

Computer and hardware modelling of archaeological sediment transport on hillslopes

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27.1 Introduction

It has been realized for many years that the archaeological residues we excavate bear only an indirect relationship to the human activities and societies which we infer from them.

On the site-scale, attempts have been made to understand artefact patterns using various techniques from mathematical models (Bradley 1970) to the so-called 'contextual approach' (Needham & Stigsørensen 1988). As various cultural and natural processes intervene in the making of these patterns (Wood & Johnson 1978, Schiffer 1987), we require some means of assessing, and if possible quantifying their impacts.

Initially, it was decided to study the natural processes, concentrating largely on the rôle of overland flow in the modification of assemblages. The working hypothesis involved is that if we can isolate the natural processes we can eliminate their effects when making cultural interpretations. Overland flow was chosen as the predominant force in the semi-arid environment in which we are working.

The approach outlined in this paper involves three major areas:

1. the empirical derivation of sediment transport models for materials in the artefact size-range, especially of pottery and flint.
2. deriving a set of integrated sediment transport formulae so that we may model diversity in artefactual patterns as well as sediment matrix.
3. demonstrating the articulation and integration of these models with those for additional processes.

27.2 Particle Transport Experiments

In the simplest case, we need to determine conditions in which particles of different physical characteristics may be moved, as well as an indication of distances travelled. Our analysis then proceeds to include any temporal variations in these, and any differences due to external factors, such as the composition of the surface.

The method involved groups of three experiments, using the Bristol University experimental flume facility at Long Ashton. Three different hydrographs were run over the two slopes available (Fig. 27.1). The first of these consists of a simple rising limb of a hydrograph and allows us to measure the entrainment parameters for different flow conditions, as well as the subsequent distances moved.

Secondly, we add a falling limb to the hydrograph to see whether there is any movement during this part of the (simulated) storm. Finally, we send a series of burst

hydrographs down the slope in order to simulate the effects of a repeated series of storms of the same intensity.

The results of these experiments show a typically wide scatter of about a theoretical constant threshold value of the Shields' criterion θ_* , which is a measure of sediment erodibility (Yalin & Karahan 1979). Even when we allow this threshold to change, allowing for hillslope flow conditions (Fig. 27.2; cf. Bettess 1984), we can see that there is a wide, apparently non-systematic variation away from this pattern (Fig. 27.3).

Plotting the behaviour of single particles for different replications of the same experiment, we see that there is a more clearly-defined relationship, with a logarithmic rather than constant relationship between flow conditions and particle parameters (Fig. 27.4). This seems to be related to the irregular shape of the artefacts compared with the theory, which is derived for spherical particles. The point at which the entrainment threshold is crossed depends on the interaction of a more complicated group of parameters than generally assumed. Paradoxically, the more submerged an artefact, the greater the entrainment criterion, although the logarithmic scale probably hides a convergence to a constant value for deep flows.

For distance moved in various conditions, the picture is less distinct. Fig. 27.5 shows the wide variability involved in this — for the smallest size-class used, a given particle's movement may vary between zero and several metres (beyond that measurable with the equipment available). Distances moved on a loam slope were different from those moved on a largely non-eroding clay slope, the most significant difference being that a small amount of apparent upslope movement was possible, due to localized scour behind the objects.

For the final set of experiments, we can see that for a repeated set of storm events, the overall probability of movement of any particle decreases through time (Fig. 27.6). This is interpreted as being related to the irregularity of the 'real' soil slope. Particles are gradually moved to points on the surface where they are in stable positions relative to flow conditions. This is probably caused by localized obstacles in the bedform which may be due to variations on the bedform-particle scale, and thus have an essentially random pattern. This accounts for the exponential tail-off of this curve, as the further a given particle moves, the more likely it is to encounter such an obstacle.

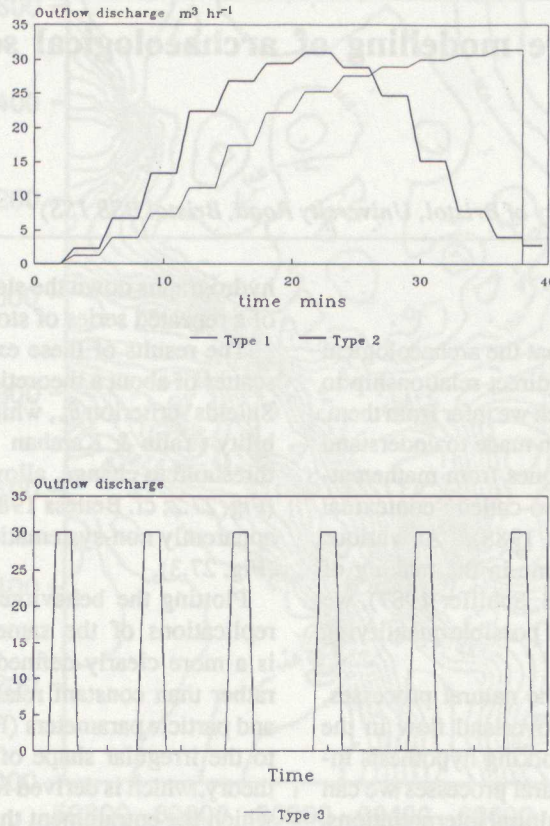


Figure 27.1: Types of hydrograph used in flume experiments

27.3 Computer Modelling of Sediment Transport

A stochastic model of sediment transport was developed for several reasons. First, the hardware model shows a great variability in the distances moved for particles of similar sizes. It also indicates that deterministic modelling of particle entrainment would require an unmanageably large number of parameters. Further, as the processes which cause overland flow (storm events) are discontinuous in time, it is an event-based model that is required. Using models developed for queues, we need to derive four components:

1. an 'arrival time' distribution of inter-(storm) event occurrences.
2. a measure of time steps in which no movement of a particle occurs within a particular storm event (a distribution of waiting times before 'service').
3. a distribution of distance moved once a particle has been entrained (amount of 'service' provided).
4. an indication of the variability of these processes through time.

The spacing and duration of storm events are controlled by climatic parameters. We can build a stochastic model which describes the patterning of these, given various assumptions into which we will not proceed in this paper. As a brief summary, however, we can say that the Poisson process effectively approximates the times between storm events (Woolhiser & Todorovic 1974).

The rest period distribution is essentially determined by random fluctuations in turbulent flow together with random patterns of bed roughness. Various authors have suggested an exponential or gamma frequency distribution, the former being a specific case of the latter (Fig. 27.7; Einstein 1942, Grigg 1970, Hubbell & Sayre 1964, Hung & Shen 1971, Yang & Sayre 1971). The shape of this distribution varies essentially with particle size and the overland flow conditions, the second again being controlled partly by climatic conditions.

For artefacts, the distributions of distances moved can be derived directly from the experimental work. Fig. 27.8 shows gamma distribution fits using the method of moments for these data, indicating a close fit. Again the distributions are dependent on particle size and overland flow properties. The derived curves are for discharges as high as could be expected for very extreme events and may be scaled to provide probabilities for less intense storms.

To incorporate movement in a second dimension, we may add either a separate step-length distribution function in this direction (cf. Sayre & Conover 1967), or a distribution for the angle of deflection from movement parallel to the slope (Hung & Shen 1971). Physically, this is related to flow turbulence, especially due to wakes produced by the artefacts themselves and bedform irregularities. For simplicity in the mathematical model, we have chosen the second approach. The experimental data show a good fit with a normal curve (Fig. 27.9), although as Hung and Shen have also noted, the actual distributions tend to have a more marked peak around the mean. This would tend to produce slightly more lateral diffusion in the model than in reality.

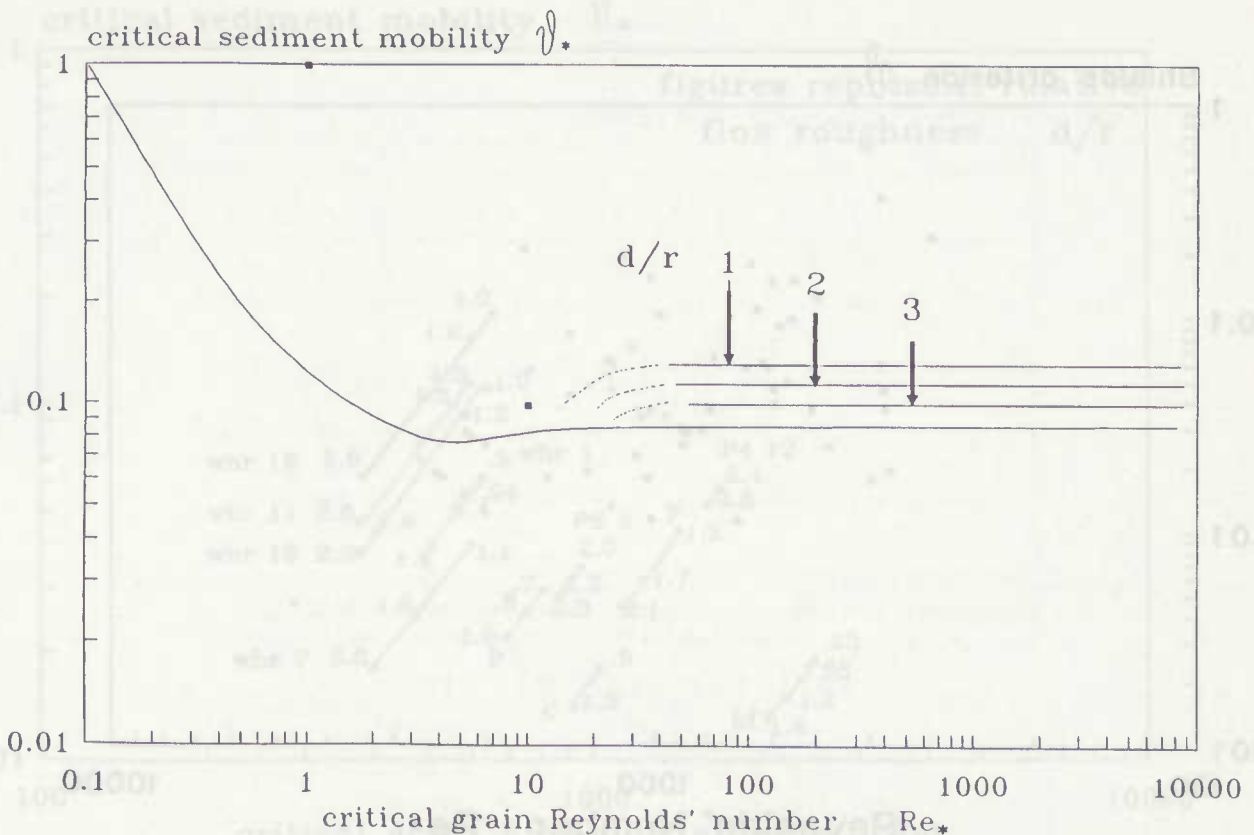


Figure 27.2: Theoretical Shields' diagram for large particles in shallow flows after Bettess, 1984. (d/r is the 'relative roughness', d being the particle dimension normal to the slope surface, and r the depth of flow)

Finally, we have seen how in repeated simulation events, the overall probability of movement decreases through time for a given particle in a storm event of given intensity. We have related this to the general increase in bed roughness with continued erosion.

To model this process, we use the concept of renewal. With repeated storms of the same or lower intensity, the overall probability of movement decreases in an exponential fashion as described above. To restart this process (return to higher probabilities of movement), either the flow discharge must be increased, or the surface slope must be modified in such a way as to alter the distribution of flows across it. Flow discharge is climatically controlled, although variations in hydrological properties may have significant effects on an interstorm basis. For the modification of the surface slope, various processes come into play, some of external origin and others due to feedback within the erosion process. External modifications are largely due to biotic factors and in an event-based model, we should take their seasonality into account. For animals, worms may be predominantly active in the summer months, whereas burrowing mammals may play a more important rôle in spring and autumn. Summer is likely to be most important time for slope modification by plant growth. Soil creep may also play a small rôle in the environment in which we are interested, and its impact is likely to be limited to autumn and winter months. Given additional human influences, we can say that slope changes can occur at any point through the year. The question is whether or not they are significant. As a first approximation,

it may thus be assumed that the renewal of the movement sequence has an essentially random pattern, and occurs as a Poisson distribution.

The main advantage of this model is that it allows us to simulate all sediment — that is the artefacts and the sediment matrix — within a single conceptual framework. This means that the interaction between dynamic topography and artefact movement can be adequately simulated. To do this, we must convert the probability distributions outlined above into a bedload transport equation as follows (Fig. 27.10):

$$Q_s = f(p, q) \quad (27.1)$$

- where Q_s is the (relative) sediment yield for each particle size [dimensionless].
 p is the probability of entrainment for a particle of a given size, derived from the distributions given above [dimensionless].
 q is the relative quantity of this particle size present [dimensionless].

The distributions for the probability of motion are represented by a suite of functions defined by the following variables:

$$p = f(\phi, o_t, s, d_b, \gamma) \quad (27.2)$$

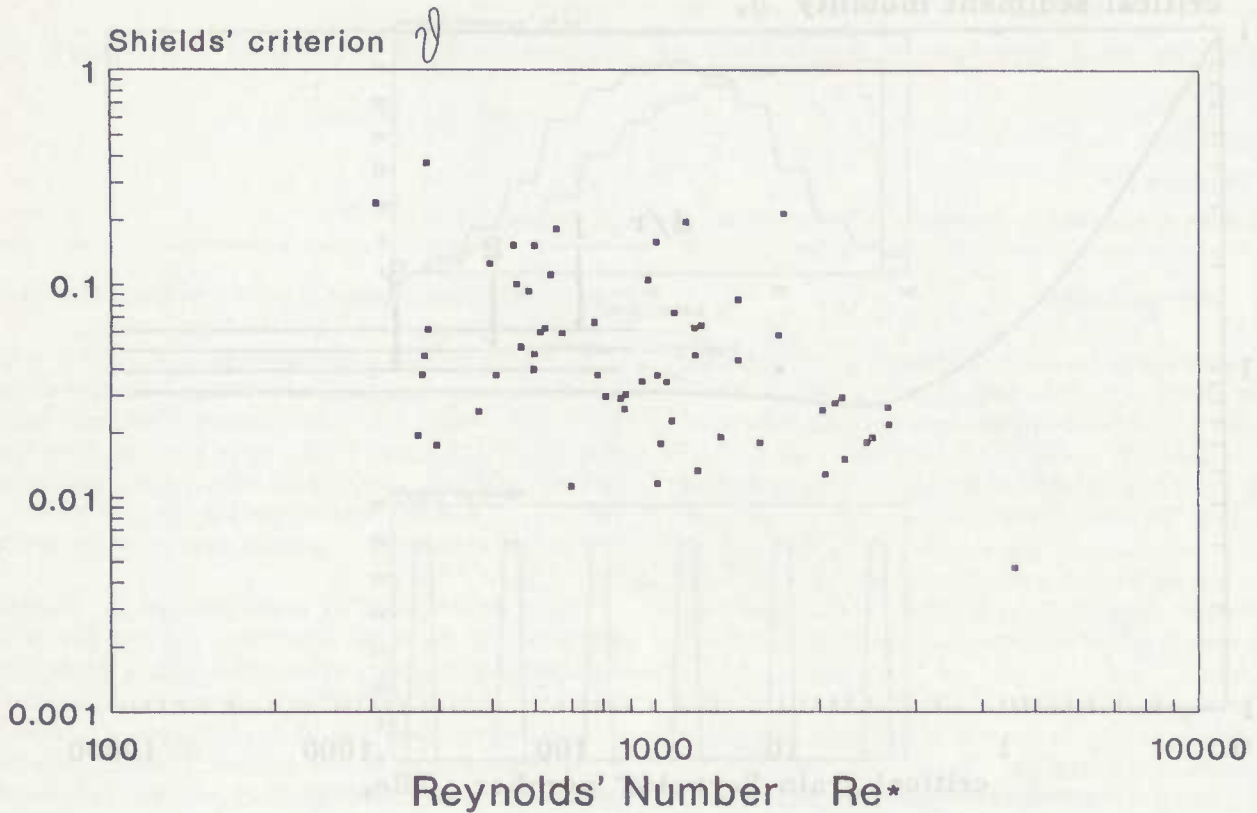


Figure 27.3: Observed conditions of entrainment of pot sherds in experiments

where ϕ is the particle size [m]
 o_s is overland flow discharge [$m^3 hr^{-1}$].
 s is the energy slope [$m m^{-1}$].
 d_b is the depth of burial of the particle [m].
 and γ is the particle density [$kg m^{-3}$].

As the effect of the depth of burial is to reduce the fluid drag force acting on the particle (cf. Streeter & Wylie 1983, p. 47):

$$F_{D\bullet} = (1 - \frac{d_b}{d_s})F_D \quad (27.3)$$

where

$F_{D\bullet}$ is the drag force acting on a partially buried particle [$N m^{-3}$].
 F_D is the drag force acting on a fully exposed particle [$N m^{-3}$].
 d_s is the particle dimension perpendicular to the slope surface [m].

we can see that the probability of movement is a linear function of the term in brackets, as lift forces may be excluded in shallow overland flows. A burial coefficient for particles which may easily be modelled, can therefore be defined as this component of equation 27.3:

$$b = (1 - \frac{d_b}{d_s}) \quad (27.4)$$

where b is the coefficient of burial [dimensionless].

For matrix sediments, modelling of the depth of burial of each particle is not viable, so that we require another estimate for the burial coefficient. As a first approximation, we determine the relative amount of burial or hiding of

smaller matrix particles as the sum of the relative particle quantities of greater size. The effect of this is to allow simulation of progressive slope armouring.

$$b_\psi = \sum_{x=\psi+1}^n q_x \quad (27.5)$$

where $\psi = 1, 2, \dots, n$ indicates the size class of the sediment.

The relation for transport of a single particle size in a given cell unit per unit time is thus:

$$Q_{s\psi} = b_d p_\psi q_\psi h_{s\psi} \Delta x \Delta y \Delta t \quad (27.6)$$

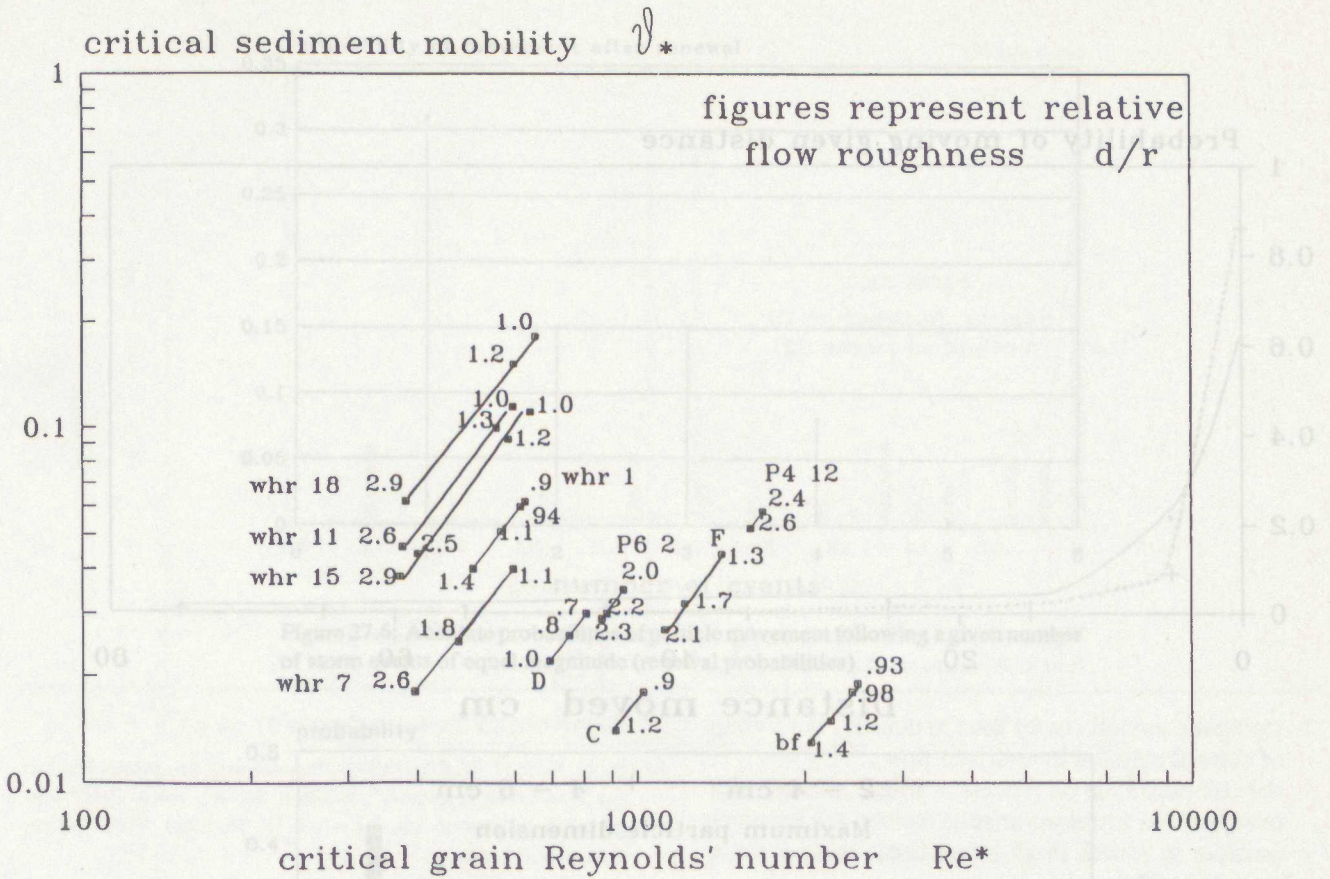


Figure 27.4: Shields' diagram with relative roughness values for particles repeatedly entrained in experiments (lines join values for the same particle)

where $Q_{s\psi}$ is the sediment discharge of a specific particle size [$m^3 hr^{-1}$].
 b_d is a bulk density coefficient, dependent on context. For example, sediments deposited in pits will tend to become less dense, whereas sediments derived from walls will appear more dense upon deposition due to the loss of organic materials [dimensionless].
 Δx is the model cell length in the x direction [m].
 Δy is the model cell length in the y direction [m].
 Δt is the model time-step [hr]
 $h_{s\psi}$ is the active layer of entrainable sediment [m]
 and $h_{s\psi} \phi_\psi$ as $\Delta t \rightarrow 0$
 $h_{s\psi} z_s$ as $\Delta t \rightarrow \infty$
 where z_s is the soil thickness [m].

So that the term for total sediment discharge within the cell is:

$$Q_{tot} = \sum_{\psi=1}^n Q_{s\psi} \quad (27.7)$$

where Q_{tot} is the total sediment discharge [$m^3 hr^{-1}$].

Thus, in the finite difference model, the change of height of a cell due to simulated erosion in a specific time step is

defined as:

$$-\Delta z = \frac{Q_{tot} - (Q_{tot} \int_x^{x+1/2\Delta x} f(s)dx)}{\Delta x \Delta y \Delta t} \quad (27.8)$$

where Δz is the change in surface height [m].
 $f(s)$ is the step length frequency distribution.

The term in brackets represents the amount of material entrained but redeposited within the original cell.

This eroded material is then redeposited at points determined by the step-length distribution described above, so that in one dimension:

$$\Delta z_{x+i\Delta x} = \frac{Q_{tot} \int_{x+(i-1/2)\Delta x}^{x+(i+1/2)\Delta x} f(s)dx}{\Delta x \Delta y \Delta t} \quad (27.9)$$

where $x + i\Delta x$ is the node point $i\Delta x$ points away from the cell x from which the sediment is derived.

27.4 Initial Model Results

The results from model simulations show overland flow to be an important factor in the patterning of artefacts. They suggest that this process is important mainly in the first ten years following site abandonment.

Fig. 27.11 shows an example of an initial and final artefact scatter after five thousand years on a straight slope inclined at five degrees. The original equally-spaced distribution has clearly been re-sorted so that clusters have been formed.

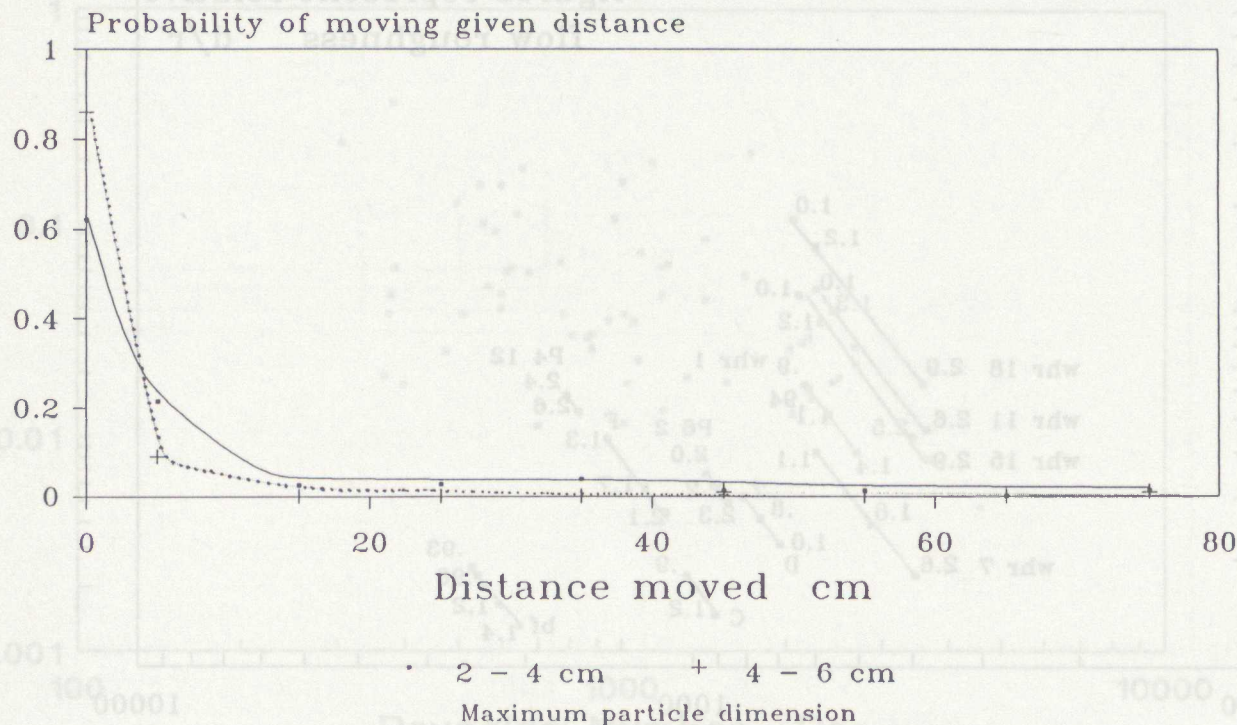


Figure 27.5: Experimental results of distance moved for two particle size classes

These clusters are purely due to the processes of transport due to overland flow, and not for example to specialized activity or storage areas.

Histograms of positions of artefacts along the slope (Fig. 27.12) show an example of how the sorting takes place. In this model run, most of the large objects (between eight and ten centimetres in maximum dimension) have been concentrated downslope, whereas some of the smaller ones (2–4 centimetres) have remained upslope. Of the other size ranges, the artefacts under two centimetres and those between four and six centimetres have almost complementary distributions, while the six to eight centimetre group also has alternating zones of low and high density. Again this sorting is entirely due to natural processes.

All artefacts have been washed away from the slope divide, and there is a certain concentration of them in the basal ten to fifteen metres at the slope base. This pattern is often seen on hillslope sites. It is closely related to the movements of matrix sediments. The artefacts towards the base of the slope become deeply buried within the soil; this occurs in the later part of slope development. There is a certain diffusivity in the vertical distribution of the artefacts, due to the point at which they became buried. However, sediment transport by overland flow does not seem to be an important factor in artefact burial across the major length of the slope surface. For this we must look to other causes: anthropogenic, faunal, floral, or other soil processes.

Notably, this stochastic model also produces slope profiles which are less symmetrical than models based on deterministic models.

27.5 Model Interactions

This group of integrated sediment transport equations are designed to be part of a much larger simulation model which attempts quantitative assessment of the rôle of natural formation processes in archaeology. This involves interactions with a variety of other processes. These may be simply related under the three broad headings of topography, hydrology and vegetation (Fig. 27.13).

Under the heading of topography, we have already mentioned the link between erosion of the sediment matrix and the artefacts in which we are interested, and this is why we require a single model to account for variation in both groups. Secondly, we also have the rôle played by various archaeological structures and contexts, which may modify the ground surface, as well as human action after the site's abandonment. Finally, we have a background of the underlying geomorphology, and in the long term, geology.

Hydrological interactions come in the form of the dynamic relationship between water flow and surface roughness, which we have already seen to be an important factor in reducing movement through time. But also, this has a short-term, localized effect on the distribution of flow velocities and therefore entrainment probabilities. We also have lateral variation in infiltration rates, which influences the spatial patterning of runoff. It can be shown that the archaeological context again has an important effect on the determination of this property, as does post-abandonment

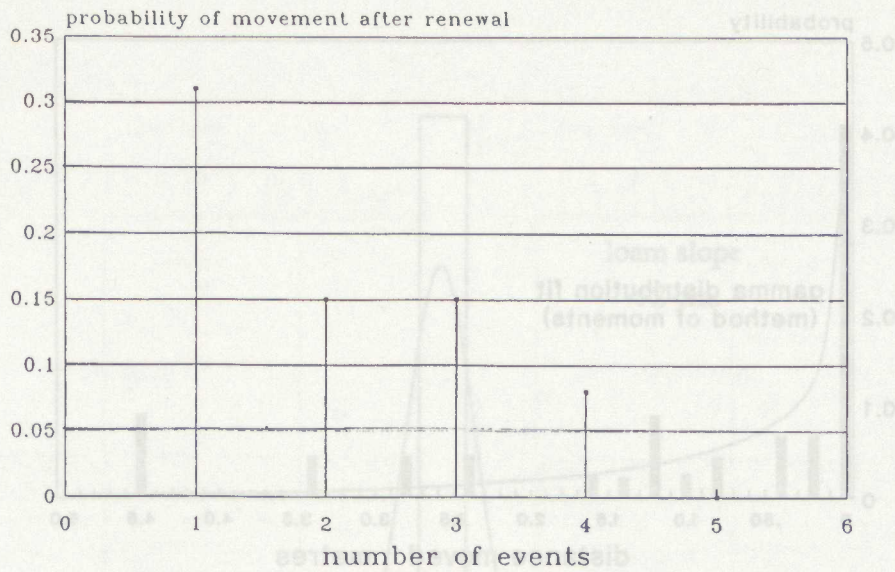


Figure 27.6: Absolute probabilities of particle movement following a given number of storm events of equal magnitude (renewal probabilities)

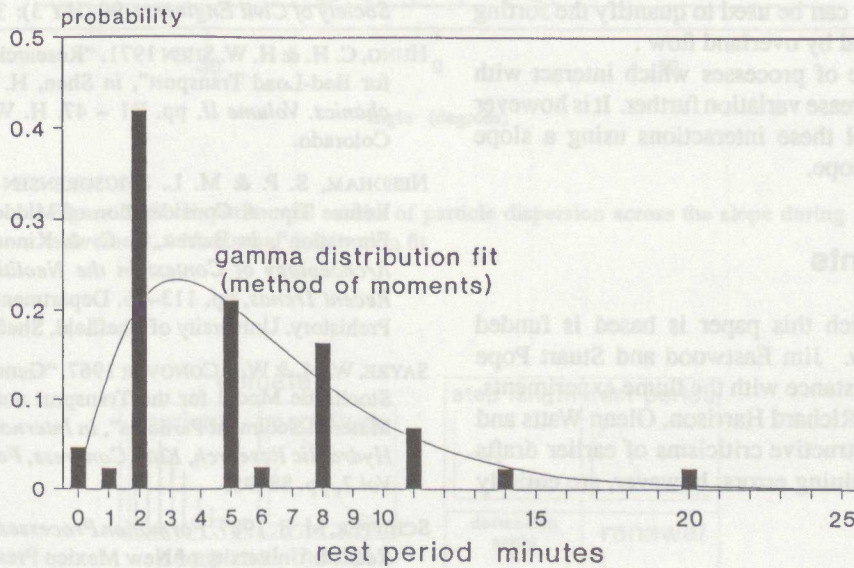


Figure 27.7: Gamma distribution fit to experimental results for rest periods between separate particle movements

land-use. Infiltration rates are also dependent on climatic factors.

Thirdly, we have an interaction between vegetation and movement, beyond the effects on the renewal process we have already mentioned. Vegetation may be an important modifier of the slope roughness affecting local entrainment patterns. Presence of vegetation may have two further and contradictory direct consequences, in that movement is either prevented by the vegetation mat, or is locally increased by flow channelization. The difference in occurrence of these is probably related to environment. Vegetation may modify the topography and significantly change the hydrological conditions.

Plant re-growth after a site is abandoned is again a function of the archaeological context and climate, as well as the subsequent use (if any) to which the land is put. This

suggests a further vulnerability to re-sorting of artefact assemblages in the period immediately following site use, before artefacts are buried.

27.6 Conclusions

Although the aim of this paper has been to outline the modelling technique rather than examine a large body of results, we can conclude with several points:

1. overland flow significantly alters perceived spatial and temporal patterns in artefactual assemblages, in certain environments, even though the time-span during which these processes are important is relatively short in relation to the whole history of the site.

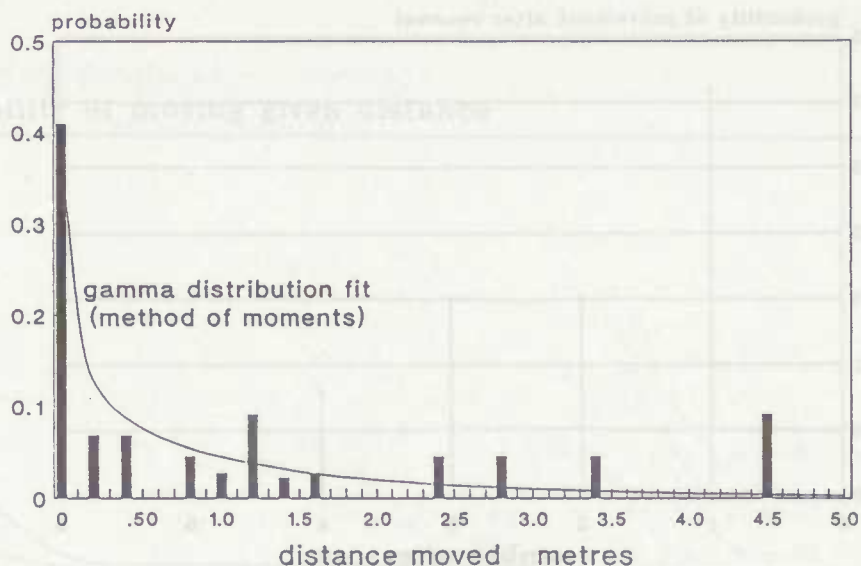


Figure 27.8: Gamma distribution fit to experimental results for distance moved (particles <2cm. on clay slope)

2. stochastic models can be used to quantify the sorting of cultural material by overland flow .
3. the complex suite of processes which interact with overland flow increase variation further. It is however possible to model these interactions using a slope model of wider scope.

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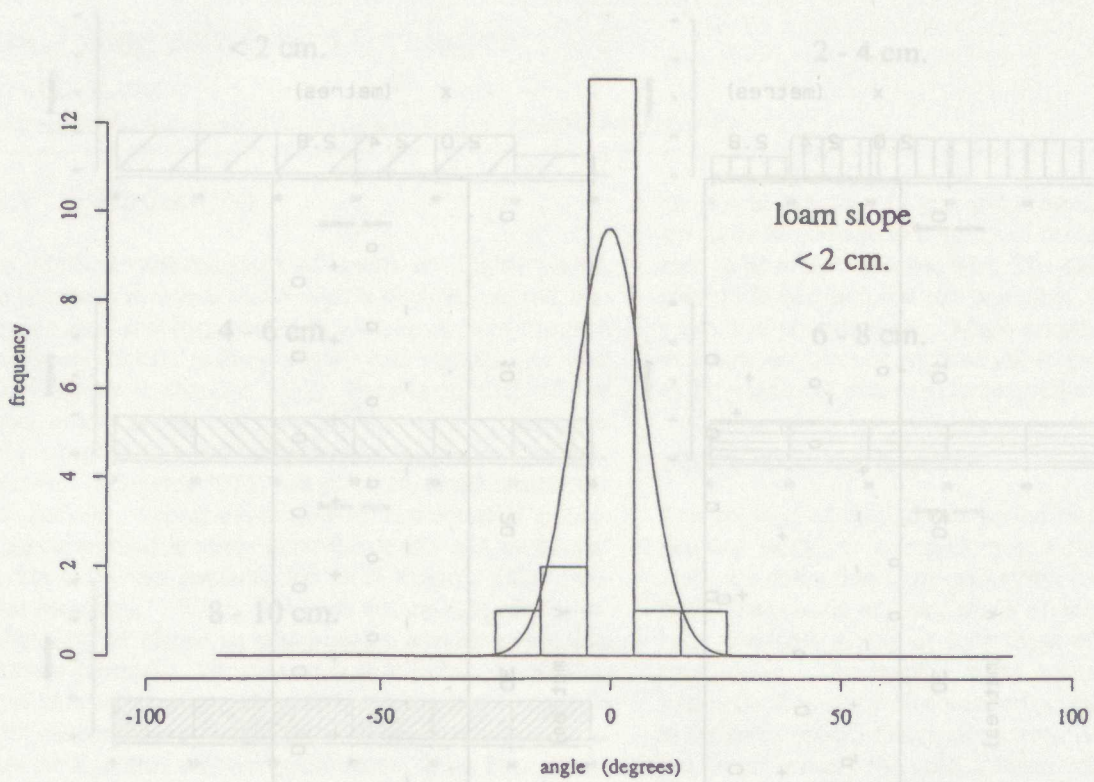


Figure 27.9: Experimental results of particle dispersion across the slope during movement, with normal distribution fit

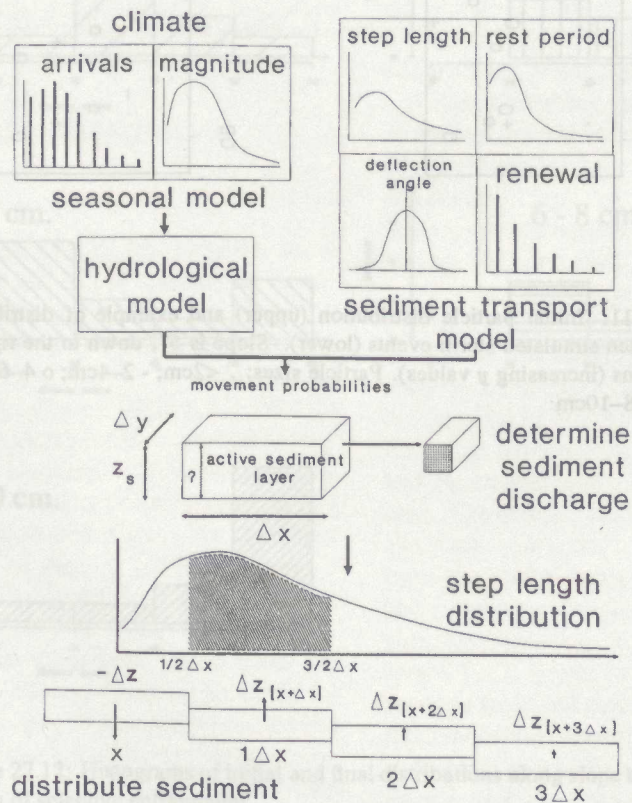


Figure 27.10: Schematic diagram of computer model structure

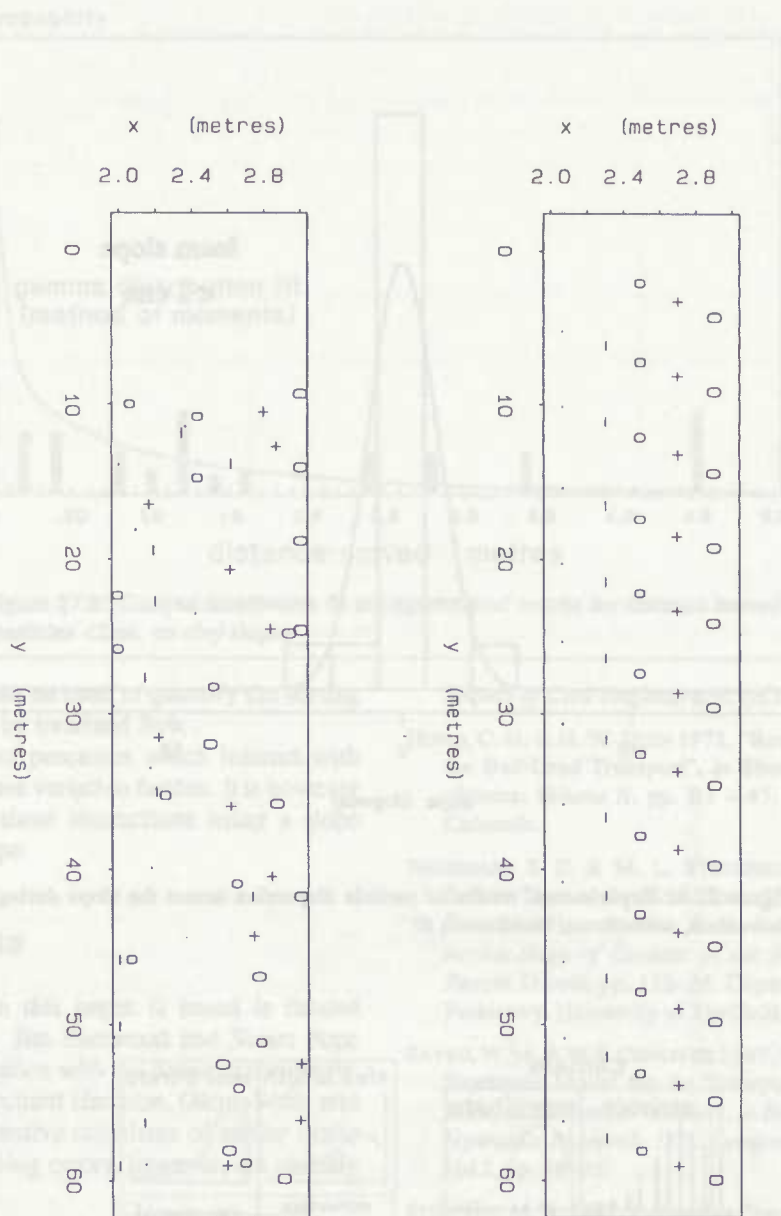


Figure 27.11: Initial particle distribution (upper) and example of distribution following ten simulated storm events (lower). Slope is 5° , down to the right of the diagrams (increasing y values). Particle sizes: . <2cm; - 2-4cm; + 4-6cm; O 6-8cm; O 8-10cm

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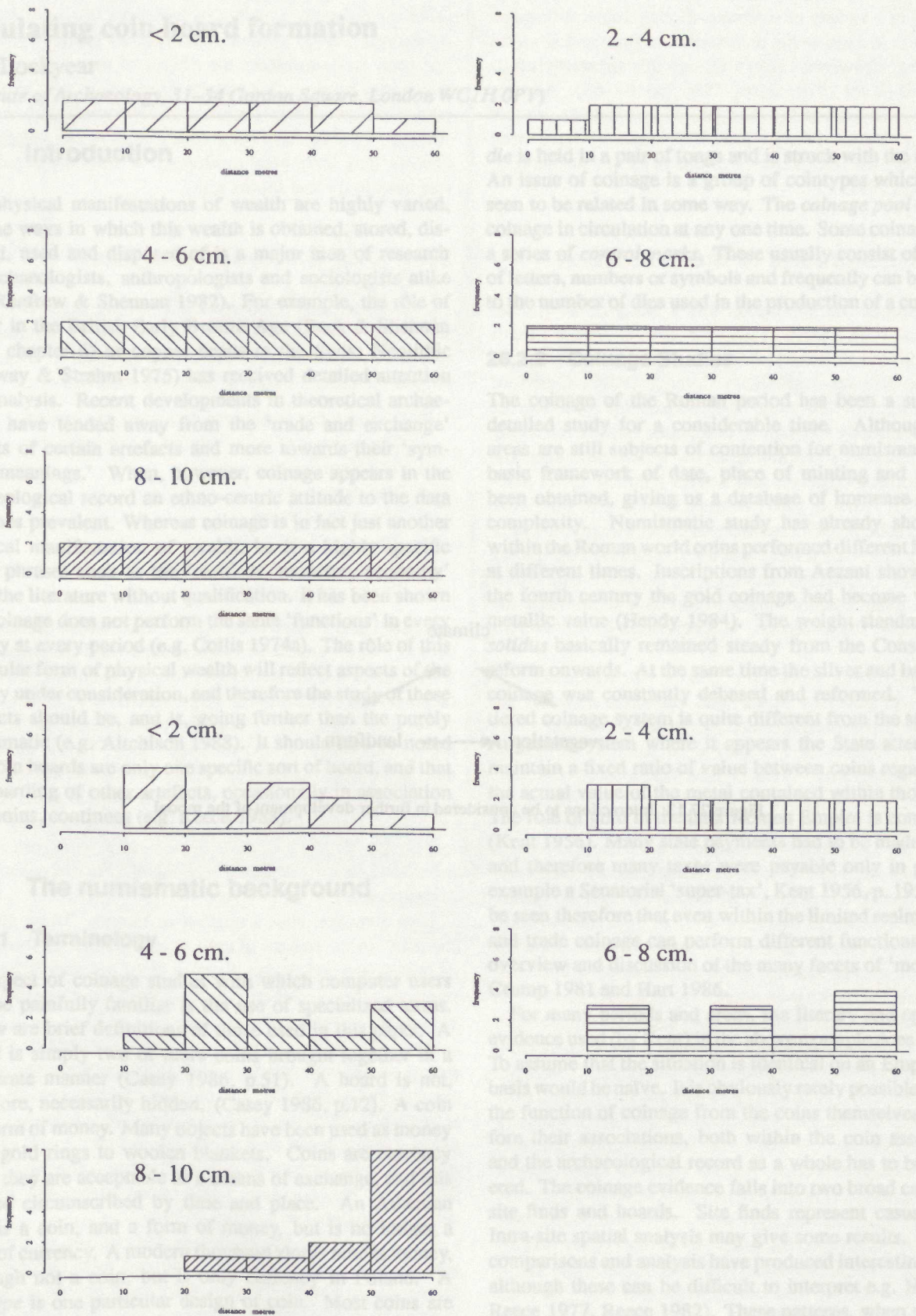


Figure 27.12: Histograms of initial and final distributions along slope to show the effects of selective entrainment

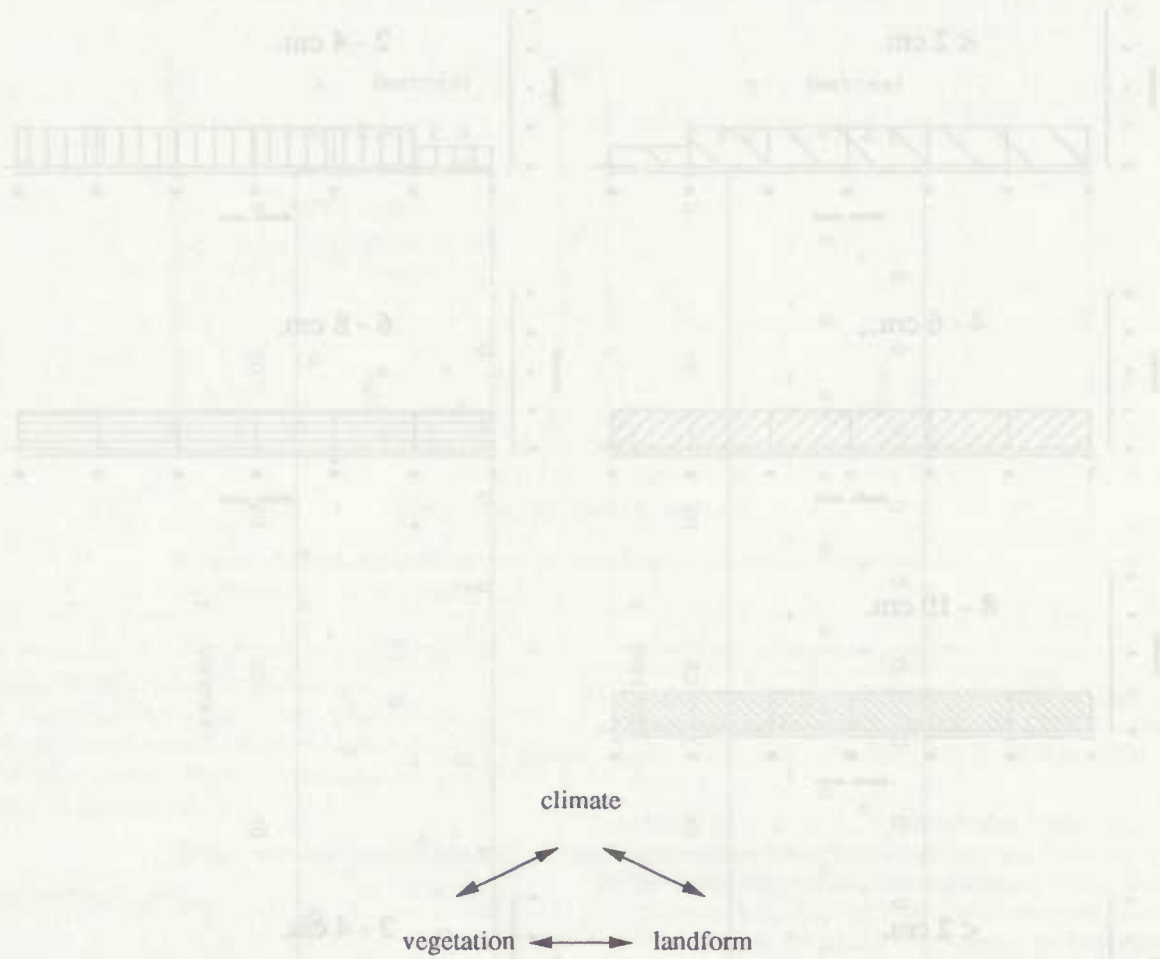


Figure 27.13: Interactions to be considered in further development of the model

