rivers at median flow was higher than in small rivers and at three times the median flow was much higher than in small rivers indicating a much harsher environment for aquatic biota. These factors suggest that FRE3 criteria should be applied to large braided rivers cautiously.

For periphyton flushing an alternative approach is to use information on the maximum velocity limit from habitat suitability curves for long filamentous algae, short filamentous algae and diatoms from habitat suitability curves (Appendix 1) of velocity to determine when, for instance, the maximum velocity for each algae type is exceeded on 80% of the median or minimum flow bed.

To summarise the discussion above it would appear filamentous algae are flushed by flows about twice the pre-existing flow and diatoms are flushed by flows about five times the pre-existing flow. In relation to invertebrate resetting Sagar's (1986) study is the most relevant to this study and it indicates that flows about three times the median are required. The study of Sagar (1986) being based on data is probably a more useful indicator of invertebrate resetting than the arbitrary figure of 80% of the bed being flushed as suggested by Jowett et al. (2008).

## 4.7. Field visit after flood

Eight days after the surface bed material survey (8 February 2008 when the flow was ~ 40 $m^3s^{-1}$), the river flooded to a peak value of 542 $m^3s^{-1}$. The flood peak was quite flat and exceeded 500 $m^3s^{-1}$ for about 12 hours. Six days later the river was visited again when the flow was 64.5 $m^3s^{-1}$. Flowing channels were inspected for evidence of bed movement and presence of periphyton and invertebrates. Some areas that were dry on the first visit were flowing channels on the second visit and they too were inspected for bed movement and presence of periphyton and invertebrates.

# 5. Results

## 5.1. Bed material sampling

Table 1 summarises the results of the surface bed material sampling. The average $d_{50}$ of all the samples is 28 mm and is the same as that reported by Griffiths (1979). The average $d_{84}$ was 54 mm. The bars had an average $d_{50}$ of 26.7 mm and an average $d_{84}$ of 51.5 mm. The remaining morphologies have very similar average statistics so the data were combined to give an overall average $d_{50}$ of 28 mm and $d_{84}$ of 55.9 mm. This $d_{50}$ was used in determining critical bed shear stress for the armour layer. Most of the channels appeared to be armoured and imbricated. Much of the very fine material (<8 mm) appeared to be sand or silt that had been deposited between the larger particles by waning flows.

**Table 1:** Summary of the results of the bed material sampling. The numbers in the table show the percentage of particles less than the stated size of their y-axis[1].

| Class | D95 (mm) | D90 (mm) | D84 (mm) | D75 (mm) | D65 (mm) | D50 (mm) | D25 (mm) | D16 (mm) | D8 (mm) | Dmax (y-axis)[1] (mm) |
|---|---|---|---|---|---|---|---|---|---|---|
| Bar | 75 | 61 | 52 | 42 | 34 | 24 | 14 | 11 | 6 | |
| Run | 51 | 42 | 36 | 30 | 27 | 21 | 13 | 10 | 7 | 90 |
| Run | 88 | 79 | 70 | 55 | 42 | 30 | 19 | 16 | 9 | |
| Bar | 82 | 70 | 59 | 48 | 39 | 29 | 18 | 15 | 10 | 150 |
| Bar | 79 | 66 | 56 | 44 | 37 | 28 | 17 | 12 | 7 | |
| Bar | 58 | 50 | 44 | 39 | 34 | 27 | 18 | 15 | 10 | |
| Run | 48 | 41 | 36 | 31 | 25 | 20 | 13 | 11 | 6 | 140 |
| Riffle | 100 | 83 | 70 | 57 | 46 | 32 | 16 | 10 | 6 | 150 |
| Bar | 60 | 47 | 38 | 30 | 24 | 18 | 11 | 8 | 6 | 120 |
| Riffle | 63 | 54 | 45 | 37 | 30 | 23 | 15 | 11 | 7 | 120 |
| Bar | 93 | 80 | 68 | 57 | 47 | 35 | 17 | 10 | 6 | 180 |
| Bar | 84 | 71 | 61 | 53 | 45 | 34 | 19 | 15 | 9 | 170 |
| Bar | 52 | 41 | 33 | 28 | 23 | 18 | 13 | 11 | 8 | 170 |
| Run | 100 | 89 | 79 | 66 | 56 | 45 | 25 | 18 | 7 | 150 |
| Run | 82 | 64 | 55 | 44 | 36 | 27 | 17 | 13 | 8 | 150 |
| Average | 75 | 63 | 54 | 44 | 36 | 28 | 16 | 12 | 8 | 144.5 |

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[1] Particles are measured by measuring their length (x-axis), breadth (y-axis) and height (z-axis).

## 5.2. Channel morphology mapping

The morphological mapping based on Froude number appeared to bias the results with most of the main braids being classified as riffles. This result was inconsistent with the inspection of the stereo vertical aerial photographs (Figure 1) taken at 74 $m^3s^{-1}$ and was discarded as being inappropriate.

**Figure 1:** An aerial view of the Crossbank reach of the Waimakariri River at a flow of 74 $m^3s^{-1}$.

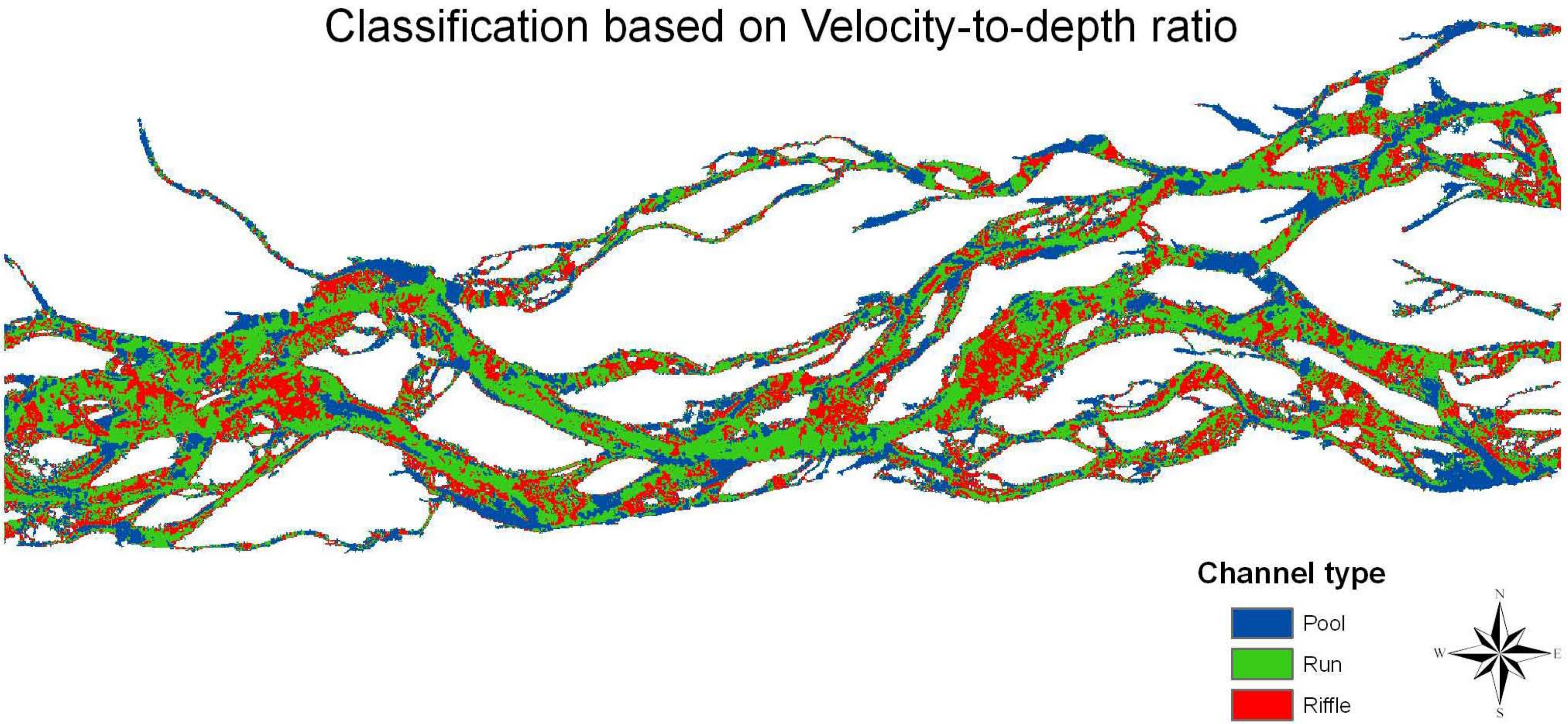

**Figure 2:** The morphological classification based on velocity to depth ratio for a flow of 93 $m^3s^{-1}$.

The morphological mapping based on the velocity to depth ratio for a flow of 93 $m^3s^{-1}$ was more discriminating and corresponded well to the morphological maps based on stereo vertical aerial photographs taken at 74 $m^3s^{-1}$ but some shallow slow water areas that were probably riffles at higher flows were classified as pools by the procedure. Figure 2 shows the results of the morphological classification based on the velocity to depth ratio of the water in each model cell.

It was clear from the aerial photos that the flow of 74 $m^3s^{-1}$ was contained within defined channels and was not flowing over bar tops. It was assumed that this would also be the case for a flow of 93 $m^3s^{-1}$. While there was accurate discrimination of the channel morphology from the modelled velocity to depth ratios there appeared to be very little difference in the average surface bed material distributions of the different classes thus all morphologies were assigned the same bed material composition.

## 5.3. Criteria for bed movement

Most of the non-bar surfaces were armoured to some degree, and thus the critical dimensionless shear stress of 0.035 was used together with the $d_{50}$ of 28 mm of the non-bar surfaces to determine the bed shear stress ($\tau_c$) of 15.9 Pa above which the bed should be deep flushed (Milhous 1998). A critical dimensionless shear stress shear stress of 0.021 {for fines removal (surface flushing)} (Milhous 1998) resulted in a bed shear stress of 9.5 Pa.

The critical bed shear stress was calculated from:

$$\tau_c = E_f * (\rho_s - \rho) * g * d$$

Where:

$E_f$ is the critical dimensionless shear stress (0.035 for the armour layer, 0.021 for fines) (Milhous 1998),

$\rho$ is the density of water (1.0 t $m^{-3}$),

$\rho_s$ is the density of the bed material (2.65 t $m^{-3}$),

g is the acceleration due to gravity (9.81 m $s^{-2}$),

and d is the particle median diameter (28 mm) (Shields 1936).

## 5.4. The relationship between flow and bed movement for the median flow bed

Figure 3 shows the predicted relationship between flow and the percentage of the median flow bed that is disturbed sufficiently to remove fines and the armour layer. As the flow increases the percentage of median flow bed that is disturbed increases and there is no obvious inflection point. Figure 4 shows the area of the river bed at a flow of 93 $m^3s^{-1}$ (closest model run to the unmodified median flow of 96 $m^3s^{-1}$) that is flushed of fine sediment (surface flushing) (46% of the median flow bed) and the area of armour disturbed (deep flushing) (27% of the median flow bed) in the Crossbank Reach of the Waimakariri River. There is clearly a large portion of the median flow bed that is not being flushed and it is the deeper and faster portions of the main braids that are being flushed.

If the pre-existing flow is accepted as being the median flow of 96 $m^3s^{-1}$ then the critical flow for long filamentous algae is 192 $m^3s^{-1}$. At that flow 66% of the median flow bed is being surface flushed and 44% is being deep flushed (Figures 3 and 5). The critical flow for diatoms of 5 times the pre-existing flow is higher than that for invertebrate resetting and is clearly too high in this case. Using Sagar's (1986) criteria for invertebrate resetting the critical flow is 288 $m^3s^{-1}$ when 77% of the median flow bed is being surface flushed and 55% is being deep flushed (Figures 3 and 6). The value for surface flushing is close to the 80% suggested by Jowett et al. (2008).

Figure 5 shows the degree of flushing for a flow of 192 $m^3s^{-1}$. When there is surface flushing there is also a portion of the bed that is deep flushed and when flows are greater than 50 $m^3s^{-1}$ to 70 $m^3s^{-1}$ there is more deep flushing than surface flushing. Figure 6 shows the degree of flushing at a flow of 288 $m^3s^{-1}$ when most of the main braids are being flushed. Even when the modelled flow is nearly 800 $m^3s^{-1}$ (not shown) there is still 7% of the median flow bed that is not flushed. These refuge areas are spread all over the river bed and may explain the rapid recolonization of braided rivers by invertebrates after significant bed moving floods. This observation is consistent with comments of Gray and Harding (2007) who note that river populations are largely supplied by stable spring and edge channels.

## 5.5. The relationship between flow and bed movement for the minimum flow bed

Figure 7 shows the modelled relationship between flow and the percentage of the 41 $m^3s^{-1}$ minimum flow bed that is disturbed sufficiently to remove fines and the armour layer. If the pre-existing flow is accepted as being the minimum flow of 41 $m^3s^{-1}$ then the critical flow for long filamentous algae is 82 $m^3s^{-1}$ . (41 x 2 = 82) (see Section 4.6). At that flow 35% of the median flow bed is being surface flushed and 17% is being

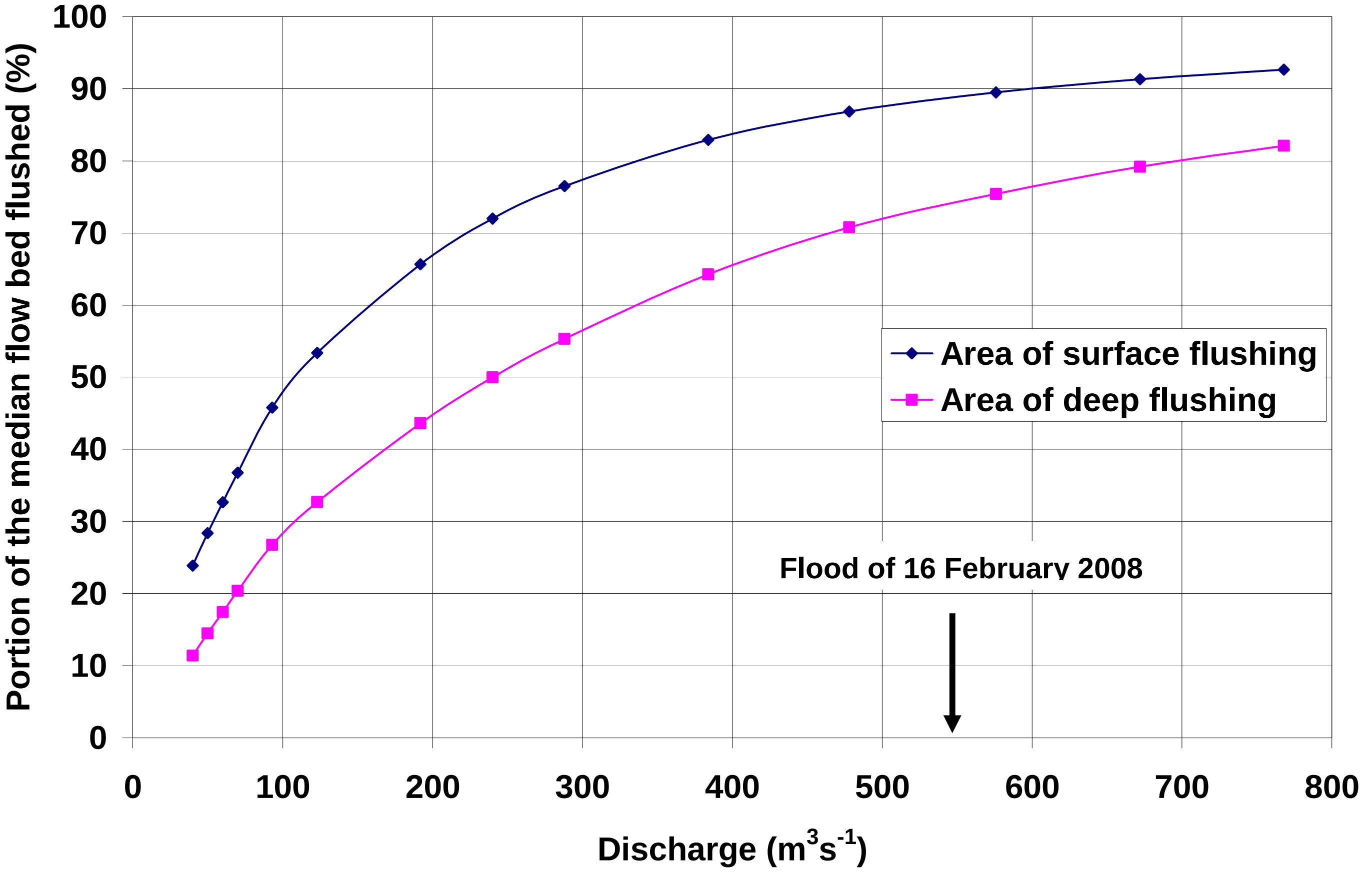

**Figure 3:** The area of median flow (96 $m^3s^{-1}$) river bed that is flushed of fine sediment (surface flushing) and the area of armour disturbed (deep flushing) at Crossbank Reach of the Waimakariri River at a range of flows.

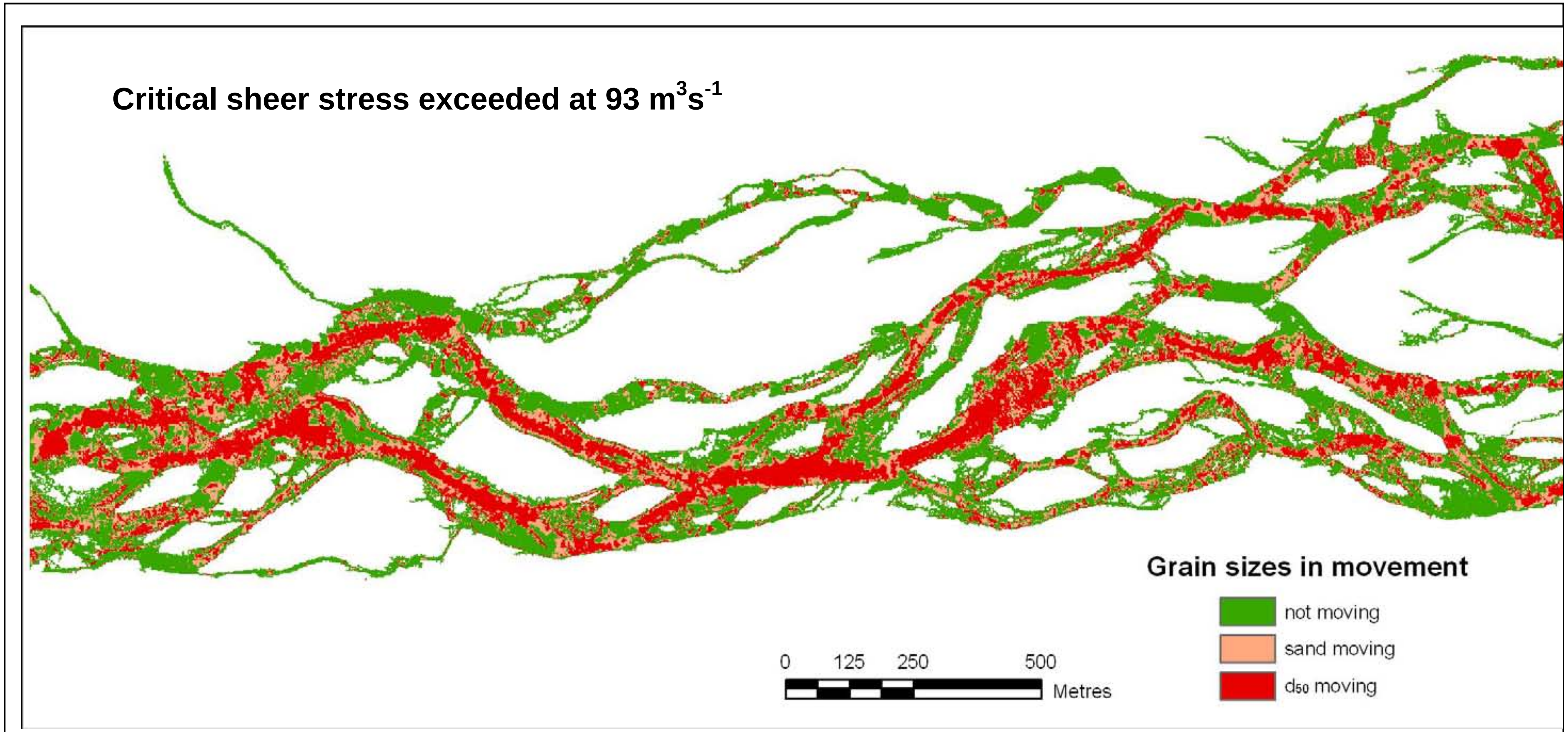

**Figure 4:** The location of likely surface and deep flushing (sand moving and d50 moving respectively) on the median flow bed when the steady flow is 93 $m^3s^{-1}$.

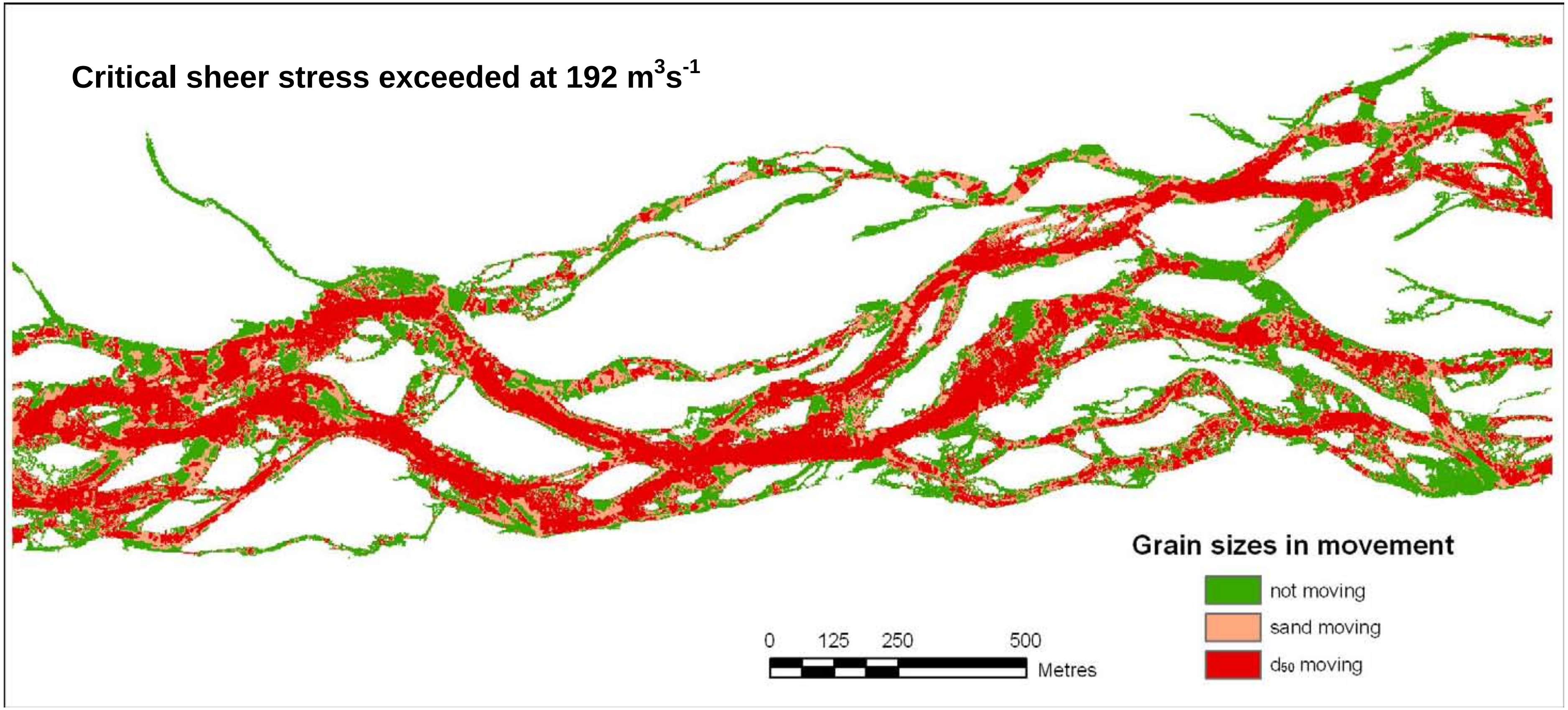

**Figure 5:** The location of likely surface and deep flushing (sand moving and d50 moving respectively) on the median flow bed when the steady flow is 192 $m^3s^{-1}$.

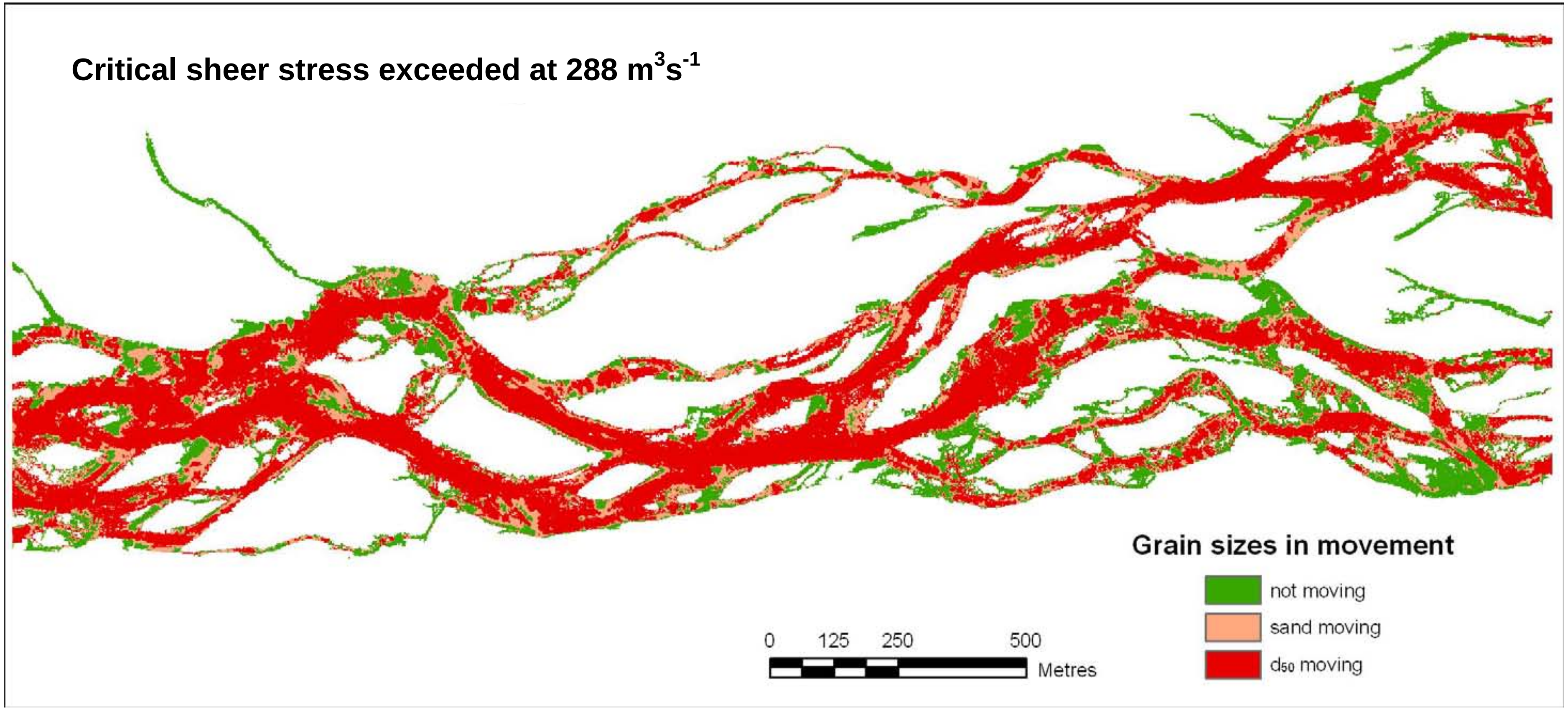

**Figure 6:** The location of likely surface and deep flushing (sand moving and $d_{50}$ moving respectively) on the median flow bed when the steady flow is 288 $m^3s^{-1}$.

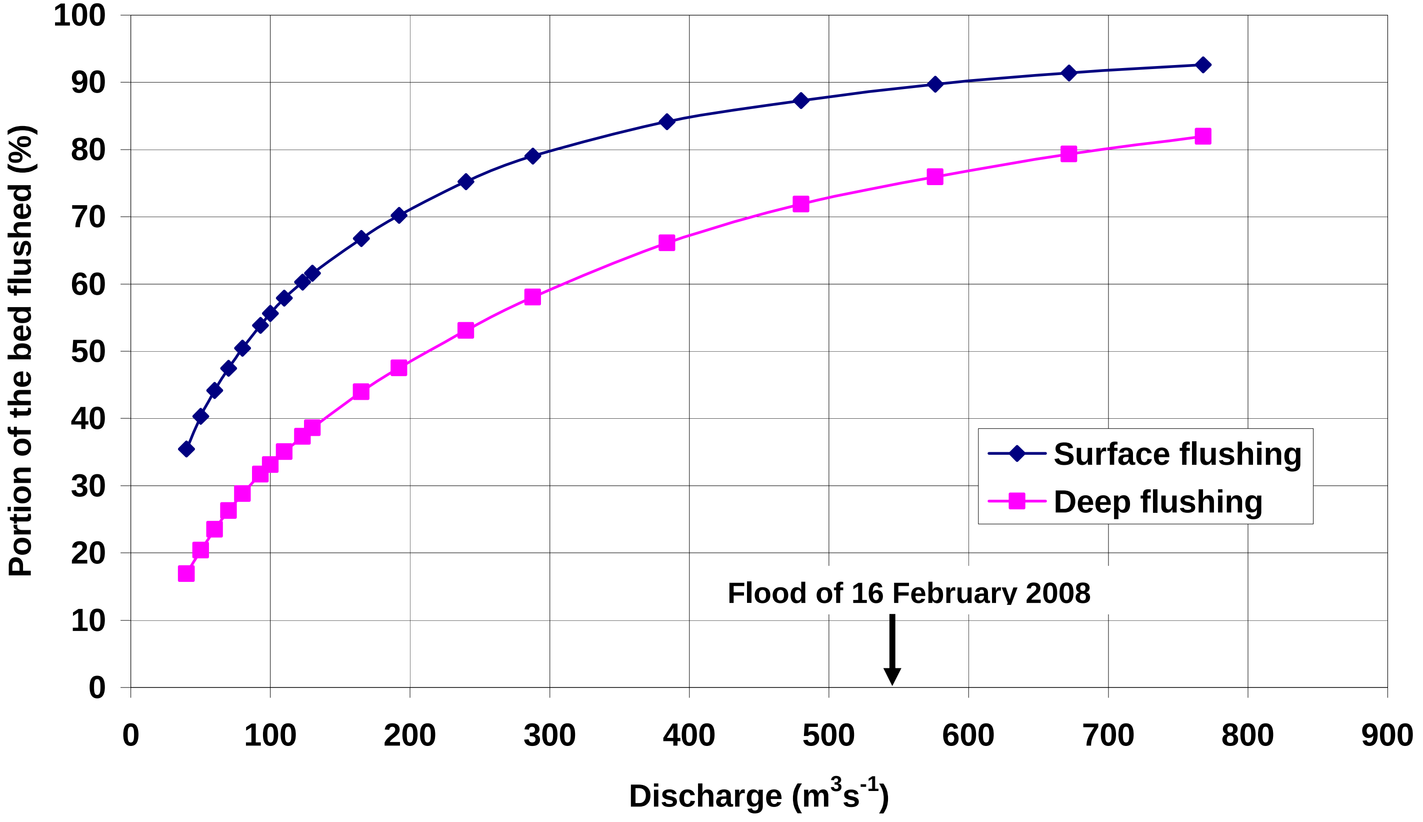

**Figure 7:** The area of minimum flow (41 $m^3s^{-1}$) river bed that is flushed of fine sediment (surface flushing) and the area of armour disturbed (deep flushing) at Crossbank Reach of the Waimakariri River at a range of flows.

deep flushed (Figure 8). Most of the bed being flushed is confined to the main braids. For diatoms the critical flow would be 205 $m^3s^{-1}$ (5 times 41 $m^3s^{-1}$) when 72 % and 49% of the minimum flow bed is being surface and deep flushed respectively (Figure 9). Using the Sagar (1986) threshold for invertebrate resetting the critical flow is 288 $m^3s^{-1}$ when 79% of the median flow bed is being surface flushed and 58% is being deep flushed. The value for surface flushing is close to 80% suggested by Jowett et al. (2008).

## 5.6. Determining periphyton flushing using velocity

The modelled velocity at a range of flows was determined for both the minimum and median flow beds. The velocity fields were classified according the maximum velocity suitable for each periphyton type as indicated the habitat suitability curves used for the Waitaki River Project Aqua study (Jowett 2003). They are illustrated in Appendix 1.

Figure 10 shows the result for the minimum flow bed. The flow where 80% of the bed has a velocity greater than that suitable for long filamentous algae is ~ 82 $m^3s^{-1}$ and is coincidentally similar to the flow predicted of twice the pre-existing flow of 41 $m^3s^{-1}$. This result is consistent with the conclusion drawn in Section 4.6 for a threshold flow for long filamentous algae. The flow where 80% of the minimum flow bed has a velocity greater than that suitable for short filamentous algae is 288 $m^3s^{-1}$ that is coincidentally the flow at which almost 80% of the bed is being flushed of sediment. While diatoms could withstand the velocities associated with higher flows they will also be removed from ~80% of the bed by the sediment flushing at 288 $m^3s^{-1}$.

Figure 11 shows the result for the median flow bed. The flow where 80% of the bed has a velocity greater than that suitable for long filamentous algae is ~ 130 $m^3s^{-1}$. This flow is only about 1.35 times the median flow. This critical flow is much less than that indicated for long filamentous algae scour in Section 5.4 that was based on an assumption of a pre-existing flow of 96 $m^3s^{-1}$. The estimate of 130 $m^3s^{-1}$ based on velocity scour is considered to be a better indicator of flow when long filamentous algae would be scoured from the median flow bed. The flow at which short filamentous algae is predicted to scoured by velocity from 80% of the median flow bed is ~300 $m^3s^{-1}$ which is a similar flow to that that would flush sediment from 80% the bed. While diatoms could withstand the velocities associated with higher flows they will also be removed from ~80% of the bed by the sediment flushing at ~300 $m^3s^{-1}$.

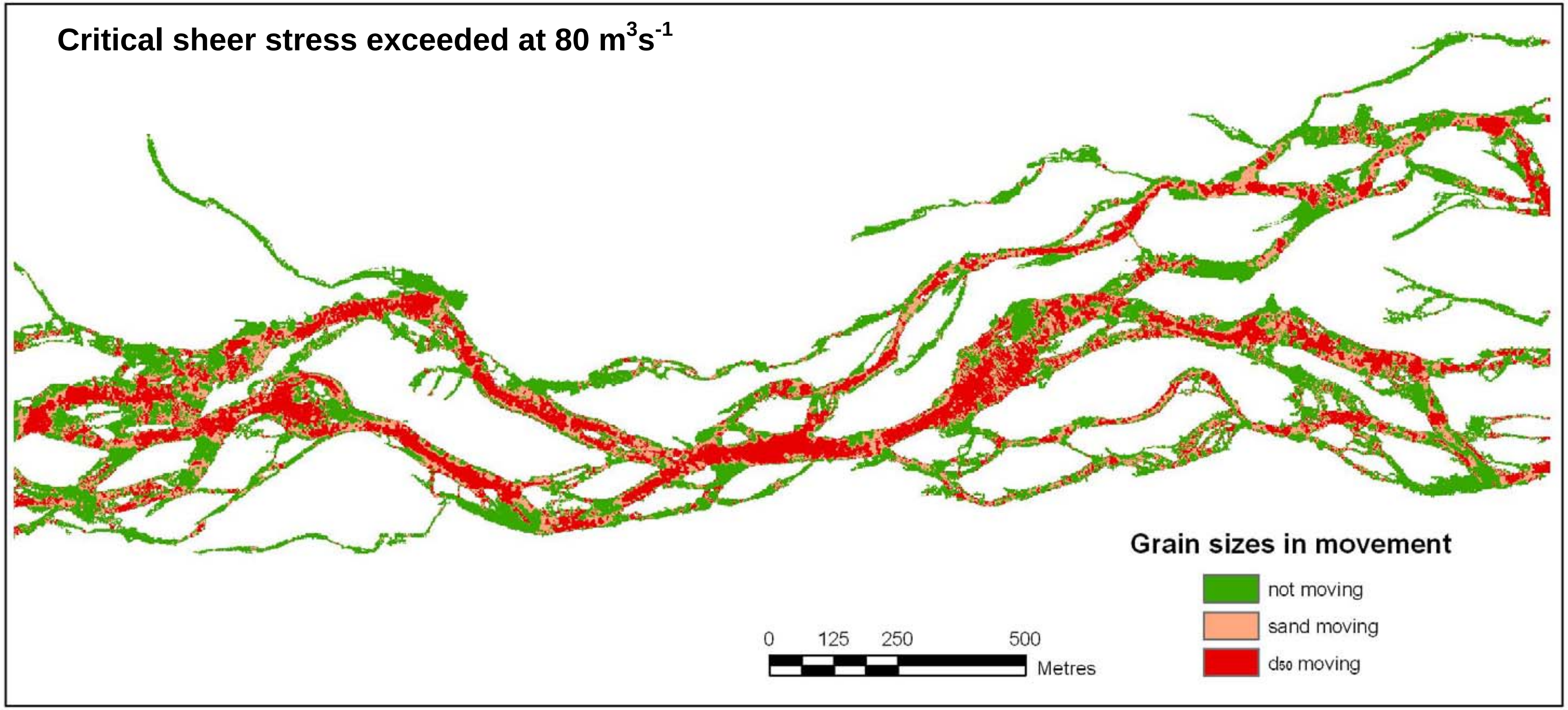

**Figure 8:** The location of likely surface and deep flushing (sand moving and $d_{50}$ moving respectively) on the minimum flow bed when the steady flow is 80 $m^3s^{-1}$ (nearest modelled flow to twice the minimum flow).

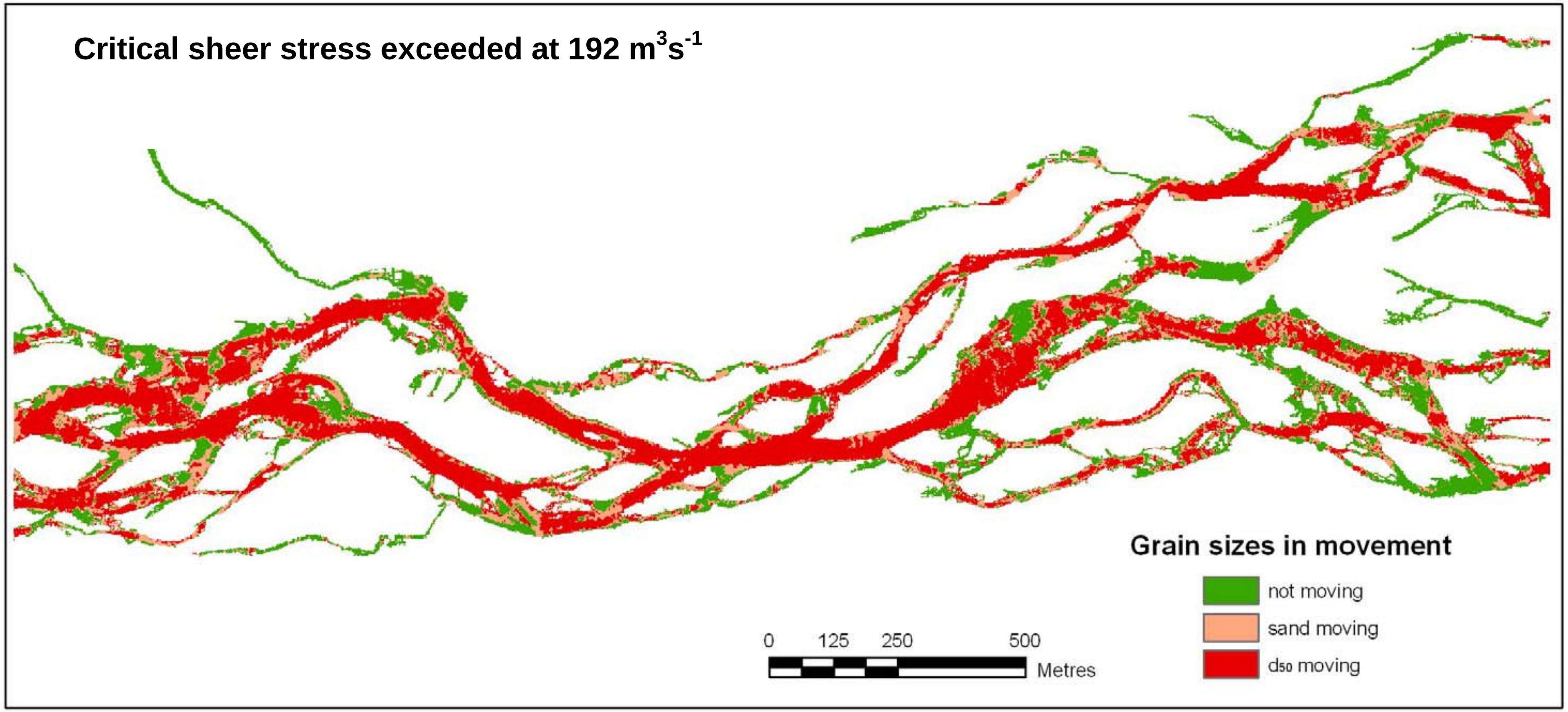

**Figure 9:** The location of likely surface and deep flushing (sand moving and $d_{50}$ moving respectively) on the minimum flow bed when the steady flow is 192 m$^3$s$^{-1}$ (nearest modelled flow to five times the minimum flow).

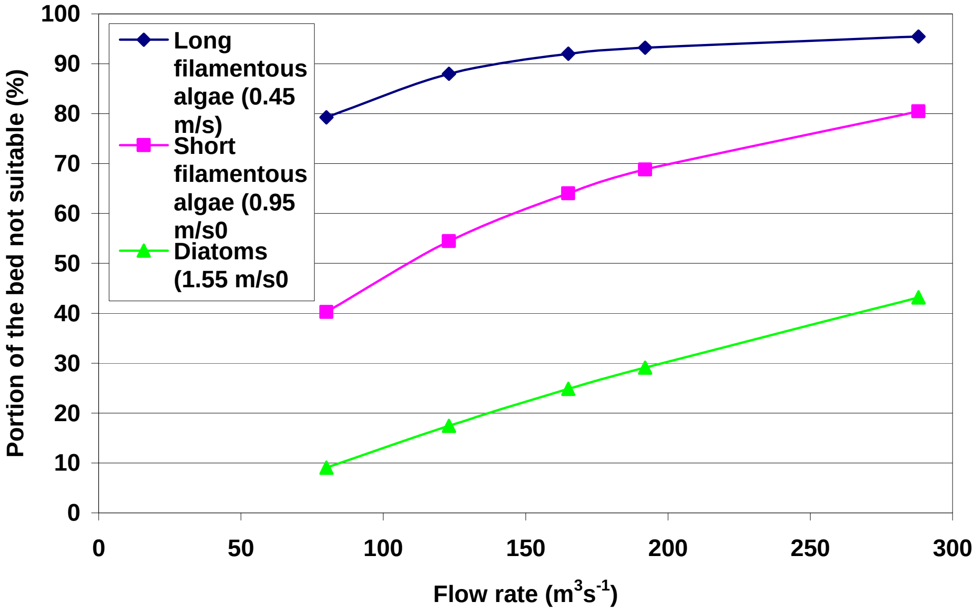

**Figure 10:** The proportion of the minimum flow bed where the velocity exceeds that suitable for three algae categories.

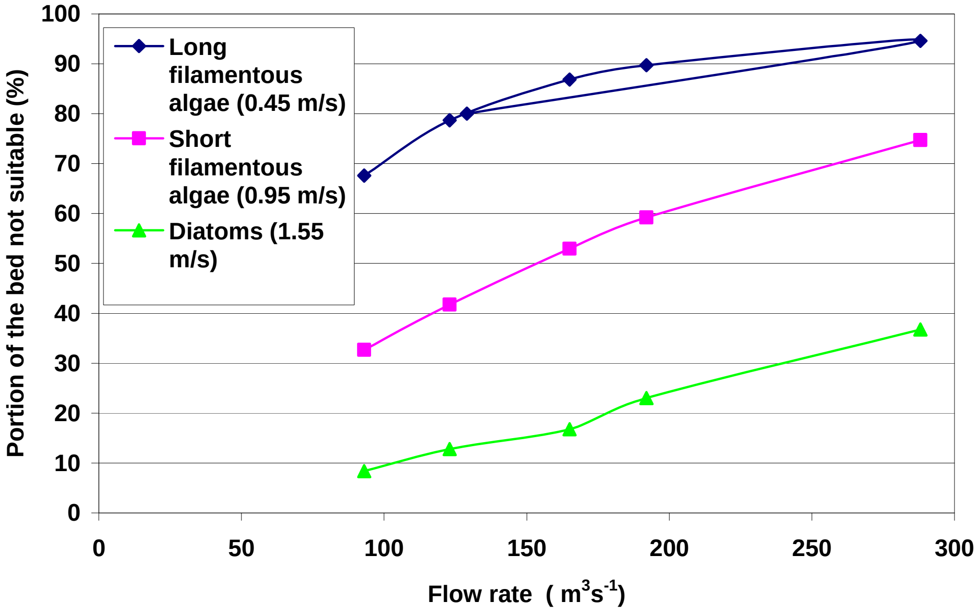

**Figure 11:** The proportion of the median flow bed where the velocity exceeds that suitable for three algae categories.

## 5.7. Field visit after flood

The first visit to Crossbank to sample the bed material size was on 8 February and before this there was a large (~1400 $m^3s^{-1}$) in mid-November and a small one (<200 $m^3s^{-1}$) in mid-December. So there was at least 6 weeks before the first visit where there was no bed disturbance during which periphyton and invertebrates could grow. While the braids were not specifically examined for the presence of periphyton and invertebrates we were aware of a thick brown cover of periphyton in the smallest of the main braids where conditions were slippery underfoot.

During the 16 February 2008 flood much of the river bed was covered in water with only a few of the higher bars with low scrub vegetation not flooded. On the second visit on 22 February 2008 most of the flowing channels were located approximately where they had been before the flood, but there were some changes to the minor channels and the two major braids on the true left of the river showed the most change. The minor channels had parts where the bed seemed to have survived the flood intact, parts where the largest particles survived or had been turned through 90°, and parts where the whole bed had been turned over or was covered by fresh deposits. Where the bed was still intact there were films of green algae on the lee of particles. Most green film covered particles inspected had *Deleatidium* and caddis larvae on their undersides. Some dry bar surfaces had been flooded because the sparse scrub had been bent over, but there was insufficient bed shear stress to mobilise coarse bed sediment and remove perennial plants.

The two major braids on the true left had been completely reworked and the particles were very clean and completely free of periphyton and invertebrates, whereas on our first visit there was a thick covering of periphyton from bank to bank on the smallest of the main braids. A shallow area beside the main stem, and connected to it, had been partly turned over but there was a significant proportion of larger particles apparently still in place and with a thin film of green periphyton on the upper surface and invertebrates on the under surface.

One area which was dry on the first visit had shallow (0.05-0.075 m deep) water flowing over it. About 50 % of large particles examined had caddis larvae and/or small *Deleatidium*.

The results from the second field visit are consistent with the results of the bed shear stress modelling in that during flooding the bed shear stress in the main braids is more than sufficient to mobilise the bed, but in shallower areas and in minor braids there was insufficient bed shear stress to mobilise all the sediment.

# 6. Discussion

## 6.1. Whole bed resetting relative to vertical erosion

The underlying assumption with the method used to determine bed movement is that bed disturbance is caused by there being sufficient bed shear stress in one case to flush fines and the other case to cause vertical erosion of the bed. However it is well recognised that much of the bed movement in braided gravel bed rivers is associated with lateral erosion of banks on the outsides of bends with consequent lateral migration of channels. Thus there is likely to be more of the bed disturbed at the nominated flow than is indicated by the flow at which 50 % of the bed comprising the $d_{50}$ or smaller is subject to vertical erosion. Any lateral erosion of dry banks is irrelevant in the context of ecological resetting because there are no benthic invertebrates on dry banks. In addition, the method does not take into account the area of the bed where there is deposition. In the absence of scour before deposition, fill is not the same as scour disturbance in terms of effects on invertebrate community structure and density. Recovery from large-scale deposition may be slow (e.g. Effenberger et al. (2006)), but recovery from smaller deposition events may be rapid. Experimental work by Olsen et al. (2007) found that fill patches recolonised much faster than scour patches, and that the most likely source of recolonists was buried individuals. Matthaei & Townsend (2000) found that invertebrate community structure differed significantly between patches that experienced scour and those that experienced fill disturbance.

Estimates of the extent of bed movement in relation to floods at the Crossbank reach have been made by Hicks et al. (2008). Using a level of detection of bed changes of ± 0.2 m, they reported for the period of February to May 2000 which had one moderate-sized flood peaking at 839 $m^3s^{-1}$ and four smaller freshes peaking between 250 and 406 $m^3s^{-1}$, ~61% of the whole riverbed underwent significant (i.e., >0.2 m) erosion or deposition. Most likely this figure underestimates the proportion of riverbed undergoing change since some portions of the bed mapped with non-significant change would have experienced compensating scour and fill. Resetting of the bed for invertebrates requires only the erosion of probably one layer of $d_{84}$ (56 mm) size material that would have gone undetected using the methods of Hicks et al. (2008), so it is possible that much more than 61% of the bed had been moved sufficiently to reset the river for invertebrates during the study period. It is not possible to use the techniques of Hicks et al. (2008) to determine the area of surficial flushing as their technique is not sensitive enough to measure the erosion of just the surface armour layer. Their method predominantly measures lateral erosion of channels and deposition of thick gravel sheets and some deposition in pools. They found the area of deposition was a little larger than the area of erosion. The fixed bed model used in this study does not model lateral erosion or deposition, but it would be reasonable to assume that many of the areas with low shear stress downstream and adjacent to areas of deep flushing would be depositional areas.

## 6.2. Ability of the modelling to determine areas of bed disturbance

For this study the river was visited for surface bed material sampling when the flow was ~ 40 $m^3s^{-1}$ and eight days later the river had a flood peaking at 542 $m^3s^{-1}$. Inspection of the river bed 6 days later when the flow was ~65 $m^3s^{-1}$ showed that while the whole river bed apart from elevated bars had been flooded, only the two major braids in the cross-section study had complete mobilisation, while the minor braids had partial mobilisation.

While the bed configuration when the river was visited before and after the flood was different from that modelled the pattern of disturbance was as predicted. However with just a brief visit and inspecting the river after a single flood it is hard to judge whether the degrees of bed disturbance from observation and modelling are the same. Nevertheless it appears that the modelling gives accurate information on the pattern of bed disturbance.

## 6.3. Comparison with FRE3

FRE3 is a flow statistic that is used to describe the frequency that river biota are subject to significant disturbances generated by flood flows. It is defined as the number of floods per year greater than three times the median flow based on a daily flow series (Clausen and Biggs 1997). This study suggest that a flow of the order of FRE3 (three times the median flow: 288 $m^3s^{-1}$) in the Waimakariri River is sufficient to disturb the bed to reset the benthos.

## 6.4. Habitat suitability at different flows

An alternative method for determining the flow at which the median flow bed is unsuitable for invertebrates is to compare the area suitable for *Deleatidium* (mayfly) as an indicator of invertebrate habitat in the median flow bed with that for larger flows. While WUA for *Deleatidium* is not a direct indicator of disturbance it might be of value to compare maps of *Deleatidium* suitability at the median flow and the threshold flow for benthic resetting as defined by Sagar (1986) Figure 12 shows *Deleatidium* habitat for the median flow. While all the median flow channels provide some habitat for *Deleatidium*, the thalweg of the major braids is not particularly good habitat and is unsuitable at higher flows (not shown). The habitat suitability for *Deleatidium* shown

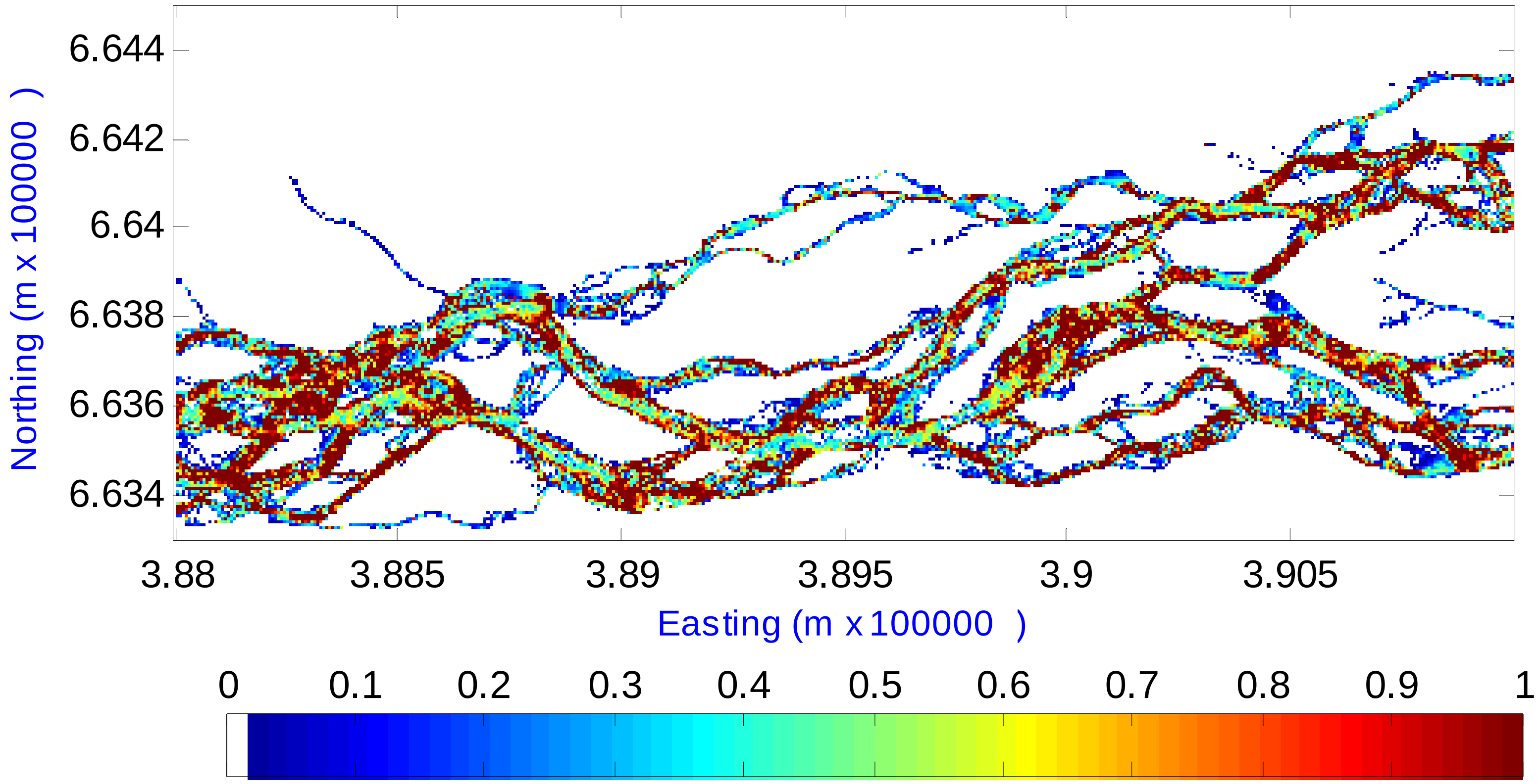

**Figure 12:** The suitability of the median flow (93 $m^3s^{-1}$) bed for *Deleatidium* habitat on a scale of 0 to 1.

in Figure 12 is based only on the suitability of the depth and velocity and does not consider bed movement. Comparison of Figures 12 and 4 shows that at some locations while the depth and velocity are suitable the bed shear estimate and assumed sediment size indicate that the bed would be being deep flushed and the habitat would not be suitable, unless the bed was armoured with material larger than that assumed.

## 6.5. Frequency of freshes and non-flushing flows

It is of interest to know the frequency distribution of time intervals between freshes of say, >288 $m^3s^{-1}$ (~ the benthos resetting flow). Figure 10 shows that there are many short periods and fewer long periods of low flow between floods or freshes of >288 $m^3s^{-1}$. The values of 25 and 40 in the legend of Figure 13 refer to the minimum and maximum take rates favoured by the Central Plains Water Enhancement Scheme (CPWES). The frequencies are for 1967 to 2001. There are similar frequencies for all scenarios for short inter-fresh periods but the length of the longest period increases with increasing take (Table 2, Figure 13). Fourteen days is a significant duration for periphyton accumulation: between 1967 and 2001 there were 188, 153 and 157 periods less than 14 days for the unmodified flow, 25 $m^3s^{-1}$ and 40 $m^3s^{-1}$ take scenarios respectively. All scenarios have the similar median inter-fresh durations (Table 2).

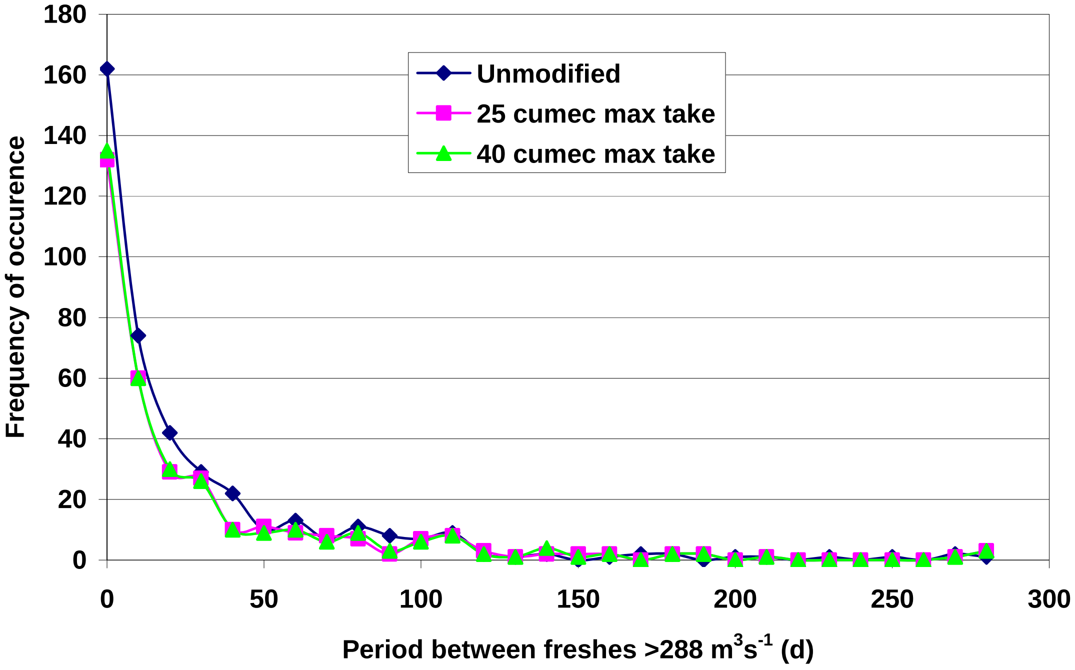

**Figure 13:** The frequency of between freshes durations for the Waimakariri River for the unmodified flow record and two CPWES scenarios.

**Table 2:** Statistics for inter-flood periods between floods > 288 $m^3$/s (record period 1967 to 2001).

| Scenario Maximum take | No of floods > 288 $m^3s^{-1}$ | No periods < 15 days between floods | No periods < 29 days between floods | No periods < 57 days between floods | Longest period between floods (d) | Median inter-flood duration (d) |
|---|---|---|---|---|---|---|
| No take | 371 | 177 | 247 | 309 | 323 | 16 |
| 25 $m^3s^{-1}$ | 328 | 162 | 216 | 263 | 417 | 15 |
| 40 $m^3s^{-1}$ | 330 | 166 | 219 | 265 | 417 | 14 |

Figures 14 and 15 are hydrographs of various take scenarios from the Waimakariri River. For very dry years the take scenario has little effect because the river falls below the statutory minimum and no takes are allowed**.** For average years the larger the maximum take the longer the apparent period of flat-lining of the hydrograph. However, it is not as simple as that, as the 40 $m^3s^{-1}$ maximum take can allow the reservoir to be filled quickly at the end of the irrigation season so there are no further takes until the irrigation season starts. Also of interest is the frequency of freshes and floods > 200-300 $m^3s^{-1}$ shown in the hydrographs and it is quite clear that there can be long periods between such events.

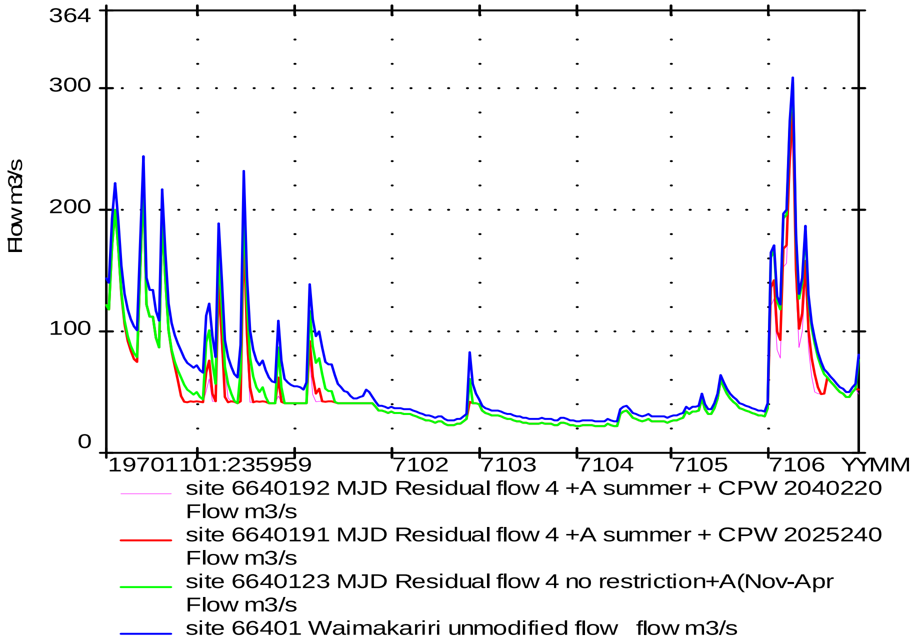

**Figure 14:** Hydrographs for the Waimakariri River for a dry year showing the unmodified flow (blue line), flow with current abstractions (green line) and the two CPW abstraction scenarios (magenta (25 $m^3s^{-1}$ maximum take) and red (40$m^3s^{-1}$ maximum take) lines).

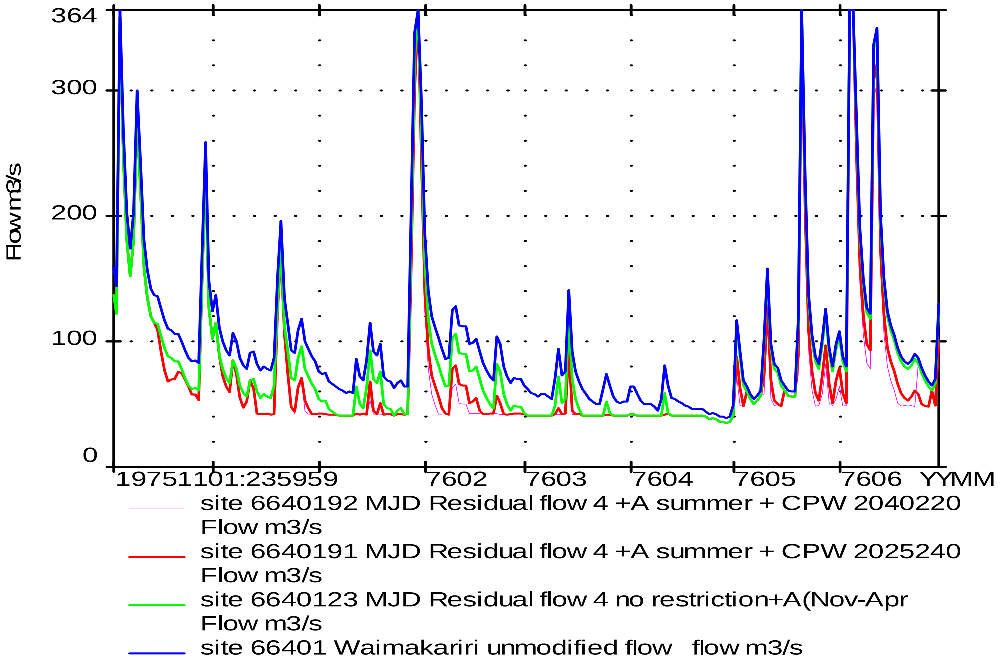

**Figure 15:** Hydrographs for the Waimakariri River for a normal year showing the unmodified flow (blue line), flow with current abstractions (green line) and the two CPW abstraction scenarios (magenta (25 $m^3s^{-1}$ maximum take) and red (40$m^3s^{-1}$ maximum take) lines).

## 7. Summary

- The surface bed material was sampled alongside the channels at low flow in areas likely to be covered at the median flow. The median grain size obtained (28 mm) was consistent with published values.

- Critical dimensionless bed shear stress values were taken from the literature as a basis for determining the area of the median and minimum flow beds that were surface and deep flushed at a range of modelled flows.

- Information from the literature was used to determine the flow at which the bed was flushed sufficiently to reset periphyton and invertebrate populations. Maps of the degree of modelled flushing at these flows were checked to see if they were consistent with the concept that most of the main braids will need to be flushed to reset the benthos.

- For the median flow bed the invertebrate resetting flow was at 288 $m^3s^{-1}$ when 77% of the median flow bed was surface flushed and 55% was deep flushed.

- For the minimum flow bed invertebrate resetting flow was also 288 $m^3s^{-1}$ when 79% of the minimum flow bed was surface flushed and 58% was deep flushed.

- The degree of bed movement at these levels of flushing was sufficient to disturb most of the main braids, but the minor braids were only partly flushed.

- The above resetting areas will be a minimum because they are based on vertical erosion of the bed and do not take into account the significant mechanisms of lateral erosion and deposition. Lateral erosion of the dry bed is irrelevant for ecological resetting and areas of shallow deposition may be rapidly recolonised by benthic invertebrates from the covered bed.

- Based on modelled velocity long filamentous algae was scoured from 80% of the minimum flow bed at a flow of 82 $m^3s^{-1}$ and from 80% of the median flow bed at a flow of 130 $m^3s^{-1}$. Both short filamentous algae and diatoms would be removed from the ~80 % of the minimum and median flow beds by surface and deep flushing at a flows of 290-300 $m^3s^{-1}$ before being scoured by velocity alone.

- Observations of river bed and benthic invertebrate presence/absence before and after a 542 $m^3s^{-1}$ flood confirmed the pattern of bed disturbance indicated by the modelled bed shear stress.

- Hydrograph analysis shows that most inter fresh durations are short with a median duration of 14-16 days, but can be as long as 312-417 days depending on the abstraction regime.

- Freshes of the order of 290 $m^3s^{-1}$ could be considered to disturb the bed sufficiently to reset the river bed from an ecological view point. However, the nature of braided rivers is such that even during large floods there are numerous and widespread areas where the bed is not disturbed, that act as refuges for benthic invertebrates and as sources of invertebrate drift and periphyton propagules that allow rapid colonisation of parts of the river following freshes and floods.

# 8. Acknowledgements

We would like to thank Dr Murray Hicks for sound advice on many aspects of the work. Dr Hicks, Dr Barry Biggs, Dr Jon Cunliffe and Dr David Arscott gave helpful advice on the method for selection of the critical flow for ecological resetting. Veit Blauhut, Max Brell and Mike Loranty are thanked for assisting with the Wolman bed material sampling on a fine but blustery north-easterly day. Comments from reviewers from Environment Canterbury and the Cawthron Institute have resulted significant improvements to the manuscript.

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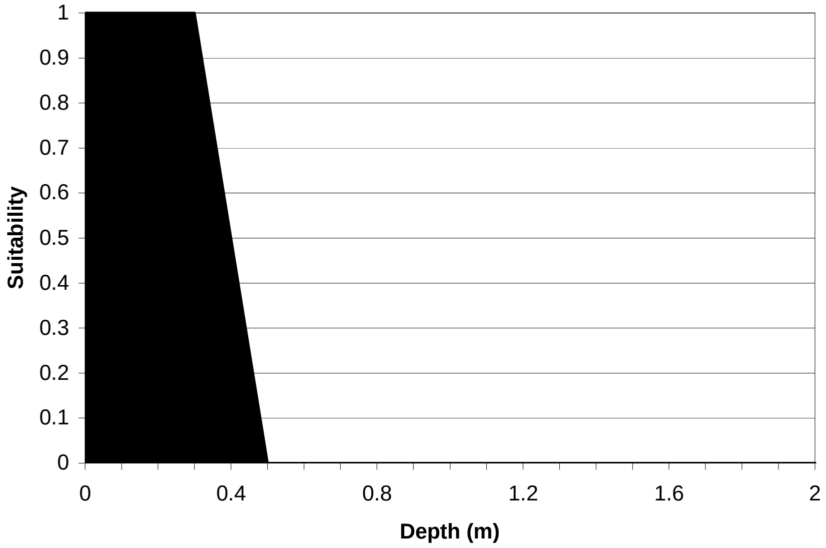
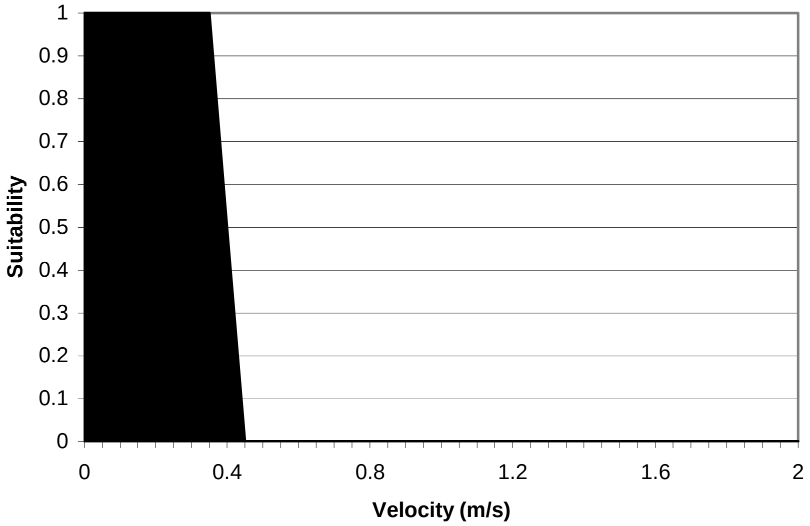
# Appendix 1: Habitat suitability curves

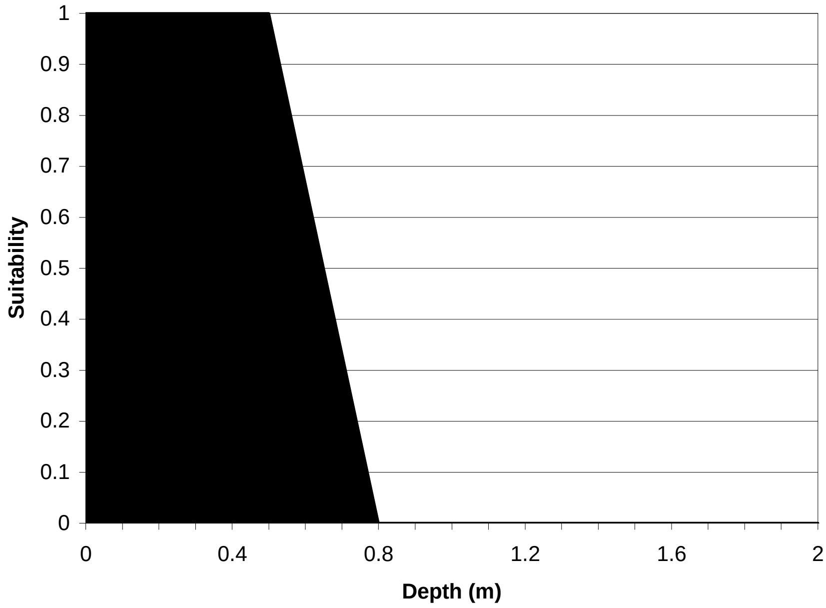
Dark areas indicate depths and velocities that are suitable for algae and white areas indicate depths and velocities that are not suitable.

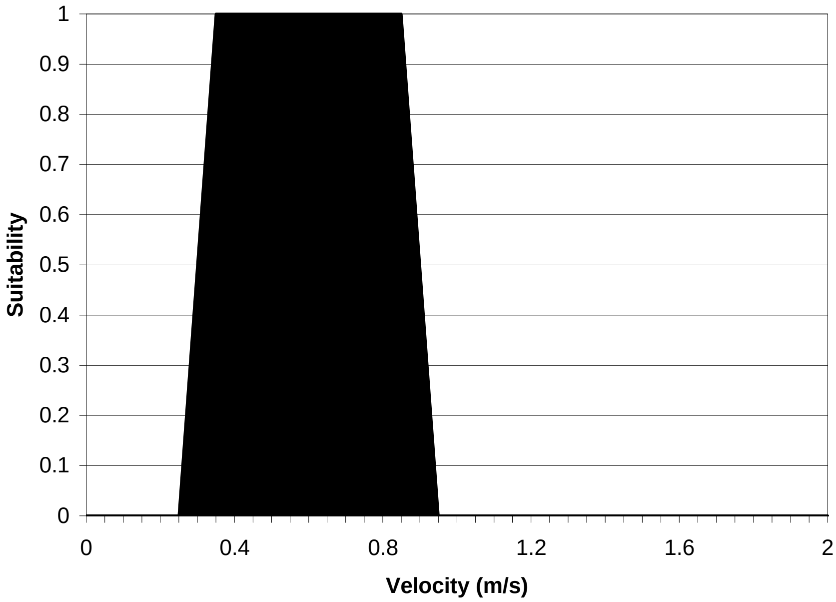
## Long filamentous algae



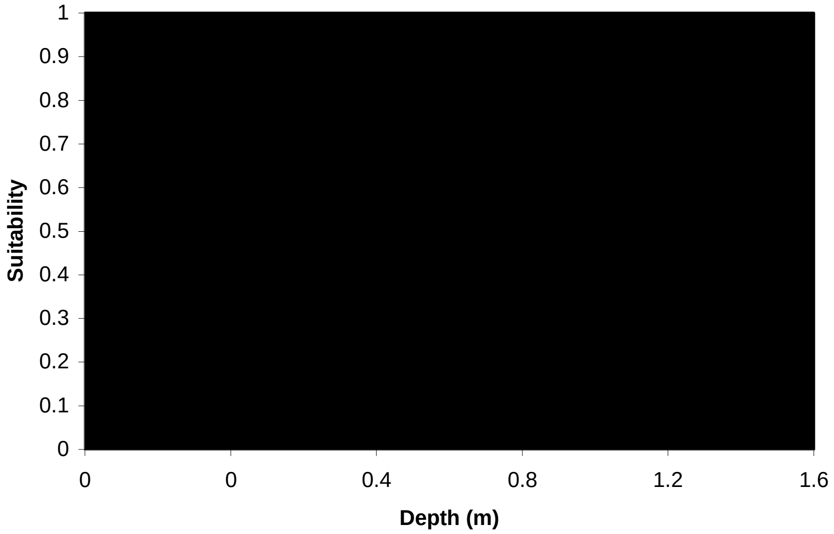


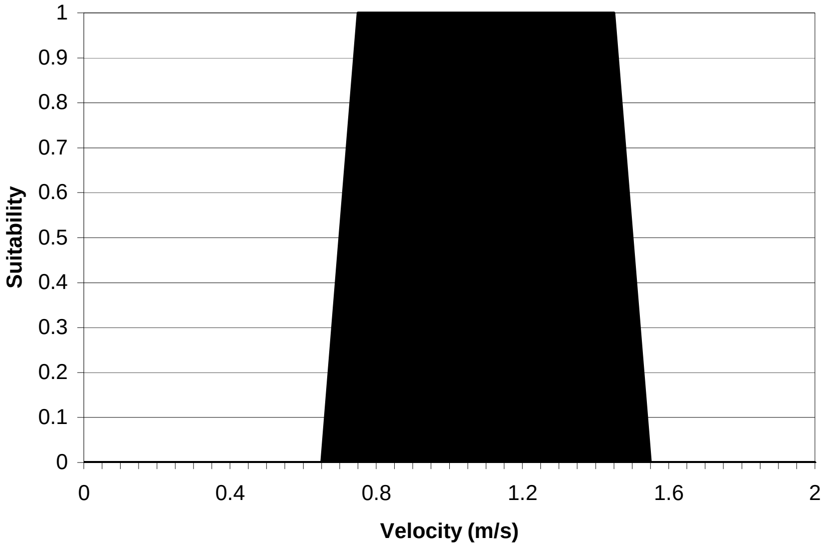
## Short filamentous algae





## Diatoms


Suitability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0
0.4
0.8
1.2
1.6
Depth (m)


Suitability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.4
0.8
1.2
1.6
2
Velocity (m/s)