Determining environmental flow requirements for substrate maintenance in cobble and boulder bed rivers in South Africa

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Abstract. To ensure a healthy and biodiverse ecosystem in cobble and boulder bed rivers, it is imperative that the channel bed is maintained. In pristine catchments this is achieved by the range of flows characteristic of the natural flow regime, which typically incorporates "maintenance" flood flows of different timing, duration and frequency. The construction of dams however, leads to a change in the flow regime, the flooding magnitude and frequency, and the sediment transport capacity. In order to maintain a healthy and productive substrate environment it is necessary that the environmental flow requirement for these rivers accommodate a "substrate maintenance flow component". This paper presents the findings of a project to develop guidelines for determining substrate maintenance flows in cobble and boulder bed rivers in South Africa. The study developed a model for predicting incipient motion based on unit stream-power theory and used this model to investigate the impact of particular flood events on invertebrate population densities.

1. Aims and Objectives

The objective of this research was to develop a mathematical model for incipient motion in cobble and boulder bed rivers based on the theory of unit stream power. This mathematical model would then be used to support the development of guidelines for substrata maintenance flows in cobble and boulder bed rivers. The study was funded by the Water Research Commission and has resulted in the publication of two research reports. The first (Cullis et al, 2007) addresses the development of the hydraulic model, while the second research report (Ratcliffe, et al, 2007) discusses the ecological impact on the aquatic invertebrates.

2. Data Collection

The research was conducted in two relatively undisturbed mountain streams in the Western Cape region of South Africa: the Molenaars River and the Berg River. Close to 800 stones ranging in size from 25 mm to 1100 mm were marked, 345 in the Molenaars and 435 in the Berg, just prior to the start of the flood season. The movement or non-movement of the marked stones was recorded after each of thirteen flood events at both study sites. The floods ranged from small freshettes that resulted in negligible disturbance to bank full floods with a average return period of over two years. The largest observed flood resulted in the movement of 44% of the marked stones at one of the study sites.

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3. Theory of Unit Stream Power

The unit stream power (per unit volume) approach, introduced by Rooseboom (1974) has the advantage over other theories of incipient motion such as the Shields equation (1936) of defining both the transporting capacity of the stream and the effort required to transport material in directly comparable scalar terms. Rooseboom (1998) was also able to use the theory of unit stream power to give mathematical justification for the parameters of the empirically derived Liu diagram (1957) of incipient motion for uniform bed material A third advantage of using the theory of unit stream power is that it directly takes into account the absolute roughness of the stream bed. For this reason it was decided to see if unit stream power could be used to determine incipient motion in the rivers.

Using the theory of unit stream power it was possible to show that incipient motion could be defined by the following equation:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{\frac{1}{3}} = \text{Constant} \qquad (1)$$

4. Incipient Motion on Beds of Uniform Particle Size Distribution

Under turbulent conditions energy dissipation occurs through the formation of turbulent eddies. The size of these eddies represent the absolute roughness (*k*) of the bed. In the case of a bed with uniform size particles the eddy size would be of the same order as the particle diameter. Based on this observation, Rooseboom (1974) showed that, by substituting *k* with *d* in Eq. (1), the critical condition for the movement of sediment along an even uniform bed in rough turbulent flow can thus be defined by:

$$\frac{\sqrt{gDs}}{V_{ss}} = \text{Constant} \qquad (2)$$

When calibrated with measured data from Yang (1973) the value of the constant was found to be 0.12 for rough turbulent flow (Rooseboom, 1998). This result gives theoretical justification to the empirically derived Liu diagram for incipient motion as applied to a bed of uniform particle size distribution.

5. Adapting the Theory of Unit Stream Power for Non-uniform Beds

In the case of a non-uniform particle size bed, the relationship between the size of the turbulent eddies that form and the particle size is not as straight forward as for a uniform bed. Because flow resistance across the bed is developed over distance it may be assumed that the average eddy size across a non-uniform bed will tend towards uniformity, with the average eddy size of the same order as that of the larger stones. As a result the absolute roughness (*k*) at a particular point is not necessarily related to the individual particle size at that point, but is instead related to the size of the larger stones in the reach, which have a greater influence on determining the average eddy size. Hence the term for the relative roughness (*d/k*) does not equal 1 and so Eq. (1) cannot be simplified to Eq. (2) as for a uniform bed.

6. Probability of Movement of Individual Stones

The number of moved and un moved stones for each study site where plotted in terms of the Eq. (1), which represents the ratio of applied power to required power in a non uniform bed. The absolute roughness (k) was taken as the size of the stone one standard deviation larger than the mean (i.e. d_{84}). The results from both study reaches where similar to those for the five observed floods at the Berg River site shown in Figure 1.

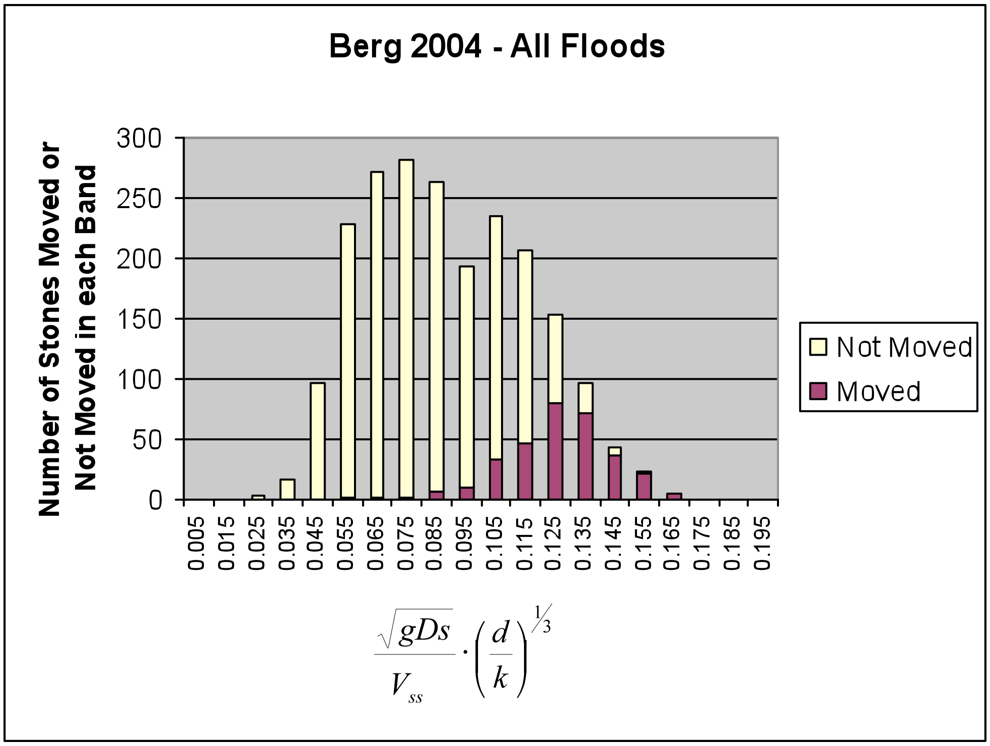

Figure 1: Movement of Stones in terms of the ratio of applied power to required power at the Berg River site: 2004 Floods

The percentage of movement in each band for the three sets of flood data, Molenaars 2003, Molenaars 2004, and Berg 2004 are plotted in Figure 2.

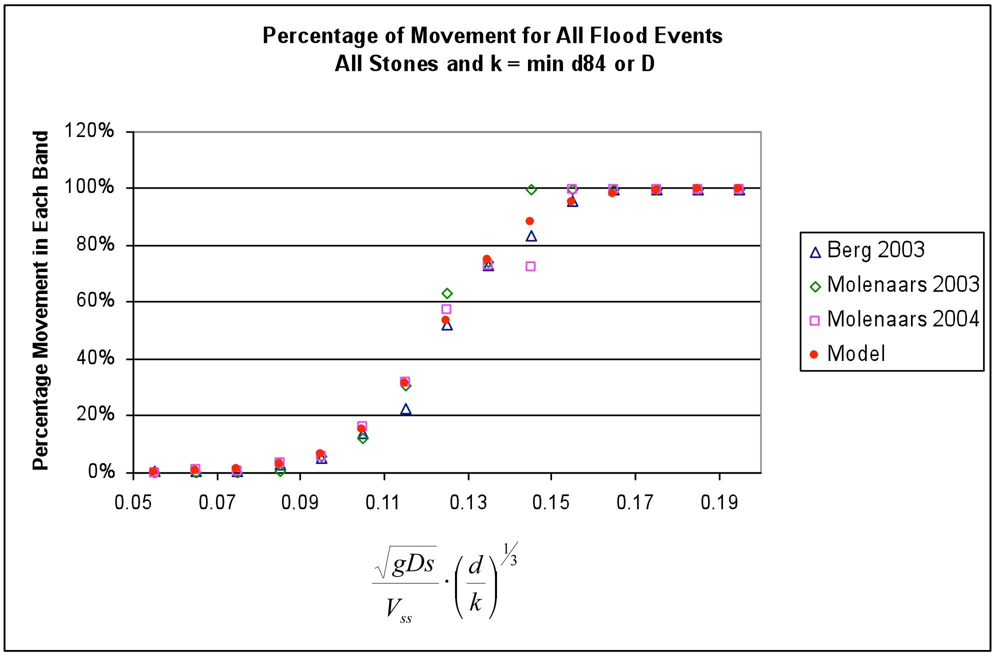

Figure 2: Percentage of Movement of Stones in Relation to the ratio of applied power to required power: Non-embedded Stones for All Flood Events

The results from all three sets of flood events appear to describe the same relationship between the percentage of movement and the ratio of applied power to required power. This relationship can be modeled by a simple logistic curve of the form:

$$PM = \frac{A.B.e^{r.C}}{A - B + B.e^{r.c}} \text{ with } C = \frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} \qquad (3)$$

where
PM = The expected percentage of movement
A = The maximum percentage of movement (99.999%)
B = The minimum percentage of movement (taken as 0.001%)
C = The ratio of applied power to required power
r = The rate of increase in the percentage of movement

By minimising the sum of the squares of the differences for all the results, it was found that the best fit was obtained when $r = 93$. The modelled results using this relationship are also shown in Figure 2.

7. Incipient Motion in Cobble and Boulder Bed Rivers

If the definition for incipient motion is interpreted as the point at which a stone is more likely to move than to not move, i.e. the probability of movement is greater than 50%, and the probability of movement of an individual stone is equal to the percentage of movement observed for the given ratio of applied power to required power, then the model developed above can be used to determine the critical ratio of applied power to required power at this point. The critical ratio (i.e. the *C* term in Eq. (3)) that resulted in an estimated 50% movement) was found to be equal to 0.12. The conclusion is that incipient motion in cobble and boulder bed rivers of non-uniform particle size distribution, i.e. the point at which a particular stone is more likely to move than to not move, can be defined by the relationship:

$$\frac{\sqrt{gDs}}{V_{ss}} \cdot \left(\frac{d}{k}\right)^{1/3} = 0.12 \qquad (4)$$

This result is consistent with the definition of incipient motion for turbulent flow on a bed of uniform particle size distribution as determined by Liu (1957) and validated by Rooseboom (1974):

$$\frac{\sqrt{gDs}}{V_{ss}} = 0.12 \qquad (5)$$

The difference between the two definitions of incipient motion is that the later one does not include the term that accounts for the difference between the individual particle size (*d*) and the absolute roughness of the bed (*k*) as for beds of uniform particle size distribution the absolute roughness is equal to the particle size ($k=d$).

8. Universal model for Incipient Motion

It is unclear at this stage if this represents a universal finding for all rivers of non-uniform particle size distribution. To be able to answer this will require the model to be tested on other rivers. The results from the two rivers tested, however, where consistent despite being of different size and having different stone size distribution. Based on this observation it could be hypothesized that the above results will be universal at least in the case of cobble and boulder bed rivers.

9. Environmental Considerations

An interesting aspect of the investigation of ecological disturbance levels as part of this study, was that the theoretical mathematical model for incipient motion described above was used to ascertain whether or not a group of previously unsampled stones for which ecological samples were taken only after the measured flood events, would have been likely to be moved or not under the particular flood events.

The results of this analysis are shown in Figure 3, which shows the average invertebrate densities (m^{-2}) for different classes of stones. The solid bars show the post flood sampling results, while the checked bars are the pre-flood results. The stones are classified as follows:

1. Stones that did not move during any flood
2. Stones that moved only in one big flood
3. Stones that moved in more then one flood event
4. Stones that were assumed to have not moved based on hydraulic model

5. Stones that were assumed to have moved only during one big flood event based on hydraulic model
6. Stones that were assumed to have moved for more than one flood event based on hydraulic model
7. Stones that were too large and so only the tops could be sampled. Stones did not move during any flood event.
8. Stones that were too large and so only the tops could be sampled after the flood events

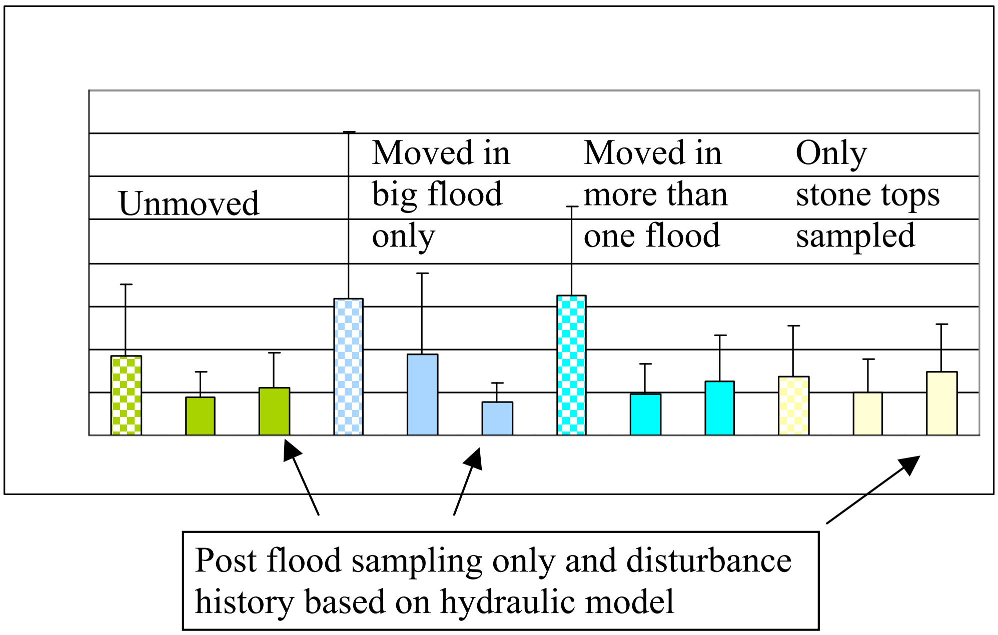

Figure 3: Average Invertebrate Densities (m^{-2}) for Different Classes of Stones

The analysis of the previously unsampled stones where used as a check to rule out possible impacts on the measured disturbance levels due to the pre-flood sampling of the main set of stones. In most cases, the observed densities of organisms on the stones that were predicted to have moved (or not moved) were very similar to the main set of stones that where known to have moved (or not moved). This gave further support to the validity of the incipient motion model.

10. Conclusions

This paper has shown how the theory of unit stream power can be used to develop a theoretical mathematical model to describe incipient motion in cobble and boulder bed rivers of non-uniform particle size distribution. The model has distinct advantages over the traditional shear stress based models in that it works with scalar quantities, incorporates the bed roughness directly, and can be used to give mathematical support to the Liu diagram of incipient motion. The model was calibrated using data from two mountain rivers in South Africa and the constant term in the derived equation was found to be equal to 0.12 for stones that were more likely to move than to not move. This conformed well to the empirically derived Liu diagram for incipient motion for riverbeds of uniform stone size distribution.

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