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Soil armouring and weathering: toward catchment-scale computational modelling

S. COHEN[1,2], G. R. WILLGOOSE[1] & G. R. HANCOCK[2]

1 *School of Engineering, The University of Newcastle, Callaghan, New South Wales 2308, Australia*
sagy.cohen@newcastle.edu.au

2 *School of Environmental and Life Sciences, The University of Newcastle, Callaghan, New South Wales 2308, Australia*

Abstract Hillslope surface armouring and weathering processes have been largely ignored in geomorphic and hydrological models due to their complexity and the uncertainty associated with them. However, their importance in a wide range of spatial processes is well recognised. An armouring and weathering computer model (ARMOUR) has previously been used to successfully simulate the effect of these processes on erosion and soil grading at a hillslope scale. In order to apply such a model across larger and more complex environments we used a Markov process conceptualisation to reduce the complexity of ARMOUR's numerics. This new armouring-weathering model (named MrARM) is now capable of large-scale two-dimensional simulations. In this paper we describe the calibration and evaluation of MrARM as well as the results of multiple hillslope-scale simulations for varying weathering rates. The MrARM armouring component was calibrated against ARMOUR results, while its weathering component was validated against recently published laboratory results. A parametric study was conducted to evaluate model predictions under various conditions. The results described here demonstrate that the modelling approach used is effective and that the simulation of the armouring and weathering processes corresponds well with previous experience with ARMOUR and with generally accepted field understanding.

Key words armouring; weathering; modelling; soil

INTRODUCTION

Armouring is a process of surface coarsening caused by removal of fine material from the top layer. Soil armouring occurs when a mixture of fine and coarse particle is exposed to overland flow over time, which preferentially erodes the fine particles. This process eventually generates a surface with a size distribution, which is equal or bigger than the transport threshold of the flow. When all transportable material has been removed a stable armour layer is formed. Consequently if the overland flow does not subsequently increase, the sediment transport, and thus erosion, is reduced to zero. If the overland flow is higher then the armour-forming flow the armoured layer may be either coarsened or destroyed (Willgoose & Sharmeen, 2006).

Weathering is the breakdown and/or alteration of rock and material near the earth surface. The overall weathering process can be divided to two interrelated processes: physical and chemical weathering (Yokoyama & Matsukura, 2006). Physical weathering is the breakdown of rock to smaller fragments by mechanical processes such as abrasion by water, mineral and ice creation, expansion and contraction due to temperature fluctuations and biological activity (Yokoyama & Matsukura, 2006). In chemical weathering, rock is usually dissolved, oxidized or reduced by a variety of chemical reactions. The overall weathering process is an interaction between physical and chemical weathering as physical weathering may depend on chemical weakening of the rock and chemical weathering acts on available fresh mineral surface exposed by physical breakdown (Riebe *et al.*, 2004).

In this research, we focus on physical surface weathering, which dominates the breakdown of rock particles at the top soil layer. This process influences the fine sediment availability and soil grading, which increase sediment transport (Sharmeen & Willgoose, 2006). This interaction creates the coupling between erosion and weathering.

The armouring effect on hillslope erosion and development has generally been neglected in soil erosion and landform evolution models, despite the growing recognition of its importance in erosion processes (Willgoose & Sharmeen, 2006). Most literature regarding armour modelling is for rivers and channel beds. Willgoose & Sharmeen (2006) simulated the effect of time-varying surface armouring on sediment flux and erosion using a physically-based model (i.e. ARMOUR).

ARMOUR, a one-dimensional (1-D) hillslope soil erosion model was used to simulate long-term erosion and armour development in two contrasting mine spoils; one cohesive, the other non-cohesive.

Armour and armouring process is also controlled by weathering. The rock weathering literature is broad and deals mostly with rock fragmentation mechanism and size distribution under different conditions (e.g. Klimpel & Austin, 1965; Lerman, 1979; Robertson *et al*., 1997; Green *et al*., 2006; Wells *et al*., 2006). There is little emphasis on weathering of surface material or long-term simulations of its influence on erosion and landform evolution. Sharmeen & Willgoose (2006) integrated a variety of weathering mechanisms into their ARMOUR model. They used it to investigate the interaction between weathering and armouring and the effect on erosion and soil grading.

Sharmeen & Willgoose (2006) are, to the authors' knowledge, the only hillslope time-varying simulations of the relationship between armouring and weathering processes and their effect on soil erosion and landform evolution. Among other things, their work has demonstrated the attractiveness of the ARMOUR model and the potential of its conceptualisation to study landforms and soils. One-dimensional simulations are an important initial stage for modelling such a complex problem and can provide valuable insights on the process and modelling approach. However, they are a simplified view of the hillslope. In order to simulate the armouring and weathering processes on natural or large-scale environments and integrate them in erosion and landform evolution models, 2-D simulations are needed.

The main limiting factor in ARMOUR for 2-D simulations is the numeric complexity of its physics, which results in high computational requirements and long run-times. Simplifying ARMOUR is possible by expressing the physically-based model with a stochastic model such as the Markov chain. This is the focus of this paper.

We will briefly describe our modelling approach, which dramatically reduces computation time, enabling parametric studies of complex environments and the integration of armouring and weathering in landform evolution models (e.g. SIBERIA). The consequent reduced computational-demand will also allow us to extend the modelling domain and enables us to explore the dynamics of soil profile morphology and its influence on the weathering-erosion cycle.

This paper presents: (1) the calibration of Markov chain model (MrARM) using data from the ARMOUR model and laboratory experimental data; (2) a simple parametric study; and (3) the results of armouring-weathering simulations under varying weathering rates.

MODELLING APPROACH

The Markov chain approach

A Markov chain is a discrete-time stochastic process with the Markov property. Markov property means that the future condition (referred to as "state") is independent of the system history providing that the current state is known. The transition from one state to the next has a known probability (transition probability), which is independent of previous states before the current (Grinstead, 1997). In a Markov chain system there will be more then just one possible state to which the system can step in to. Therefore, there are multiple transition probabilities in each step. Those multiple transition probabilities are expressed as a matrix called a "transition matrix" (Ross, 1993).

In our model, the state will be the percentage of material in each soil grading and the transition matrix will represent how the weathering and erosion processes change that grading. The transition between time steps will thus alter the soil grading of the simulated landscape, mimicking the observed physical process.

Markov chain models are a useful approach in environmental modelling since they provide a flexible and elegant conceptual device for describing and analysing spatial and temporal processes (Collins, 1975). In the relevant literature there are many examples of using Markov chain (especially Monte Carlo application) in environmental modelling. There are even several Markov chain modelling of erosion (e.g. Kanso *et al.*, 2005; Ostroumov *et al.*, 2005) and landform evolution (e.g. Gournellos, 1997).

MrARM modelling concept

The MrARM model (the model and calibration are described in detail in Cohen *et al.* "Using the Markov chain approach to simplify a physically-based armouring-weathering model on hillslopes: the MrARM model" (in preparation)) simulates the change in soil grading on the surface as a result of time-varying erosion and weathering. The erosion (i.e. armouring) component is based on simplification of the physical processes simulated in ARMOUR using the Markov chain approach. In this case, surface grading in each iteration is expressed by a simple transition matrix:

$$\begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_n \end{bmatrix}_{t+1} = E \times \begin{bmatrix} Et_1 & 0 & 0 & 0 \\ 0 & Et_2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & Et_n \end{bmatrix} \times \begin{bmatrix} G_1 \\ G_2 \\ \vdots \\ G_n \end{bmatrix}_t \tag{1}$$

where G_k is the proportion of size class k, E is the erosion rate and Et_k is the erosion transition for class k and where the t subscript is for time. Both E and Et are calculated using physically-based equations derived from the ARMOUR model.

Weathering of particles is based on a particle splitting mechanism (where the particle splits into two different volume fragments; Wells *et al.*, 2008) expressed by the Markov chain approach. The interaction between the size classes is controlled by the weathering transition matrix and the effect of weathering on the particle distribution is calculated by:

$$G_k = \sum_{r=1}^{M} G_r WT_{r,k} \tag{2}$$

where $WT_{r,k}$ is the weathering transition value in the matrix r row and k column and size class. WT is calculated to each size class according to the weathering rate and the volume of its particle after breaking in a user-defined proportion.

Model calibration

Calibration of MrARM is required. Initial values were derived from the ARMOUR experiments (Willgoose & Sharmeen, 2006) and were matched to the armouring simulation of ARMOUR for the Ranger Uranium Mine experiment (Willgoose & Riley, 1998; 24 m–0.21° hillslope divided into six equal nodes, 200 years simulations).

Armouring component

We calibrated the armouring component of MrARM by fitting the time-varying particle size distribution plots to the ARMOUR simulations at each of the six nodes down the hillslope. Figure 1 shows the change at the coarsest five size classes in the outlet node in both models. It demonstrates the close match with of calibration, a maximum variation of 5% over 50 000 iterations (equivalent to 200 years).

The differences between the ARMOUR and MrARM results occur due to difference in the behaviour of just one grading class, the most erodible grading class in each node. As demonstrated in Fig. 1, the 1.0-mm class reaches a close to equilibrium behaviour in the ARMOUR simulation (Fig. 1(b)) while the same class dose not reach an equilibrium in the MrARM results (Fig. 1(a)). This is due to the simplification in the way the Shields transport threshold is treated within MrARM. This change affects the coarser classes as well since their proportions increase as a result. Since this change in behaviour only results in a maximum change of 5%, we are confident in the capability of MrARM to accurately simulate the armouring process under these conditions.

Weathering component

The weathering component of MrARM was calibrated to the Wells *et al.* (2008) experimental data. Wells *et al.* (2008) measured and simulated the change in the mass of five weight classes as a

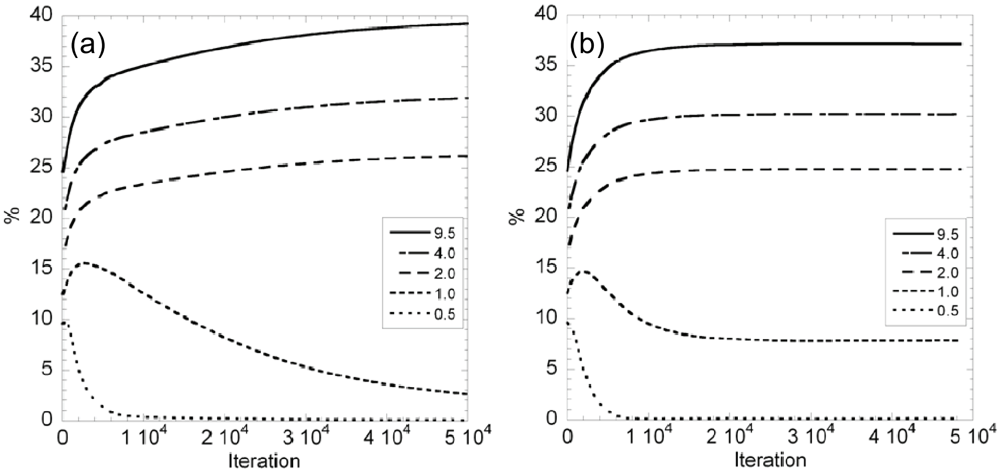

Fig. 1 Proportion of the coarsest five (out of 18) size classes (in mm) in the overall soil grading over time (50 000 iteration is equivalent to 200 years) in: (a) MrARM, and (b) ARMOUR.

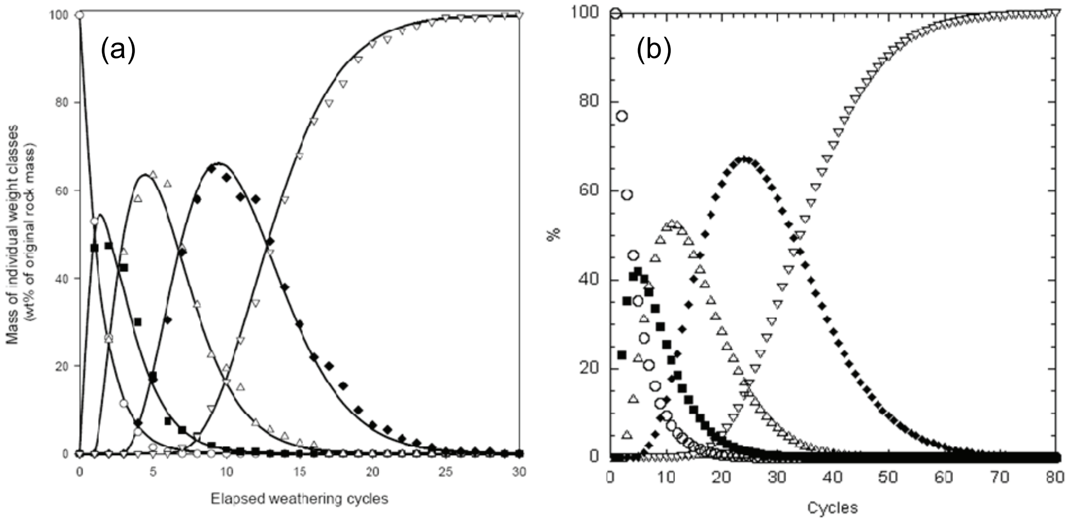

Fig. 2 Change in fragment proportion over cycles of weathering: (a) Wells *et al.* (2008) analytical (line) and Monte Carlo simulations, and (b) MrARM weathering component simulation: O, >50%; ■, 25–50%; Δ, 10–25%; ♦, 1-10%; ∇, <1%.

result of weathering of a rock from the Ranger site. They found excellent correlation between the break-in-half weathering geometry and the analytical results. The results of our Markov weathering model show good agreement with to the Wells *et al.* (2008) results (Fig. 2) giving us confidence in the MrARM weathering model.

RESULTS AND DISCUSSION

Armouring simulations

In the previous section we used the Ranger data (Willgoose & Sharmeen, 2006) to calibrate the armouring component of the MrARM model. In this section we compare MrARM and ARMOUR results under a range of conditions. We simulated the armouring of a 24-m hillslope with six nodes for: (1) two slope gradients (0.1° and 2°); (2) reduced runoff (by half); and (3) finer soil grading. The comparison between ARMOUR and MrARM was conducted by examining the simulated d_{50} (median diameter) plots of the hillslopes.

The 50 000 iteration simulations (equivalent to 200 years) correspond well to both final d_{50} values and behaviour in most cases. The highest variation in d_{50} was in the low slope gradient simulations in which MrARM has predicted a 4.4 mm d_{50} in node 2 (Fig. 3(a)) while ARMOUR predicted a d_{50} of 4.9 mm (Fig. 3(b)). This node also exhibits the most significant variation in

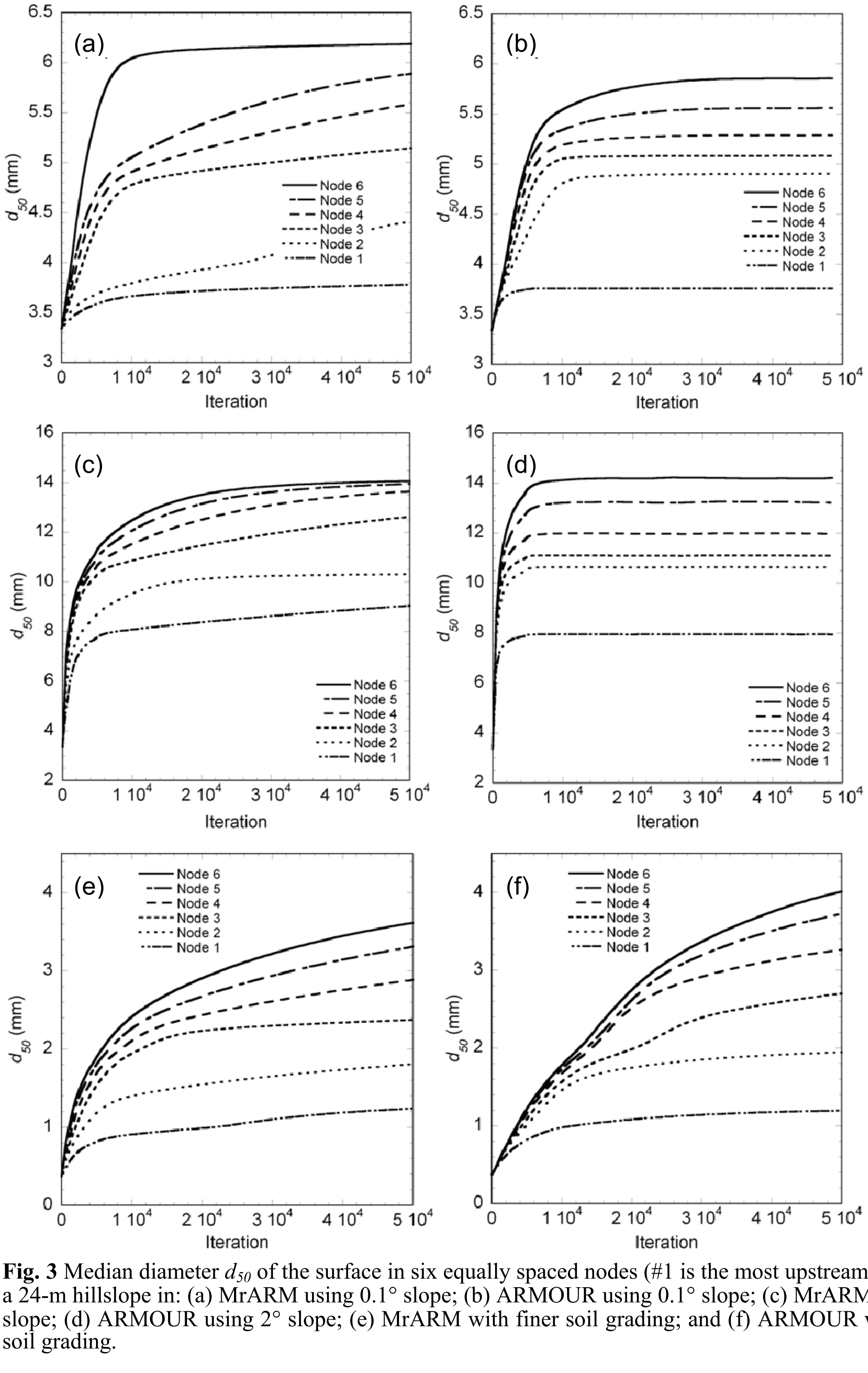

Fig. 3 Median diameter d_{50} of the surface in six equally spaced nodes (#1 is the most upstream node) on a 24-m hillslope in: (a) MrARM using 0.1° slope; (b) ARMOUR using 0.1° slope; (c) MrARM using 2° slope; (d) ARMOUR using 2° slope; (e) MrARM with finer soil grading; and (f) ARMOUR with finer soil grading.

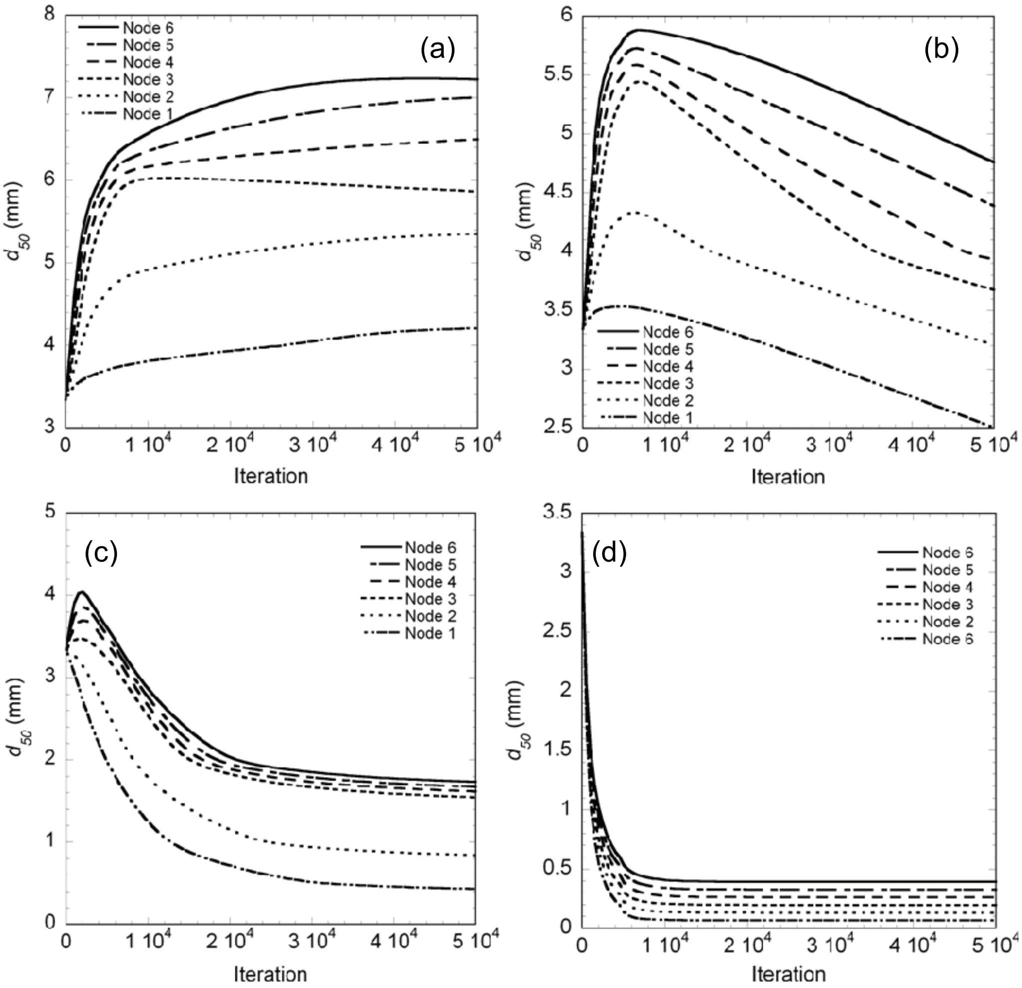

Fig. 4 Median diameter d_{50} of the surface in six equally spaced nodes (#1 is the most upstream node) on a 24-m hillslope in under different weathering rates: (a) factor of 0.1; (b) factor of 1; (c) factor of 10; (d) factor of 100.

behaviour over time. The reduced runoff simulation showed nearly identical results to the low-gradient simulations in both MrARM and ARMOUR (Fig. 3(a) and (b), respectively) and are therefore not displayed or discussed.

The differences observed in the calibration procedures (Fig. 1), in which the highest erodible class did not reach a state of equilibrium in MrARM as opposed to the ARMOUR simulation, can also be seen in both the low and high slope gradient results. Unlike the asymptotic equilibrium behaviour shown by the ARMOUR results the d_{50} values of most MrARM nodes continue to increase. The finer soil grading simulation demonstrate that this difference in behaviour is not a function of the rate of the process since it shows quite similar armouring rates in both MrARM and ARMOUR simulations (Fig. 3(e) and (f), respectively).

Combined armouring-weathering simulations

Our final set of simulations involved simultaneously using the calibrated armouring and weathering models from the previous sections. Figure 4 shows the results of four simulations (six nodes, 24-m slope at 0.21° slope gradient) with different weathering rates. The extremely low weathering rate (Fig. 4(a)) produced similar results to previously described armouring low slope gradient simulation presented in Fig. 2(a) (in which no weathering was simulated). As the weathering rate increased by a factor of 10 (Fig. 4(b)) the grading at each node starts to decrease after an initial steep increase. This steep increase is the result of erosion of the initial soil grading, which is relatively abundant with fine and erodible materials. Once the erodible materials have been removed (after approx. 10 000 iterations) the surface is armoured. The decrease in d_{50} after this time is solely the result of the weathering process breaking down the armour layer particles. This decrease in d_{50} indicates that the weathering rate is higher than the erosion rate, resulting in a transport-limited erosion regime.

Increasing the weathering rate by an additional factor of 10 (Fig. 4(c)) starts to show a more substantial dominance of the weathering process over armouring on the evolution of surface grading. Nodes 1 and 2 (which are higher on the hillslope and therefore have less runoff and erosion) are completely dominated by weathering; there is no increase in d_{50} at the beginning of the simulation and therefore no armour has been created. Nodes which are lower on the hillslope (3–6) still show some armouring in the early stages of the simulation.

For the highest weathering rate (Fig. 4(d); a further factor of 10 increase) the entire hillslope is completely weathering dominated. No armour has been created anywhere and the differences in final surface grading between the nodes are small. This latter observation is important because armouring creates a grading distribution that varies downslope (with discharge) while weathering creates a distribution that is the same everywhere. There is a state of equilibrium between erosion and weathering and the whole hillslope is transport-limited.

CONCLUSIONS

Hillslope-scale simulation of armouring and weathering is an important step in the investigation of these processes and their influence on soil and morphology. Our aim is to explore these important processes on a larger scale, which is impractical with existing models (e.g. ARMOUR). We therefore developed a simplified conceptual model based on the Markov chain approach (i.e. MrARM), which dramatically decreases the numeric complexity and thus computer run-time (by a factor of approx. 10^6) which enables large-scale implementation. The model armouring component was calibrated by matching the ARMOUR Ranger Uranium Mine data (Willgoose & Sharmeen, 2006). The weathering component was calibrated to Wells *et al.* (2008) laboratory and modelling results.

A simple parametric study was conducted in order to explore the behaviour of the model under various conditions. The results shows that for most nodes down the hillslopes the MrARM predictions were a close match to ARMOUR with a maximum deviation of less then 10% over 200 years of simulation.

Armouring-weathering simulations by MrARM (Fig. 4) illustrate the influence of increasing weathering rate on soil grading and armour development on a hillslope. We found that even for large weathering rates, that while an armour layer may develop quickly, it will slowly be reduced to a weathering-dominated (transport-limited) erosion regime. For extreme weathering rates (relative to erosion rates) no armour layer was formed on the surface and soil grading will quickly reach an equilibrium with very fine soils.

Our new model and the modelling approach allow a more detailed exploration of hillslope response to the weathering and armouring processes. We are now in the process of applying the model at a larger spatial scale (catchment) which will provide important insights on the spatial distributions of the armouring and weathering processes and their affect on soil development and erosion patterns.

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