WORKING PAPER 522

A MODEL TO ESTIMATE THE IMPACT OF CLIMATIC CHANGE ON HILLSLOPE AND REGOLITH FORM

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January 1989

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Abstract

By placing a model for the evolution of hillslope and regolith form in explicitly climatic terms, the effect of climatic change can be forecast directly. This provides a tool for investigating the impact of expected changes, for instance those due to the accumulation of greenhouse gasses in the atmosphere. The model is based on budgets for vegetation biomass, total sediment representing elevation, and regolith expressed as a deficit relative to bedrock composition.

The numerical model presented contains components representing vegetation growth, leaf fall, organic soil accumulation, solution, soil creep, splash, wash, and shallow landslides. Expressions are rationally based on empirical and theoretical work, with strong interactions between the various components. The results are illustrated relative to the present climate of Luxembourg, showing the forecast effect of temperature changes of 10°C in either direction on vegetation cover, soil thickness and erosion rates. The method is designed to have a wide range of applicability, and may be used either to make local forecasts or to point to environments which are sensitive to the temperature changes now forecast for the next century.

1. Introduction

Over the next century, it is estimated that the increased levels of carbon dioxide and methane in the atmosphere will raise global temperatures by up to 5°C on average, and will also tend to increase average rainfall, although with great local variations. Although the most direct effects of these changes will be felt through the submergence of low lying areas and changes in agricultural productivity, there will also be changes in the landscape and soil cover, associated with severe erosion in some areas, which will also become serious in the long term. The numerical model presented in this paper attempts to address this problem, providing a methodology and a set of provisional parameter values which offer a framework for forecasting landscape and regolith changes.

There is a substantial literature on numerical modelling of hillslope evolution over time. Much of it is based on the continuity or mass balance equation (Kirkby, 1971) for total sediment, with process laws expressed empirically in terms of gradient and slope length or catchment area (e.g. Musgrave, 1947). This approach is suitable for processes which are limited by the transporting mechanism, that is 'transport limited' removal (Carson and Kirkby, Chapter 5). On the scale of the whole hillside, this is a reasonable approximation for soil creep, rainsplash, and wash erosion. There is a second group of 'weathering limited' or 'detachment limited' processes, in which transport of sediment is limited by availability. The critical test of whether a process is effective transport or weathering limited relies on the mean distance of travel in individual events. Where this distance is an appreciable fraction of the total slope length, the process should either be treated as weathering limited, or on the continuum of 'erosion limited' removal which spans between the two extreme cases Kirkby 1979, 1984). This approach may be used effectively for solution (Kirkby, 1986) and for shallow landslides (Kirkby, 1984).

In a similar way, a soil 'deficit' may be defined as the amount of material, in 'rock equivalent' units which needs to be replaced to convert the regolith back into bedrock, replacing material carried away by solution etc. A continuity equation for this soil deficit similarly provides a basis for forecasting the concurrent gross changes in soil depth over time, as a balance between the addition of weathered bedrock to the soil through solution and its removal by all the mechanical processes operating. Using the same process rates as before, a regolith model may be combined with the hillslope profile model to show the evolution of hillside and regolith together (Kirkby, 1985a).

The models referred to above are essentially long term models, in which the detail of individual hydrological events is compressed. In order to relate process rates to climate, an explicit hydrological model is required, which takes some account of at least the distribution of individual rainfall events. Through an explicit, though necessarily approximate, procedure for aggregating events, the long term model needs to be expressed in an integrated form. Terms for distance or catchment area in hillslope evolution models are recognised as surrogates for discharge, and this linkage is made explicit through the aggregated hydrological model.

An important part of the hydrological response is through the vegetation cover, and the hydrological model is therefore needed to allow vegetation to grow, and in turn build up an organic soil. The interaction with vegetation is not only an important component of the hydrological budget, but there are also recognised to be very strong influences of vegetation on rates of sediment and solute transport. In particular, both crown cover and organic soil content are very effective in limiting surface sealing and wash erosion. For base rich parent material, the amount of organic soil also has a strong influence on solution rates.

2. Model structure.

The overall model structure is described here in terms of its main components. These are hillslope hydrology, transport limited processes, erosion limited processes, boundary and initial conditions, and controls for model and slope stability. The model is a finite difference model for a series of equally spaced points down a hillside strip of constant width. Table 1 lists the main input parameters, which are referred to by their number (e.g. #3 for slope relief), in the more detailed discussion of each component below.

The model is formally a solution of continuity or storage equations for elevation and soil depth. For elevation:

$$\partial z/\partial t + \partial(S+V)/\partial x = 0 \qquad (1)$$

where z is surface elevation in 'rock equivalent' units,
S, V are respectively rate of mechanical and dissolved material transport per unit flow strip width,
x is horizontal distance measured down the flow strip
and t is elapsed time.

For the soil, a proportion p may be defined as the fraction of bedrock material present at any depth in the soil profile, which may be obtained from a 'by volume' analysis fo soil and bedrock material. p_s, the minimum value of p is usually near the base of the A horizon, representing the top of the weathering profile. Soil deficit, w is defined as the total equivalent depth of material needed to restore the weathered soil to bedrock composition, and has the dimensions of depth. It can therefore be used as a precise generalisation of the concept of soil depth, and is formally defined as:

$$w = \int (1-p)\, dx \qquad (2)$$

The continuity equation for soil deficit is obtained by balancing additions to the deficit due to solutional removal against reductions of deficit due to mechanical stripping of surface soil. Thus:

$$\partial w/\partial t = \partial[V - S(1-p_s)/p_s]/\partial x \qquad (3)$$

with the same notation as above. Formally, it is required to express the sediment and solute transports, and the surface proportion p_s, in terms of position to obtain a solution to these equations for elevation and soil deficit. Figure 1 shows the main inter-relationships which have been used to forecast process rates from topography, and from climate via the hydrology.

The hillslope hydrology is estimated from hillslope form and simple climatic values without, at present, a seasonal component. The distribution of storms is represented through the number of rain days per year (#6), which gives an explicit distribution of daily rainfalls (Ahnert, 1986) which is used to represent rain storms. Actual evapotranspiration is estimated from total precipitation (#4) and potential evapotranspiration (#5). The net rainfall is used to estimate levels of subsurface flow, based on a TOPMODEL formulation with an exponential soil water store (Beven & Kirkby, 1979). The main soil parameter, m is derived from a term for current soil thickness (× #8) plus a term for organic soil content (× 5mm per $kg.m^{-2}$ biomass), using values forecast within the model for the previous time period. Lateral saturated hydraulic conductivity at the surface is calculated from m (÷ #10, a characteristic response time).

Actual evapotranspiration is used as a basis for estimating net primary production of vegetation, and leaf fall estimated from current biomass. The set of equations used is similar to those used by Kirkby and Neale (1986), and uses the same parameter values, calibrated against a world wide range of available data, though without the seasonal components of climate. The Vegetation and organic components are assumed to be the same for all points on the slope, because preliminary work showed that downslope variations were normally slight. The model estimates natural vegetation cover, but some account may be taken of agricultural practise through two parameters which determine how much of the natural leaf fall is gathered from the ground (#27), and how much additional material is gathered from the living plant (#26), again scaled to the natural rate of leaf fall. Much of the effect of an efficient unirrigated agriculture may, for example, be obtained by setting the first of these parameters to almost 100%, to simulate complete harvesting of an annual crop. The ways in which vegetation is used in the model to influence erosion rates are indicated in figure 2.

It has been recognised that storm duration has a strong influence on the distribution of overland flow downslope (Dunne & Aubry, 1985; Yair & Lavee, 1985). This effect is obtained through a parameter (#9) which gives the mean overland flow distance during a storm. To allow for a distribution of storm durations, this parameter is used to provide a gradual cutoff in contributing length. For each storm, the local soil water deficit is calculated from the local level of time-averaged subsurface flow and the excess, if any, contributes to overland flow over an appropriate contributing length downslope. In this way overland flow, and its erosive effects, assumed proportional to overland flow squared, may be integrated downslope over the distribution of daily rainstorms. The wash erosion may also be limited by an erosion threshold, controlled in part by vegetation cover as it changes. The forecast wash erosion thus responds in a complex way to both gradient and slope position, even though the basic underlying rate is related to discharge squared times gradient. This is because discharge already incorporates responses to the topography and vegetation through subsurface flow and storm duration effects, which are important respectively in humid and arid areas. The underlying mathematical derivation is given in the Appendix.

Rainsplash, soil creep and solifluction transport are all modelled as directly proportional to gradient, with similar magnitudes for splash and creep, but with a 10x increase for solifluction, based on the annual number of frost days (#7). Crusting effects are indirectly incorporated, through the vegetation controls on subsurface runoff (through the soil parameter m), but there may be scope for a more direct linkage than at present. Finally creep/ splash and wash rates are constrained by local current soil depth (#21). For creep this is intended to show the truncation of the shear profile with depth in a shallow soil. For wash, shallow soils generally have coarser material because of less weathering, so that the depth factor indirectly reflects the size selectivity of wash transport, though there may be scope for incorporating this effect more directly. Because travel distances are generally small in relation to the total slope length, splash, creep, solifluction and wash are all treated as transport limited processes, although this approximation is no longer adequate at the scale of the field plot.

Another group of parameters (#13-16) is concerned with rates of shallow landsliding, which is treated as an erosion limited process, because the travel distances involved are of the same order as the total slope length in many cases. The methodology closely follows that used in Kirkby (1984), though here using horizontal, instead of the vertical increments of distance used there. Parameters represent a lower threshold (#14), below which slopes are ultimately stable, and a rate of free degradation (#13) per unit gradient above this threshold. A higher (talus) threshold (#15) is that above which material will not come to rest, and a final equivalent distance (#16) gives the effective height of fall of a slide mass, which is used to determine its momentum, and the distance the slide mass runs on at gradients below the talus threshold. As formulated at present, the landslide thresholds and rates are not modified by the degree of soil weathering or by soil depth, and it is recognised that there is scope for including a more direct interaction.

Solution processes are modelled using the methods presented in Kirkby (1985a & b, 1986), treating solution as a weathering limited process. This assumes that material, once removed in solution, is effectively carried out of the hillside completely. Solution rates are modelled using a linear model, with an effective insoluble residue (#19), and a solution rate which reflects the amount of organic soil (#17-18), which is significant for base rich parent materials. The relationship between soil deficit (*i.e.* depth) and proportion of bedrock remaining is calculated from the effective insoluble residue (#19) and a scale depth (#20). All subsurface flow, calculated as described above, is assumed to contribute to solutional transport. The continuity equation for soil deficit formally links the rates of solutional and mechanical transport to the changing soil thickness at each point downslope. By going back to the underlying basis (Kirkby, 1985b) for this approach, it may be seen that a particular soil depth may be closely identified with an explicit weathering profile, for a given parent material.

Initial conditions must be specified to give the total slope length and relief (#1 & 3), the initial soil thickness (#30) and vegetation/ organic soil characteristics (#31-33). The initial slope form may be set as any series of straight line segments, only constrained by the requirement that the slope falls monotonically from divide to base. For the examples illustrated here, the initial form has generally consisted either of a uniform straight slope from divide to stream; or a summit plateau, into which a stream rapidly incises a valley at the start of the simulation. The latter condition perhaps makes fewest assumptions about the previous geomorphological history of the area, in the absence of clear stratigraphic or other evidence. The use of a uniform initial slope gradient, generally with gradient 0.5 (26.5°) makes the implicit assumption that landslides have reduced the hillside to their stable gradient prior to the start of the simulation, so that attention is focussed on the operation of slower processes.

The model is set within fixed boundaries. The upper boundary is a divide, across which there is no flux of water or sediment, and which is considered to be symmetrical, in that the divide is not allowed to migrate. There is a symmetrical valley bottom at the slope base, normally with a stream removing sediment and solutes at a fixed horizontal location. Three mutually exclusive possibilities have been used for the rate of basal sediment removal, with an option set by a dummy parameter (#23). The first and simplest is that the stream removes all sediment at an elevation which falls linearly over time (#22). The second is that removal takes place at an elevation which falls inverse exponentially to a given base level (#25). The third condition is that the stream is considered to have an increment of sediment transport, proportional to its height above base level, as it passes the base of the slope profile. This condition allows a dynamic interaction between stream and slope. If the slope delivers more than the stream's sediment increment, then the stream can only remove part of the sediment, and the slope base aggrades until its elevation provides the necessary stream sediment increment. For this condition, stream elevation is used as an implicit surrogate for stream gradient in determining the stream sediment increment. Elevations close to base level are deemed to imply a low stream gradient, and contrariwise. This formulation requires the specification of a valley bottom width (#24) which is held constant over the course of the simulation.

The choice of a basal boundary condition for soil deficit is more problematic. Setting soil depth to zero is unrealistic, in that low gradient streams do not always flow on bedrock. The alternative used is the rather weak condition that soil depth at the slope base is exactly the same as at the previous point upslope. This is roughly equivalent to an assumption of symmetry around the stream axis, but there is scope to re-examine the choice of soil boundary condition.

The model provides estimates, at each time increment, of the rates of change in vegetation biomass and organic soil biomass, which are taken to apply at all points equally. At each horizontal distance increment downslope, rates of change of elevation and soil deficit are also estimated. Computational stability is maintained by using a variable time increment. This is chosen by scanning the relative rates of change of vegetation biomass, organic soil biomass, slope gradient and gradient in soil deficit at all points downslope. The time step is then normally chosen as the largest increment which will keep the absolute change in these variables to 20% or less. Exceptions are allowed to set a maximum allowable time step, to bring total simulation times exactly to preselected times for printouts etc (#28-29) , and to allow reversals in rates of change of, for example, soil thickness. This procedure maintains stability of the underlying partial differential equations in an efficient and conservative way.

Although the model has been run for sediment and solute transport down flow strips of unform width, it is possible to use the model to calculate stability criteria in the sense of Smith and Bretherton (1972). This evaluates the strength of tendency for small random hollows on the hillside to enlarge (instability) or refill (stability in this sense). Ideally, a slope should have a neutral stability value at its base. Longer slopes would then tend to be gullied, and shorter slopes would not generally have a stream at their foot to remove sediment. For illustrative comparisons here however, slope lengths have arbitrarily been held constant as climate has been allowed to vary.

The model has been implemented in QL SuperBASIC, a procedure based dialect of the BASIC programming language, and compiled for the Sinclair QL microcomputer, using Digital Precision TURBO. A full listing is included in the Leeds School of Geography Working Paper which is associated with this paper.

4. Example runs, related to the climate of Luxembourg

Although it is plain that there is not yet suffiecient empirical control on all model parameters, the scope of the model is illustrated here in the context of the climate of Luxembourg. A reasonable set of parameter values is assumed, and their implications are followed in terms of the evolution of slopes and soils over a period of 200,000 years of fixed conditions. Runs are then repeated for conditions which differ only in temperature, although not extending to conditions cold enough to permit local glaciation. These runs should span the range of conditions which has been encountered in glacial and interglacial periods, providing some insight into the rate and type of respnse to changing conditions. Finally a few runs illustrate the changes which are forecast in the shorter term, to landscapes which have been evolved under a different climate. These runs are most relevant to the sensitivity of the landscape, soils, and erosion rates to changes which may result from high concentrations of greenhouse gases.

Luxembourg is taken to have an annual precipitation of 1200mm, and the annual march of temperature shown in Figure 3 (WMO, 1965). As temperature is allowed to change, the potential evapotranspiration and number of frost days has been recalculated by moving this annual curve bodily by the required amount. Starting from an initially bare surface, vegetation ond organic soil biomass approach an equilibrium over about 50 years (Figure 4a). As the vegetation cover becomes established, with consequent effects on hillslope hydrology, a very rapid decline in erosion rates is forecast, as shown in figure 4b, assuming an initial 0.1m of soil everywhere. By the time the organic components reach equilibrium, a total decline of 5 orders of magnitude is forecast, and it may be seen that there is about a twenty times decrease within the first decade. This may not fully match the rate of decline observed in the first year by Collins and Dunne (1988) as a result of physical surface changes on Mt. Saint Helens ash deposits, but indicates that strong responses to vegetation are inherent in the model structure.

Alternative initial forms and process sets were tried. Figure 5 illustrates some of the alternatives. Figure 5a & b shows a slope 100m long and 40m high, with a level initial plateau, and a steep (76°) slope to the stream, which is held at a fixed level. In (a), there are no landslides, whereas (b) allows a substantial rate of sliding. It may be seen that the effect of this difference is evident in the landscape long after the slopes are well below landslide thresholds, both in slope form and in the soil thickness, especially near the divide. It may be seen that for the more realistic case, with landslides, the form after about 50,000 years is an almost uniform gradient with little soil cover. In (c), the conditions differ from (b) in having a longer (150m) slope length, and a less steep (45°) basal slope, and there is again a tendency for the slope to begin to develop, mainly through landslides, to a stage of almost uniform gradient with only a thin soil cover. In subsequent runs, a simpler initial form has been adopted, for comparing different temperature regimes, with a uniform 100m slope from divide to stream in all cases.

Figure 6 shows the forecast evolution of this initial slope for the current climate of Luxembourg. (a) shows the growth of first a summit convexity and then a basal concavity. Both the growth of the concavity and the thickening of the soil are strongly influenced by the rates of solution, particularly for this case where there is no downcutting at the slope base. (b) shows the thickening of the soil at various positions. All points show a more or less linear thickening of the soil to begin with. This shows some tendency to approach an equilibrium between mechanical and solutional rates of denudation, particularly near the divide. Subsequently, the effect of the basal still-stand becomes dominant, and the soil moves into a phase of more rapid deepening, which becomes evident soonest near the slope base.

Figure 7 shows the main sequence of runs, in which conditions are as shown in Table 1, and as described above for the present Luxembourg climate. The only difference in parameters is in the potential evapotranspiration, which has been raised, mainly in ratio steps of $(2)^{1/2}\times$ from 100mm to 1600mm, corresponding to mean annual temperatures of approximately 2°C, through the normal 10°C, to 27°C. It may be seen that, with increasing temperature over this large range, there is a dramatic increase in basal concavity, and overall erosion rates; and a marked decrease in soil depths and summit convexity. Overall, this temperature range spans from cool temperate to warm semi-arid conditions, and is forecast to produce a range of forms, which corresponds well with accepted views on the qualitative differences between climatic zones.

Figures 8 and 9 summarise some of the main differences between the slope profiles over the range of potential evapotranspiration (PE). Figure 8 shows the short term responses, and figure 9 the long term changes over 100,000 years. Figure 8a shows the assumed relationship between PE and mean temperature, calibrated against current conditions. (b) shows the estimated actual evapotranspiration (AE), as a ratio of rainfall and PE, based on equation (A1) with n=3.

It may be seen that AE/rainfall approaches 1.0 for the highest temperatures; and AE/PE becomes very close to 1.0 at low temperatures. (c) shows the forecast equilibrium levels of vegetation and organic soil biomass, which both show a maximum within the range.

For vegetation, the general increase of equilibrium biomass with temperature is related to the increasing AE, and the maximum partly to the increasing rates of respiration loss with temperature, and partly to the levelling off of AE as it becomes limited by available rainfall. Although no seasonal effects have been incorporated into the model presented, it should be noted that the annual range of evapotranspiration is likely to increase with temperature for temperate latitiudes so that, as average biomass is increased, it is also likely to show increasing seasonal variations. For the organic soil, decomposition rates rise faster than production rates at high temperatures, and slower at low temperatures, so that the organic soil shows a maximum depth at 7-8°C. At cooler temperatures, there is a smaller input from leaf fall, so that it takes progressively longer to approach equilibrium.

Figure 9a shows a minimum in erosion rates (mechanical plus chemical) at about 550mm (14°C). This may be seen as corresponding to the temperate minimum of Langbein and Schumm's (1958) curves relating erosion rates to rainfall. As formulated, the forecast increase in erosion rate at high temperatures is occuring concurrently with an increase in vegetation biomass. The increase is thus being driven primarily by the fall in organic soil biomass, which forces the reduced runoff to flow progressively more overland. This increase in erosion is associated with wash transport, which concurrently increases the width of the basal concavity (Figure 9b). At temperatures below the erosion minimum, the modest decrease in erosion rates is primarily attributed to the decrease in frost frequency. The associated broadening of the summit convexity is, however, thought to be due to the decreasing impact of solution at the base of the slope.

Figure 9c shows the cumulative effect of solution in terms of soil deficit in the lower part of the slope. Here there is a possible maximum at the lowest temperatures. This curve is influenced partly by the decrease in solution with decreasing runoff, and partly with the changes in mechanical erosion implicit in figure 9a. At low temperatures, solution falls faster than mechanical denudation with increasing temperature, leading to a modest decrease in soil thickness. At higher temperatures, solution rates continue to fall while mechanical denudation increases sharply, giving a more rapid decrease in soil thickness. As formulated, the model gives a strong linkage between organic soil and inorganic soil. Where conditions favour the accumulation of organic soil, overland flow is reduced, giving greater solution and less wash erosion, so that a weathered regolith is able to accumulate; and *vice-versa*.

5. Example responses to changes in conditions

Two final illustrations show how the landscape might react to changes in climate or land use. Figure 10 shows the potential influence of agriculture on a slope evolved under natural vegetation. For the first 200,000 years, slope evolution occurred under current climatic conditions, as shown in figure 6a above. Subsequently, there has been a period of agriculture, for which the only change in conditions has been that 90% of the leaf fall material has been removed as a crop, instead of contributing to the organic soil. As a result, the equilibrium organic soil drops from 7.6 to 0.8 $kg.m^{-2}$ over a 50 year period. The previously negligible amount of overland flow increases to about 2mm a year, and remains at that level for about 1,000 years, while the surface is eroded, particularly at mid-slope, to form a more concave profile. As the inorganic soil thins, overland flow increases further. After 5,000 years, the surface has been lowered by almost 2m in the middle of the slope, while the elevation of the soil base has hardly changed. Thereafter, the soil is almost totally stripped away, starting at mid-slope, until after 10,000 years there is no soil anywhere, and almost all the rainfall runs off overland. At the base of the slope, the soil deficit has fallen to very low values through the downslope transport of unweathered material from above. It is plain from figure 10, however, that a stratigraphic section at the base of the slope would show buried weathering horizons which have never been eroded. This example shows the cumulative effect of poorly managed agriculture, through the removal of the soil resource at an accelerating rate which soon outstrips renewal through weathering.

Figure 11 shows another illustrative scenario. The slope begins to develop for 100,000 years at temperatures 5°C cooler than at present. This is followed by 10,000 years of present temperatures. There is then 5,000 years of the same temperatures, but with 50% of the leaf fall removed as a crop, equivalent to a non-intensive form of cultivation or grazing. It may be seen that this sequence produces only minor changes, though with some thinning of the soil about 20m from the top of the slope. There is then a further 1,000 years of more intensive agriculture, in which 90% of thee leaf fall is cropped. This results in massive erosion, mostly concentrated in the second half of the period. As in the previous example, there is a period of soil thinning, during which erosion rates and overland flow increase rather modestly. Finally, the soil becomes completely stripped at some point on the slope and, from then on, erosion proceeds catastrophically. There is thus a sharp threshold, beyond which the buffering effect of the soil, in storing hillslope water, is irreversibly lost.

6. Conclusions

The model presented here provides a tool for investigating the interactions between topographic, soil and vegetation factors in the evolution of an integrated slope form in the long term. It also provides a means of exploring the response of a hillside to short term changes, including those associated with the accumulation of greenhouse gases and with agriculture. The interactions actually included are not seen as definitive, though based on survey of existing literature, but as a basis for discussion and refinement. A critical component of the model is the interaction between both organic and inorganic soils and hillslope hydrological response. Here this interaction is taken to be strong and unidirectional. Other interactions with vegetation have, perhaps, been underestimated. For example no interaction has been included to reduce splash and increase overland flow directly in response to crown cover, independent of effects acting through the organic soil. Thus the amount of wash erosion under annual cultivation might be overestimated, since the damaging effects of lost organic soil are included, while the crown cover protection is not.

With these reservations, the model puts forward one very clear message. It is that soil is a resource which must be conserved, not only for its direct agricultural potential, but also for its role as a hillslope water store, which buffers storm rainfall and reduces ovverland flow. Where the soil is being thinned, even gradually, by erosion, then conservation measures are needed to prevent a catastrophic acceleration in erosion rates. The growth of a vegetation cover which is protected from cropping may be the only practicable remedy in critical areas.

Appendix:
Derivation of expressions used for wash transport rates

Actual evapotranspiration, E is estimated from potential evapotranspiration rate, P and annual rainfall, R using:

$$E = R(\alpha^{n}-1)/(\alpha^{n+1}-1) \qquad \text{(A1)}$$

where α is the ratio R/P

and n is an empirical exponent which takes a value of 3-4. This gives $E \simeq P$ for high rainfalls (α>>1), and $E \simeq R$ for low rainfalls (α<<1). The net runoff, $i = R-E$, is available to provide an average deficit D below soil saturation, by assuming that subsurface outflow per unit flow strip width, q_s follows the exponential soil water store (Beven & Kirkby, 1979). Thus:

$$Q_s = ix = (m^2/t_s) \wedge \exp(-D/m) \qquad \text{(A2)}$$

In a daily rainfall of r, there will be local production of overland flow runoff at rate ($r-D$) on days when rainfall exceeds the deficit. Following Carson & Kirkby (1972, p.215; Ahnert, 1986), the frequency density of daily rainfalls of r is:

$$(N/r_0) \exp(-r/r_0),$$

where N is the number of rain days per year,

and r_0 is the mean rain per rain day = R/N.

Summing overland flow production over this frequency distribution, the total overland flow produced in an average year is:

$$(N/r_0) \int (r-D) \exp(-r/r_0)\, dr = R \exp(-D/r_0)$$

The total overland flow discharge, q_o is obtained by integrating the left hand expression, first with respect to distance and then over the distribution of daily rainfalls:

$$Q_o = (N/r_0) \int_r \{\exp(-r/r_0) \int_y \phi(y)(r-D)dy\}\, dr \qquad \text{(A3)}$$

where $\phi(y)$ is the proportion of rainfall contributing from a distance y upslope from point of interest. this proportion reflects the distance travelled by overland flow during the actual storm. The distance integration is only applicable for positive values of runoff (*i.e* $r>D$). If the average distance travelled by flow in the storm is y_c, then the form used for ϕ is derived by differentiating the cumulative contributing distance (which would be simply y if storms were long):

$$y[1-(y/y_c)^2]/[1-(y/y_c)^3].$$

This gives a constant unit contribution from nearby points, falling gradually to zero at distances of the order of y_c.

In equation (A3), it is possible, in principle, to evaluate the two integrals:

$$I(x) = \int_x \phi \; dy \quad \text{and} \quad J(x) = \int_x \phi D \; dy.$$

Each is, in general, a function of distance from the divide. Using this notation, the total overland flow at distance x, resulting from a storm of r is:

$$q_o(r) = rI(x) - J(x) \qquad \text{(A4)}$$

which is positive, and therefore meaningful for all $r>J/I$. Summing, for this range of daily rainfalls over their frequency distribution:

$$Q_o = (N/r_0) \int_r (rI-J) \exp(-r/r_0) \; dr$$
$$= R \; I(x) \exp[-J/(Ir_0)] \qquad \text{(A5)}$$

The expression used to estimate wash transport, s from a single daily rainstorm of r is:

$$s \propto q_o(r) \; [\Lambda q_o(r)-\theta] \qquad \text{(A6)}$$

where θ is the threshold flow power for wash erosion. The critical rainfall event for erosion, r_c is then obtained from (A5) and (A6) as:

$$r_c = (\theta/\Lambda+J)/I \qquad \text{(A7)}$$

Substituting (A5) into (A6), and integrating over the frequency distribution of rainfalls, the total wash sediment transport is:

$$S \propto (N/r_0) \int_r \{\exp(-r/r_0) \; (rI-J)(\Lambda rI-\Lambda J-\theta) \; dr \qquad \text{(A8)}$$

with the integration carried out for all $r>r_c$. Carrying out the integration, substituting for r_c and collecting terms:

$$S \propto N \; I \; (\Lambda Ir_0+\theta) \exp(-r_c/r_0) \qquad \text{(A9)}$$

This expression, which is used to forecast wash transport in the model presented, may be seen as a generalisation of more familiar transport laws, of the Musgrave (1947) type. Thus, if the soil water deficit D is held constant downslope, and storms are long, the integrals I and J become $I = x$ and $J = Dx$. For this special case:

$$Q_0 = Rx \exp(-D/r_0)$$

$$r_c = \theta/(\Lambda x) + D$$

$$S \propto Rx\ (\Lambda x + \theta/r_0) \exp\{-[(\theta/(\Lambda x) + D]/r_0\}$$

There is still further simplification in the case of a zero erosion threshold, θ, to give $S \propto R\ r_0\ x^2 \exp(-D/r_0)$ (*cf* Carson & Kirkby, 1972, p.216). The differences between this simple form and the full form of equation (A9) have been made to deal with three factors:

(i) The variable soil water deficit downslope in response to soil and topography. This problem is particularly important in humid areas.

(ii) The possibility that overland flow may not travel the full length of the hillside during the course of a storm. This problem is particularly acute for arid areas.

(iii) The possible existence of a threshold for wash erosion. The work of Leslie Reed (oral comm) and Dietrich *et al* (1986),suggests that this is most important where there is a well developed turf mat to be breached.

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TABLE 1. Parameters used in model, with suggested ranges of values

#	Description	Values: Suggested	Min	Max
1	"slope length in metres"	100	20	1000
2	"number of sub-divisions"	20	5	100
3	"slope relief in metres"	40	5	250
4	"mean annual rainfall in mm"	1200	10	5000
5	"Mean annual Pot E-T in mm"	400	0	5000
6	"Number of rain days per year"	160	2	365
7	"Number of frost days per year"	50	0	365
8	"Soil storage parameter in mm/m of soil"	5	0	100
9	"OF travel dist (m) during storm"	250	5	50000
10	"Lateral soil flow response time in sec"	10	1E-2	1000
11	"m to soil erosion for unit slope & mean rain"	5	0	5000
12	"m to veg"n erosion for unit slope & mean rain"	50	0	5000
13	"Slide retreat in mm/y above thresh"d grad"	0	0	5000
14	"Final threshold gradient for landslides"	.4	.1	5
15	"grad above which no material comes to rest"	.7	.2	5
16	"equivalent metres fall for initial slide momentum"	20	1	100
17	"Solute conc"n (mg/l) with no organic soil"	25	0	5000
18	"Extra mg sol"n / kg organic soil / mm water"	.25	0	5
19	"Effective % insoluble residue"	40	0	100
20	"Weathering Soil thickness scale in m"	1	.1	10
21	"Soil depth at which creep etc is halved"	.1	0	5
22	"mm/Kyr stream lowering"	0	-1000	1E9
23	"1:Absolute 2:/m above base level 3:Sedi Inc/m."	1	1	3
24	"valley bottom width in metres"	10	1	250
25	"base level elevation in m"	0	-1000	1000
26	"Extra crop taken from plant as % of Leaf Fall"	0	0	100
27	"% normal Leaf Fall gathered from ground"	0	0	100
28	"Total Kyrs before stop/change"	100	1E-3	100000
29	"frequency to re-plot in Kyrs"	10	1E-4	1000
30	"Soil thickness everywhere in m"	.1	0	5
31	"Vegetation Biomass in kg/sq.m"	0	0	200
32	"Organic soil Biomass in kg/sq.m"	0	0	100
33	"% Vegetation ground cover"	0	0	100
34	"%/yr survival of cover with NO growth"	5	0	100

Figure Captions

1. The main interrelationships included in the model.

2. Interactions included between vegetation and erosion rates.

3. Assumed annual march of temperature for Luxembourg.

4a. The approach of vegetation and organic soil to equilibrium for current Luxembourg parameters.
 b. The initial fall in erosion forecast as vegetation becomes established on a bare inorganic regolith.

5. Examples showing the influence of initial slope form:
 a. 100m plateau: no landslides
 b. 100m plateau: with landslides
 c. 150m plateau: with landslides

6a. Evolution of the slope form, starting from 'standard' parameters and initial form, for current Luxembourg conditions. Soil deficit is shown to scale.
 b. The evolution of soil deficit at different locations downslope.

7. Slope evolution forecast for a range of conditions, differing only in temperature.

a. 100mm PE (2.4°C)	b. 140mm PE (3.6°C)
c. 200mm PE (5.6°C)	d. 300mm PE (8.4°C)
e. 475mm PE (12.0°C)	f. 560mm PE (13.5°C)
g. 672mm PE (15.8°C)	h. 800mm PE (17.4°C)
i. 1100mm PE (21.5°C)	j. 1600mm PE (27.2°C)

8. Forecasts of short term responses to climatic differences.
   a. Temperature
   b. Actual evapotranspiration as a fraction of rainfall and PE
   c. Equilibrium biomass for vegetation and organic soil

9. Forecasts of long term responses to climatic differences, for slopes shown in figure 7.
   a. Mean erosion rate over 100,000 years
   b. Soil deficit at 75m after 100,000 years
   c. Width of summit convexity after 100,000 years.

10. Forecast response to the following example sequence:
    (i) 200,000 years of current conditions (as in Fig 6)
    (ii) 10,000 years with same climate, but with 90% removal of leaf fall as a crop.

11. Forecast response to the following example sequence:
    (i) 100,000 years with temperature 5°C cooler than at present, and no cropping.
    (ii) 10,000 years with temperature as at present, and no cropping.
    (iii) 5,000 years with 50% cropping, at same temperature.
    (iv) 1,000 years with 90% cropping, at same temperature.

Program listing for SlopeCCL_bas: November 1988 version

```
100 IMPLICIT% row,col,I,j,xn,ndat,y,of_type,base_type
110 DIM a$(80),b$(80),title$(80): WINDOW 512,256,0,0: PAPER 0: CLS:Title
120 MODE 4: init: not_first=0: ndat=40: DIM xdat (ndat), ldat(ndat), udat(ndat),
    cudat$(ndat,70)
130 REPeat forever
140 set_up
150 time=0: CLS #0: REPeat time
160 f_title: grow_veg: hydrology: main_slope:crit:update: IF F1_flag: indata 0
170 IF t_flag: new_times
180 IF ((F3_flag) AND (NOT flag)): new_plot 4,1: print_out 0: n$(7 TO 9)='  ':
    f_title
190 IF F2_flag: EXIT time
200 F3_flag=0: IF time>=tfinal
210 up_front
220 AT #7,0,23: INK #7,7: STRIP #7,0:PRINT #7,'< PRESS KEYS =';
230 REPeat loop: ftest: F3_flag=0: IF F1_flag OR F2_flag OR t_flag: EXIT loop
240 f_label: IF F1_flag: indata 0: END IF : IF F2_flag: EXIT time: END IF
250 IF t_flag: new_times
260 header 2: CLS #0
270 END IF
280 END REPeat time
290 IF F2_flag: ed_win 1
300 n$=FILL$(' ',15): F1_flag=0: F2_flag=0: F3_flag=0: t_flag=0:END REPeat
    forever
310 REMark ********** End of program core **********
320 REMark ###################################################################
330 DEFine PROCedure set_up
340 AT #0,0,0: INPUT #0,'Enter Run Title:'!title$: IF f7>0: OPEN #3,ser: PRINT
    #3, DAY$;' ';DATE$;':_';title$: PRINT #3: CLOSE #3
350 time=0: indata 1
360 scr 1: gr_win 1: PRINT #6,' ';title$: CSIZE #2,2,0: PRINT #2,' SLOPE AND SOIL
    MODEL: mjk Apr 1988';
370 PRINT #0,'Enter slope dimensions': FOR I=0 TO
    2:xdat(I)=in(cudat$(I),xdat(I),ldat(I),udat(I),I+1,0)
380 xlen=xdat(0): xn=xdat(1):zl=xdat(2): dx=xlen/xn: DIM
    elev(xn),delev(xn),soil(xn),dsoil(xn),of_dis(xn),instab(xn)
390 next_print=tprint: it=0
400 axes 0,xlen,0,zl,0,0: CLS #0: SAVE_SCR
410 re_draw=0: INK 7: OVER 0: REPeat re_draw
420 op=0: ox=0: oz=zl:CLS #0:row=0:elev(0)=zl: fg=0: draw ox,oz:REPeat row
430 np=in('"0" to end; or % of slope at uniform gradient',100-op,0,100-op,row,0):
    IF NOT np
440 np=100-op: ex=np*1E-2*xlen: grad=oz/ex: ELSE
450 ex=np*1E-2*xlen: grad=in('Tangent gradient over segment',0,0,oz/ex,row+1,0):
    END IF
460 nx=ox+ex: nz=oz-ex*grad: op=op+np: ni=INT(nx/dx):FOR I=-INT(-ox/dx) TO ni
470 elev(I)=oz-(I*dx-ox)*grad: draw I*dx, elev(I): END FOR I
480 row=row+2:IF row >3: CLS#0: row=0
490 ox=nx: oz=nz:IF op>=100: EXIT row
500 END REPeat row
510 PRINT #0,'Is initial form OK ? ';:IF yes:EXIT re_draw
520 END REPeat re_draw
530 SHOW_SCR
540 OPEN #8,scr_130x42a38x190: INK #8,7: PAPER #8,0: BORDER #8,1,2
550 new_plot 7,0: f_label: header 2: SAVE_SCR
```

```
560 END DEFine set_up
570 REMark ==========================================
580 DEFine PROCedure up_front
590 CLS #2: CSIZE #2,2,0: PRINT #2,' SLOPE AND SOIL MODEL: mjk Apr 1988';:
    CSIZE #2,0,0
600 INK #0,7: CLS#0:PRINT #0,\' CLIMATIC PARAMETERS'
610 PRINT #0," R'fall(mm) Pot E-T(mm) Rain days Frost Days "
620 PRINT#0,TO 5;Rain;TO 16;pot_ET; TO 29;xdat(5);TO 40;xdat(6);
630 END DEFine up_front
770 REMark ======================================
900 DEFine PROCedure grow_veg
910 LOCal I,x,y,tot,otot,loop,p$(60)
920 IF time=0
930 _base=Built_Wndo(#9,420,80,46,100): INK #9,7: PAPER #9,2,0,2: CLS #9
940 PRINT #9,'ENTER INITIAL SOIL AND VEGETATION VALUES'
950 FOR row=1 TO 7
960 I=row+28: p$=cudat$(I)&' ('&ldat(I)&' to '&udat(I)&'): '
970 REPeat loop: AT #9,row,0: CLS #9,4: PRINT #9,p$;:x=EDITF(#9,xdat(I),10): IF
    (x<=udat(I)) AND(x>=ldat(I)): xdat(I)=x: EXIT loop
980 END FOR row: Close_Wndo #9,_base
990 IF f7>0
1000 OPEN #3,ser: FOR I =29 TO 35:PRINT #3,cudat$(I);' = ';xdat(I)
1005 PRINT #3,'Estimated Temp = ';FORMAT_FP$(temp,4,1);' and Actual E-T =
     ';FORMAT_FP$(act_ET,5,1)
1010 CLOSE #3: END IF
1020 init_soil=xdat(29): MV=xdat(30): MH=xdat(31):pcov=xdat(32)*1E-2:
     pers=xdat(33)*1E-2
1025 vcrop=xdat(34)*1E-2: hcrop=xdat(35)*1E-2
1030 mean_soil=init_soil: FOR y=0 TO xn: soil(y)=init_soil
1040 DIM of_dist(xn),cum_ofdist(xn): otot=0: FOR y=0 TO xn-1
1050 x=(y+.5)*dx/Xcrit: tot=x*(1+x): tot=tot/(1+tot)
1070 of_dist(y)=(tot-otot)*Xcrit: cum_ofdist(y)=tot*Xcrit
1075 otot=tot: END FOR y
1080 new_plot 6,1: print_out 1: END IF
1090 mm=mm0*mean_soil+3*MH: theta=soil_theta+pcov*(veg_theta-soil_theta)
1100 IF eq_flag: veg_equil
1130 END DEFine grow_veg
1140 REMark =======================
1200 DEFine PROCedure hydrology
1210 LOCal x,oz,nz,grad,dd,od,nd,sodl
1220 DIM local_def(xn), of_dis(xn),cum_def(xn)
1230 oz=elev(0):dd=mm*mm/t_soil*365/Runoff/1000: FOR y=0 TO xn-1
1240 nz=elev(y+1): grad=(oz-nz)/dx: x=(y+.5)*dx
1250 nd=grad*dd/x: IF nd>0: nd=mm*LN(nd): ELSE nd=0
1255 nd=nd*(nd>0): IF y=0: od=nd
1260 local_def(y)=(od+nd)*.5
1263 sum=0:FOR dy=0 TO y: sum=sum+of_dist(dy)*local_def(y-dy)
1266 cum_def(y)=sum: x=cum_ofdist(y): sum=sum/x/r0: IF sum<50:
     of_dis(y)=x*Rain*EXP(-sum)
1270 od=nd: oz=nz: ftest: END FOR y: END DEFine hydrology
1280 REMark ===========================
1400 DEFine PROCedure main_slope
1410 LOCal old_ht,new_ht,x,chem,sed,rat
1420 old_ht=elev(0):flag=0: DIM delev(xn),dsoil(xn): slide=0:
     old_def=soil(0): sol=0
1430 FOR y=0 TO xn
1440 IF y=xn
1450 slope_base
```

```
1460 ELSE
1470 new_ht=elev(y+1):x=(y+.5)*dx:grad=(old_ht-new_ht)/dx
1475 IF y=0: mean_grad=0: ELSE mean_grad=(grad+old_grad)*.5
1480 new_def=soil(y+1):depth=(new_def+old_def)*.5: ps=prop(depth)
1490 slow_proc: weathering: landslide
1500 sed=(slow+slide+sol)/dx
1510 chem=(sol-(1-ps)/ps*(slow+slide))/dx
1520 delev(y)=delev(y)-sed:delev(y+1)=sed
1530 dsoil(y)=dsoil(y)+chem: dsoil(y+1)=-chem
1540 IF y=0:divide
1550 old_ht=new_ht: old_def=new_def: old_grad=grad: old_depth=depth
1555 rat=(nslow+oslow+nslide+oslide)*.5/x+dsol: IF rat=0: instab(y)=0: ELSE
     instab(y)=((nslow+nslide-oslow-oslide)/dx+dsol)/rat
1560 END IF : ftest
1570 END FOR y
1580 END DEFine main_slope
1590 REMark ============================================
1600 DEFine PROCedure crit
1610 LOCal new_ht, old_ht,new_er,old_er,test,max,ycrit,new_def,
     old_def,new_th,old_th: crit$='nowhere'
1620 max=thr*10/tprint: old_ht=elev(0): old_er=delev(0): old_def=soil(0):
     old_th=dsoil(0)
1630 FOR y=0 TO xn-1
1640 new_ht=elev(y+1):new_er=delev(y+1): new_def=soil(y+1): new_th=dsoil(y+1)
1650 test=ABS(new_ht-old_ht): IF test<1E-2*dx: test=1E-2*dx/thr
1660 test=ABS(new_er-old_er)/test
1680 old_er=new_er:old_ht=new_ht
1690 IF test>max:max=test: crit$='elev @ '&INT((y+.5)*dx+.5)
1692 test=ABS(new_def-old_def): IF test<1E-2*dx: test=1E-2*dx/thr
1694 test=ABS(new_th-old_th)/test: old_th=new_th: old_def=new_def
1696 IF test>max: max=test: crit$='soil @ '&INT((y+.5)*dx+.5)
1700 ftest: END FOR y
1710 test=dcov(pcov):IF pcov>5E-2: test=ABS(test/pcov)
1715 IF test>max:max=test: crit$='veg cover'
1720 test=net_prod(MV): IF MV>5E-2: test=ABS(test/MV)
1725 IF test>max:max=test: crit$='veg biomass'
1730 test=hum_prod(MV,MH): IF MH>5E-2: test=ABS(test/MH)
1735 IF test>max: max=test: crit$='organic soil'
1740 mt_step=thr/max: time_step=mt_step
1750 IF time+time_step>=next_print:time_step=next_print-time:flag=1
1755 IF time+time_step>=tfinal: time_step=tfinal-time: flag=1
1760 time=time+time_step:it=it+1
1770 info
1780 END DEFine crit
1790 REMark ======================================
1800 DEFine PROCedure update
1805 LOCal I,y,ch,ss,st,z,a$(100),b$(100)
1810 mean_soil=0
1820 FOR y=0 TO xn:elev(y)=elev(y)+delev(y)*time_step:
     ss=soil(y)+dsoil(y)*time_step: ss=ss*(ss>0): mean_soil=mean_soil+ss:
     soil(y)=ss: END FOR y
1825 z=pcov_eq-pcov: st=dcov(pcov): IF ABS(z)<=ABS(st)*time_step/50:
     pcov=pcov_eq: ELSE pcov=pcov_eq-z*EXP(-ABS(st*time_step/z)): END IF
1826 z=MV_eq-MV: ss=hum_prod(MV,MH): st=net_prod(MV): IF
     ABS(z)<=ABS(st)*time_step/50: MV=MV_eq: ELSE
     MV=MV_eq-z*EXP(-ABS(st*time_step/z)): END IF
1827 z=MH_eq-MH: IF ABS(z)<=ABS(ss)*time_step/50: MH=MH_eq: ELSE
     MH=MH_eq-z*EXP(-ABS(ss*time_step/z)):END IF
```

```
1828 MH=MH*(MH>0): MV=MV*(MV>0): pcov=pcov*(pcov>0)
1830 mean_soil=mean_soil/(xn+1): ftest: IF flag:new_plot 6,1: print_out 1:
     next_print=next_print+tprint
1833 ch=0: IF f7>3: OPEN #3,ser: ch=3
1835 a$=FORMAT_FP$(it,7,0)&FORMAT_FP$(time,10,2)&FORMAT_FP$(pcov*100,6,1)
     &FORMAT_FP$(MV,8,3)&FORMAT_FP$(MH,10,3)&FORMAT_FP$(slow/xlen*1E6,14,2)
     &FORMAT_FP$(slide/xlen*1E6,10,2)&FORMAT_FP$(sol/xlen*1E6,9,2)
1837 FOR I=0 TO ch STEP 3: PRINT #I,a$
1838 IF f7>3: CLOSE #3
1840 END DEFine update
1850 REMark ============================================
2000 DEFine PROCedure divide
2010 delev(y)=delev(y)*2: dsoil(y)=dsoil(y)*2
2020 END DEFine divide
2030 REMark ==========================================
2200 DEFine PROCedure slope_base
2205 LOCal msed
2210 SELect ON base_type
2220 =1: delev(xn)=-sed_inc
2230 =2: delev(xn)=-sed_inc*(elev(xn)-base_level)
2240 =3: msed=slow+slide:
     delev(xn)=(msed+msed-valley_width*sed_inc*(elev(xn)-base_level))
     /(valley_width+dx)
2245 REMark : for type 3, sed increment applies only to mechanical sediment
2250 END SELect
2260 dsoil(xn)=dsoil(xn-1): REMark neutral assumption at stream
2270 END DEFine slope_base
2280 REMark ===========================================
2400 DEFine PROCedure slow_proc
2411 IF y>0: oslow=wash_rate(mean_grad)
2415 sod=cum_ofdist(y)
2420 sod1=cum_def(y): slow=wash_rate(grad)
2430 nslow=wash_rate(mean_grad): IF y=0: oslow=-nslow
2500 END DEFine slow_proc
2510 REMark ...................................
2540 DEFine FuNction wash_rate(gg)
2541 LOCal rc,rat,wash
2542 REMark Wash rate entered iin program (normal value:rw=2e-6 Myr)
2545 wash=kc*gg: IF gg>0
2550 rc=(sod1+theta/gg)/sod: rat=rc/r0: IF rat<50
2555 rc=r0*sod: rc=EXP(-rat)*rc*(theta+rc*gg): wash=wash+rc*Rain/r0*rw
2556 END IF : END IF
2557 IF creep_depth>0: rat=depth/creep_depth: rat=rat*rat: wash=wash*rat/(1+rat)
2560 RETurn wash: END DEFine wash_rate
2570 REMark ======================================
2600 DEFine PROCedure landslide
2610 IF y>0: oslide=slide_rate(mean_grad,xslide):
     nslide=slide_rate(mean_grad,oslide): ELSE oslide=0: nslide=0: ov_sq=0:
     old_tg=0
2620 xslide=slide: slide=slide_rate(grad,slide): old_tg=mean_tg: ov_sq=vsq
2630 END DEFine landslide
2640 REMark ................................
2650 DEFine FuNction slide_rate(gg,slide_in)
2660 LOCal det,pq,tg,acc,csn,travel,sg: IF no_slides
2665 det=0: ELSE
2670 pq=(1-ps)/(1-p0): csn=1/SQRT(1+gg*gg)
2680 sg=(pq^ms)/stable_grad: tg=sg+inv_tg*(1-pq)^mt
2683 det=0: IF pq>0: det=ret_rate*csn*(gg-1/sg)
```

```
2685 IF det>0: mean_tg=(old_tg*slide_in+dx*det/tg)/(slide_in+det*dx): ELSE
     mean_tg=old_tg
2686 REMark : residual stable angle weighted by slide mass
2690 acc=gravity*(gg-mean_tg)*csn
2700 vsq=ov_sq+2*acc*dx: vsq=vsq*(vsq>0)
2720 det=det*dx+slide_in: IF acc<0: travel=-.5*ov_sq/acc:
     det=det*travel/(dx+travel)
2730 IF det<0: det=0: vsq=0
2740 END IF : RETurn det
2750 END DEFine slide_rate
2760 REMark ==============================
2900 DEFine PROCedure weathering
2910 dsol=(nc_sol+c_sol*MH)*Runoff*1E-3: sol=dsol*x: sol=sol*(grad>0)
2920 END DEFine weathering
2930 REMark ....................
2940 DEFine FuNction prop(deficit)
2950 IF deficit=0: RETurn 1: ELSE RETurn 1-1/(soil0/deficit+1/(1-p0))
2960 END DEFine prop
2970 REMark =========================
3000 DATA 'slope length in metres',100,20,1000
3010 DATA 'number of sub-divisions',20,5,100
3020 DATA 'slope relief in metres',40,5,250
3030 DATA 'mean annual rainfall in mm',700,10,5000
3040 DATA 'Mean annual Pot E-T in mm',500,0,5000
3050 DATA 'Number of rain days per year',175,2,365
3060 DATA 'Number of frost days per year',50,0,365
3070 DATA "Soil storage parameter in mm/m of soil",5,0,100
3080 DATA 'OF travel dist (m) during storm',250,5,50000
3090 DATA 'Lateral soil flow response time in sec',10,1E-2,1000
3100 DATA 'm to soil erosion for unit slope & mean rain',5,0,5000
3110 DATA "m to veg'n erosion for unit slope & mean rain",50,0,5000
3120 DATA 'Relative wash rate (years!)',2,0,100
3130 DATA "Final slide retreat in mm/y above thresh'd grad", 0,0,5000
3140 DATA "Exponent for threshold gradient in (1-p)",0,0,10
3150 DATA 'Final threshold gradient for landslides',.4,.1,5
3160 DATA "Exponent for talus gradient in (1-p)",0,0,10
3170 DATA 'grad above which no material comes to rest',.7,.2,5
3180 DATA "Solute conc'n (mg/l) with no organic soil",25,0,5000
3190 DATA "Extra mg sol'n / kg organic soil / mm water",.25,0,5
3200 DATA 'Effective % insoluble residue',40,0,100
3210 DATA 'Weathering Soil thickness scale in m',1,.1,10
3220 DATA 'Soil depth at which creep etc is halved',.1,0,5
3230 DATA 'mm/Kyr stream lowering',0,-1000,1E9
3240 DATA "1:Absolute 2:/m above base level 3:Sedi Inc/m...",1,1,3
3250 DATA 'valley bottom width in metres',10,1,250
3260 DATA 'base level elevation in m',0,-1000,1000
3270 DATA "Total Kyrs before stop/change",100,1E-3,100000
3280 DATA "frequency to re-plot in Kyrs",10,1E-4,1000
3290 DATA 'Soil thickness everywhere in m',.1,0,5
3300 DATA 'Vegetation Biomass in kg/sq.m',0,0,200
3310 DATA 'Organic soil Biomass in kg/sq.m',0,0,100
3320 DATA '% Vegetation ground cover',0,0,100
3330 DATA '%/yr survival of cover with NO growth',5,0,100
3340 DATA 'Extra crop taken from plant as % of Leaf Fall',0,0,100
3350 DATA '% normal Leaf Fall gathered from ground',0,0,100
3360 DATA 'end'
4000 REMark ===========================
4010 DEFine PROCedure Title
```

```
4020 w_base=Built_Wndo(#9,360,120,73,73): PAPER #9,4:INK #9,0: CLS #9
4030 CSIZE #9,0,1:PRINT #9,\' ';FILL$('+-',57)
4040 PRINT #9,' + Slope evolution with changing conditions +'
4050 PRINT #9,' + Copyright Mike Kirkby: April 1988 +'
4060 PRINT #9,' ';FILL$('-+',57);
4070 a$=INKEY$(250): Close_Wndo #9,w_base
4080 END DEFine Title
4090 REMark ===========================
4100 DEFine PROCedure ASSIGN_VALUES
4120 Rain=xdat(3):pot_ET=xdat(4):r0=Rain/xdat(5):kc=(1+9*(xdat(6)/365))*1E-3
4130 temp=SQRT(pot_ET)/1.2-6: ratio=Rain/pot_ET
4140 s=1: t=0: FOR I=0 TO 3: t=t+s: s=s*ratio
4150 act_ET=pot_ET*ratio/(1+s/t): Erat=act_ET/pot_ET
4160 Runoff=Rain-act_ET: mm0=xdat(7): REMark NO allowance for waterlogging in
     reducing decomposition rates
4170 Xcrit=xdat(8): t_soil=xdat(9)/3600/24:
4180 soil_theta=xdat(10)*r0: veg_theta=xdat(11)*r0: rw=xdat(12)*1E-6
4190 ret_rate=xdat(13)*1E-3:ms=xdat(14): stable_grad=xdat(15): mt=xdat(16)
4200 talus_grad=xdat(17): inv_tg=1/talus_grad
4210 nc_sol=xdat(18)*1E-6: c_sol=xdat(19)*1E-6:p0=xdat(20)*1E-2
4220 soil0=xdat(21): creep_depth=xdat(22): gravity=9.81
4230 sed_inc=xdat(23)*1E-6
4240 valley_width=xdat(25): base_level=xdat(26)
4255 mt_step=0: thr=.2: REMark max % change in slope etc in time step
4256 eq_flag=1
4260 END DEFine ASSIGN_VALUES
4270 REMark ====================================
4280 DEFine PROCedure veg_equil
4290 LOCal u,v,du,loop,d: d=1E-4
4300 u=0:REPeat loop:v=dcov(u):du=v*d/(dcov(u+d)-v):u=u-du:IF ABS(du)<1E-4:
     EXIT loop
4310 pcov_eq=u: u=0
4320 REPeat loop: v=net_prod(u):du=v*d/(net_prod(u+d)-v):u=u-du:
     IF ABS(du)<1E-4: EXIT loop
4330 MV_eq=u: u=0
4340 REPeat loop: v=hum_prod(MV_eq,u): du=v*d/(hum_prod(MV_eq,u+d)-v):u=u-du: IF
     ABS(du)<1E-4: EXIT loop
4350 MH_eq=u: eq_flag=0
4360 IF f7>0: OPEN #3,ser: PRINT #3, 'Equilbrium cover =
     ';INT(pcov_eq*100+.5);'%'\'Equilbrium Veg Biomass =
     ';.1*INT(MV_eq*10+.5);'kg/sq.m'\'Equilbrium Organic soil =
     ';.1*INT(MH_eq*10+.5);'kg/sq.m'
4365 SELect ON f7=4: header 3: CLOSE #3: =1 TO 3: CLOSE #3: END SELect
4370 END DEFine veg_equil
4380 REMark ........................
4390 DEFine FuNction dcov(pcov): RETurn (1-pers)*(Erat-pcov): END DEFine dcov
4400 DEFine FuNction net_prod(MV): RETurn
     3.3E-3*act_ET-6E-3*EXP(temp*8E-2)*MV-leaf_fall(MV)*(1+vcrop): END DEFine
4410 DEFine FuNction leaf_fall(MV): RETurn MV/6.07/LN(MV+1.4)
4420 DEFine FuNction hum_prod(MV,MH): RETurn
     leaf_fall(MV)*(1-hcrop)-12*MH*EXP(.12*temp-5.75): END DEFine
19990 REMark ====================
20000 DEFine PROCedure new_plot (ink_col,type)
20005 LOCal oz,nz,ow,nw: OVER 0: header 2: SAVE_SCR
20010 REMark type=0 for elev: =2 for soil: =1 for both
20020 INK ink_col-2*(type=1),0,2: IF type >0
20030 oz=elev(0): ow=oz-soil(0): FOR y=1 TO xn:fg=0: FILL 1:nz=elev(y): draw
    y*dx,nz: nw=nz-soil(y): draw y*dx,nw:draw (y-1)*dx,ow: draw (y-1)*dx,oz:
```

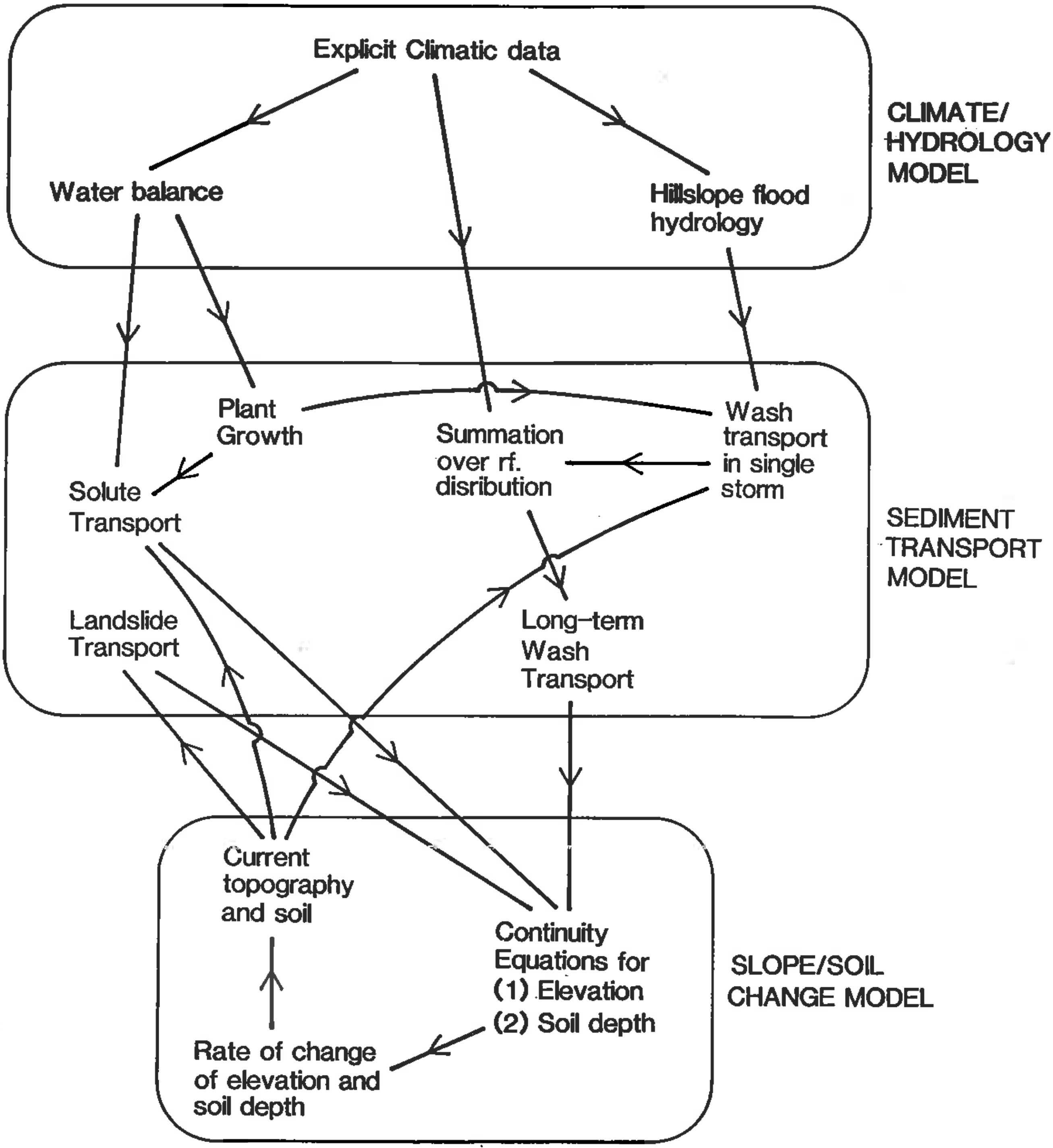
```
    draw y*dx,nz: oz=nz: ow=nw: FILL 0
20040 END IF : IF type<2
20050 INK ink_col: fg=0: FOR y=0 TO xn: draw y*dx,elev(y)
20060 END IF
20070 info: END DEFine new_plot
20075 REMark =====================
20080 DEFine PROCedure info
20090 CLS #8:PRINT#8, 'Time'!.1*INT(time*10+.5)!'Yr': IF time>0: PRINT
    #8,'after'!it!'Its of'\mt_step!'Yr'\'Crit ';crit$;
20100 END DEFine info
20110 REMark ========================
20120 DEFine PROCedure print_out(f%)
20125 LOCal q,nz,oz,grad
20130 IF f7<(3-f%): RETurn
20140 OPEN #3,ser: PRINT #3\\'FORM at TIME ';time;' after ';it;' ITERATIONS'
20150 PRINT #3,"Dist(m)";TO 10;"Elev'n(m)";TO 21;"Eros'n(mm/Ky)";TO
    35;"Instability";TO 47;"Soil depth(m)";TO 60;"OF Disch(mm/y)"
20160 oz=elev(0): FOR y=0 TO xn
20165 IF y<xn: nz=elev(y+1): q=of_dis(y): grad=(oz-nz)/dx: oz=nz: ELSE q=0
20170 PRINT #3,FORMAT_FP$(y*dx,6,1);FORMAT_FP$(elev(y),10,1);
    FORMAT_FP$(-delev(y)*1E6,15,1);FORMAT_FP$(instab(y),10,2);
    FORMAT_FP$(soil(y),15,3);FORMAT_FP$(q/dx/(y+.5),14,3)
20180 ftest: END FOR y: PRINT #3: IF f7=4*(1-eq_flag): header 3: END IF : CLOSE
    #3: END DEFine print_out
20190 REMark ======================
20200 DEFine PROCedure header (ch)
20205 IF ch=2: CLS #2: CSIZE #2,0,0
20210 PRINT #ch,' ITER Time(yr) % cov Veg-kg/sqm-Soil mm/Ky Den:
    Slow Slide Chem ';
20220 IF ch=3: PRINT #3
20230 END DEFine header
20240 REMark ======================
24000 DEFine PROCedure print_use
24010 LOCal _base,of7: of7=f7: _base=Built_Wndo(#9,256,60,128,80): INK #9,7:
    PAPER #9,2: CLS #9
24020 PRINT #9,'SET OR RESET LEVEL OF PRINTER OUTPUT'\"'0' for NONE"\"'1' for
    parameters & graphs only"\"'2' for printout at preset times only"\
24025 PRINT #9,"'3' for printout with every re-drawing"\
    "'4' for line print every iteration"
24030 REPeat loop:f7= (INKEY$(#9,-1) INSTR CHR$(255)&'01234')-2:IF f7>=0:
    EXIT loop
24040 Close_Wndo #9,_base
24050 IF ((of7<4) AND (f7=4)):OPEN #3,ser: PRINT #3: header 3: CLOSE #3
24060 END DEFine print_use
25000 DEFine PROCedure init
25010 LOCal a,k1$(1): f9=0: ed_win 1: nrow=41*(2-PEEK(163890)):REMark Initialise
    to text screen & set up flags/ defaults
25030 sc_base=ALLOCATION(33792)
25040 RANDOMISE: f7=0: print_use
25060 DIM n$(15): n$=FILL$(' ',15):IF f7=1: OPEN #3, ser: PRINT #3,
    CHR$(27)&'2';: CLOSE #3
25070 F1_flag=0: F2_flag=0: F3_flag=0: t_flag=0: CLS: END DEFine init
25080 REMark ----------------------
25090 DEFine PROCedure gr_win (clean)
25100 WINDOW 512,256,0,0: PAPER 0: IF clean: CLS
25110 WINDOW 480,186,16,60: PAPER 0: INK 7: SCALE 1,0,0
25120 sc_factor=480: sc_factor=sc_factor/1.35/186
25130 OPEN#2,scr_512x10a0x0: INK#2,0: PAPER#2,7
```

```
25140 WINDOW #0,512,40,0,10: INK#0, 7: PAPER#0, 2: IF clean: CLS
25150 OPEN #4,scr_126x10a16x50: INK #4,7: PAPER #4,0
25160 OPEN #6,scr_250x10a142x50: INK #6,7: PAPER #6,0
25170 OPEN #5,scr_104x10a392x50: INK #5,7: PAPER #5,0
25180 OPEN #7,scr_480x10a16x246: PAPER #7,0
25190 IF clean: CLS #2: CLS #0: CLS #4: CLS #6:CLS #5: CLS #7
25200 CLOCK #4,'$d %d $m %y %h:%m': f9=2: f_title
25210 END DEFine gr_win
25220 REMark ------------------------
25230 DEFine PROCedure ftest
25240 LOCal a, v, I, m$(15)
25250 a=KEYROW(0) && 255
25260 IF a=0: RETurn
25270 IF (a&&64)>0: t_flag=1: n$(10 TO 15)='Times': REMark '4'
25280 IF (a&&2)>0:F1_flag=1: n$(10 TO 15)='Values':REMark F1
25290 IF (a&&4)>0 : print_use
25300 IF (a && 8)>0: F2_flag=1: n$(4 TO 5)='F2':REMark F2
25310 IF (a && 16)>0: F3_flag=1: n$(7 TO 8)='F3':REMark F3
25320 IF (a&&128): n$='FINISHED':f_title: CLS #7: AT #0,0,0: DEALLOCATE sc_base:
    STOP: REMark 7
25330 IF (a && 1)>0: SHOW_SCR: REMark F4
25340 IF (a && 32)>0: sdump: REMark F5
25350 f_title: END DEFine ftest
25360 REMark ------------------------
25370 DEFine PROCedure f_title: AT #5,0,0: PRINT #5,n$;: END DEFine
25380 REMark ------------------------
25390 DEFine PROCedure sdump
25400 IF f7<1: RETurn
25410 IF f9>1: CLS#5: CLS#7
25420 OPEN #3,ser: PRINT #3, CHR$(10)& CHR$(12);: CLOSE #3: up_front: SCOPY
25430 OPEN #3, ser: PRINT #3,CHR$(27) ;'2';CHR$(12);: IF f7=4: header 3
25435 CLOSE #3: f_label: n$(13 TO 15)=' ': f_title: CLS #0: header 2
25440 END DEFine sdump
25450 REMark ------------------------------
25460 DEFine PROCedure f_label
25470 PAPER #7,2: INK #7,7: CLS #7: PRINT #7," New values Restart Plot Wipe Graph
    out New Times Printer? Quit";
25480 STRIP #7,7: INK #7,0: AT #7,0,0: PRINT #7,"F1";: AT #7,0,13: PRINT #7,
    'F2';:AT #7,0,23
25490 PRINT #7,'F3';:AT #7,0,30: PRINT #7,'F4';:AT #7,0,37: PRINT #7, 'F5';:AT
    #7,0,49: PRINT #7, ' 4';: AT #7,0,61: PRINT #7,' 5';: AT #7,0,72:
    PRINT #7,' 7';
25500 END DEFine f_label
25510 REMark ------------------------------
25540 REMark : type=0 to load to vdu: 1 to save from vdu: 2 to swap with vdu
25550 DEFine PROCedure scr(type)
25560 LOCal vdu,qu,all,y: vdu=131072: qu=1024: all=32768
25580 SELect ON type
25590 =0:MOVE_MEMORY sc_base TO vdu,all
25600 =1: MOVE_MEMORY vdu TO sc_base,all
25610 =2: FOR y=31 TO 0 STEP -1: MOVE_MEMORY vdu+y*qu TO sc_base+qu*(y+1),qu:
    MOVE_MEMORY sc_base+qu*y TO vdu+y*qu, qu: END FOR y:
    MOVE_MEMORY sc_base+qu TO sc_base,all
25630 END SELect
25640 END DEFine scr
25650 REMark ---------------------
25660 DEFine PROCedure ed_win(clean)
25670 FOR I=2 TO 7:OPEN #I,scr_: CLOSE #I
```

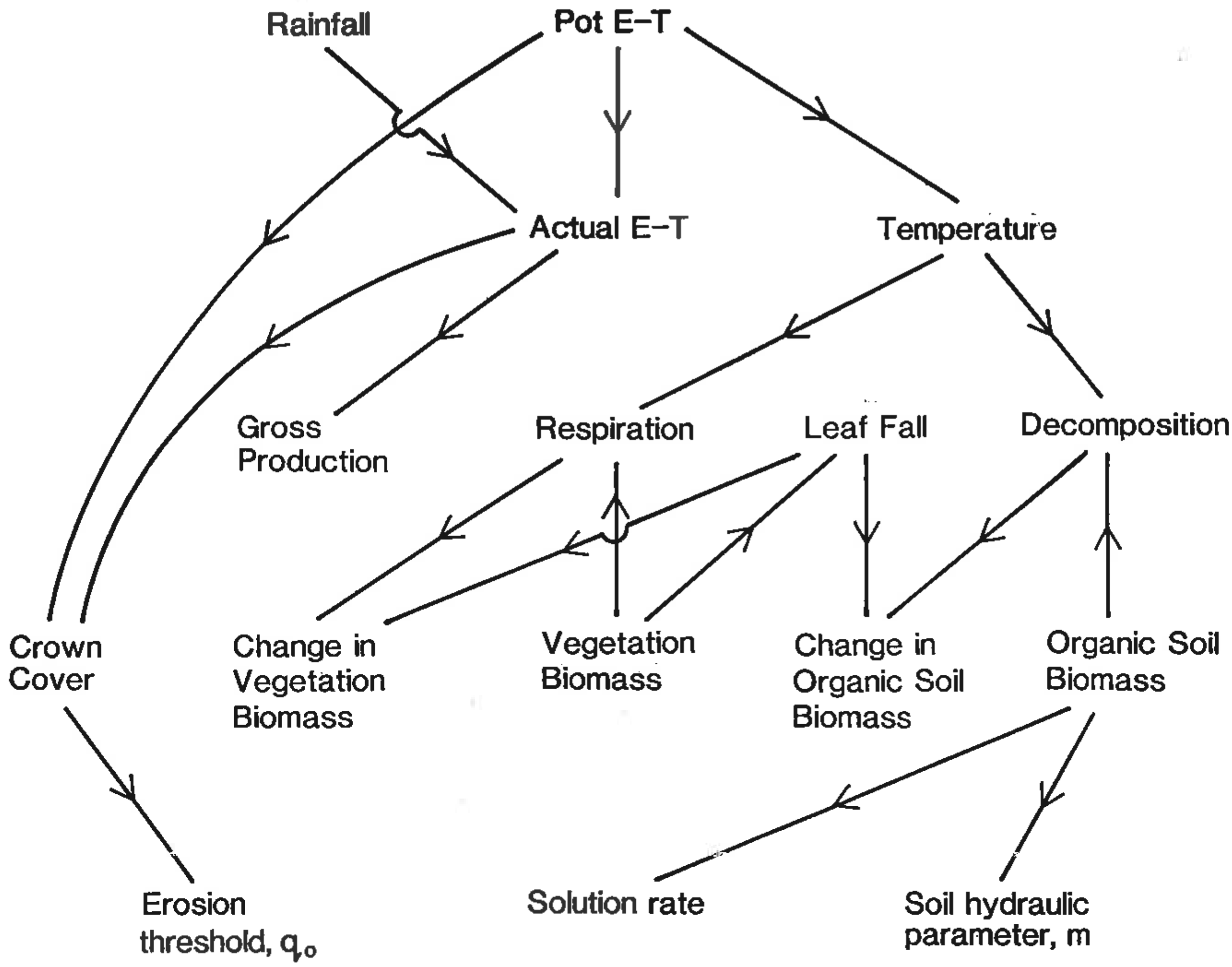
```
25680 IF clean: WINDOW 512,256,0,0: PAPER 2: CLS
25690 WINDOW #0,496,250,8,3:INK#0,5:PAPER #0,0: OVER #0,0: FILL #0,0
25700 WINDOW#1, 496,250,8,3:INK 7:PAPER 2: OVER 0: FILL 0
25710 f9=1: IF clean: CLS: CLS #0
25720 END DEFine ed_win
25730 REMark ——————————————
25740 DEFine FuNction IN$(prompt$,cue$,row,col)
25750 AT #0, row,col: CLS #0, 4: PRINT #0, prompt$;: RETurn EDIT$ (#0,cue$,10)
25760 END DEFine IN$
25770 REMark ——————————————
25780 DEFine FuNction in(prompt$,cue,ll,ul,row, col)
25790 LOCal xc,cloop,pc$(100): xc=cue: pc$='Enter '&prompt$& ' ('&ll&' to
      '&ul&'): '
25800 REPeat cloop: AT #0,row,col: CLS #0,4: PRINT #0,pc$;:xc=EDITF(#0,xc,10):
      IF xc>=ll) AND (xc<= ul): EXIT cloop
25810 RETurn xc: END DEFine in
25820 REMark ——————————————————
25850 DEFine PROCedure draw(x,yq)
25860 IF fg=0: LINE plotx(x),ploty(yq):fg=1:ELSE LINE TO plotx(x),ploty(yq)
25870 END DEFine draw
25880 REMark ——————————————————
25890 DEFine PROCedure BAR(x,xa,y,ya): REMark histogram bar
25900 OVER -1:INK 4:FILL 1
25910 LINE plotx(x),ploty(y) TO plotx(xa),ploty(y) TO plotx(xa),ploty(ya) TO
      plotx(x),ploty(ya) TO plotx(x),ploty(y)
25920 FILL 0:OVER 0:INK 7: END DEFine BAR
25930 REMark ——————————————————
25940 DEFine PROCedure RANGE(x_min,x_max,y_min,y_max)
25950 LOCal hx,hy,loop
25960 IF ((f9=1) OR (f9=4)): gr_win 1
25970 IF x_max<x_min: hx=x_max:x_max=x_min:x_min=hx
25980 IF y_max<y_min: hx=y_max: y_max=y_min: y_min=hx
25990 hy=y_max-y_min:hx=x_max-x_min:ax=sc_factor/hx:bx=-x_min*ax:
      ay=1/hy:by=-y_min/hy
26000 IF sy=0
26010 sy=10^(INT(LOG10(hy))): loop=0: REPeat loop: IF hy/sy>=3:EXIT loop: ELSE
      sy=sy/(2+.5*(loop=1)): loop=1+loop-3*(loop=2)
26020 END IF : IF sx=0
26030 sx=10^(INT(LOG10(hx))): loop=0: REPeat loop: IF hx/sx>=6: EXIT loop: ELSE
      sx=sx/(2+.5*(loop=1)): loop=1+loop-3*(loop=2)
26040 END IF : f9=3
26050 END DEFine RANGE
26060 REMark ——————————————————
26070 DEFine PROCedure axes(nx,xx,ny,xy,sx,sy): REMark sx,sy zero for
      auto-scaling
26080 LOCal loop,zx,zy,z,y,x
26090 RANGE nx,xx,ny,xy: CLS
26100 LINE plotx(nx),ploty(0) TO plotx(xx),ploty(0):LINE plotx(0),ploty(ny) TO
      plotx(0),ploty(xy)
26110 zx=plotx(0):IF zx<0:zx=0:END IF :IF zx>sc_factor:zx=sc_factor
26120 zy=ploty(0):IF zy<0:zy=0:END IF :IF zy>1:zy=1
26130 IF xy>0:FOR y=sy TO xy STEP sy:linex y
26140 IF ny<0:FOR y=-sy TO ny STEP -sy:linex y
26150 IF xx>0: FOR x=sx TO xx STEP sx:liney x
26160 IF nx<0:FOR x=-sx TO nx STEP -sx:liney x
26170 f9=4:END DEFine axes
26180 REMark ——————————————————
26190 DEFine FuNction plotx(x):RETurn ax*x+bx
```

```
26200 DEFine FuNction ploty(yq): RETurn ay*yq+by
26210 REMark ================================
26220 DEFine PROCedure linex(y)
26230 LOCal uy: uy=ploty(y): INK 2: LINE 0,uy TO sc_factor, uy
26240 CURSOR zx,uy,0,-10:PRINT y;
26250 END DEFine linex
26260 REMark ================================
26270 DEFine PROCedure liney(x)
26280 LOCal ux,uy:INK 2:uy=plotx(x): LINE uy,0 TO uy,1
26290 ux=480-uy*480/sc_factor-6*LEN(x): ux=ux*(ux<0)
26300 CURSOR uy,zy,ux,-10:PRINT x;
26310 END DEFine liney
26320 REMark ================================
26330 DEFine PROCedure indata (fresh)
26340 LOCal p$(70),ll,ul,x,loop,ld,test,row: IF NOT fresh: CLS #0: ed_win 0:
      scr 2
26350 IF not_first=0
26360 RESTORE 3000: ndat=0: REPeat ndat: READ p$: IF p$=='end': EXIT ndat: ELSE
      cudat$(ndat)=p$:READ xdat(ndat),ldat(ndat), udat(ndat): ndat=ndat+1
26370 END IF
26380 IF f7>0: OPEN #3,ser:PRINT #3, \'NEW PARAMETER VALUES at time ';time:
      CLOSE #3
26390 REPeat test
26400 FOR loop=3 TO 26
26410 p$=cudat$(loop): row=loop-3
26420 x=xdat(loop):ll=ldat(loop): ul=udat(loop)
26430 base_type=xdat(24): IF (((loop+base_type)>27) OR (loop<25))
26440 xdat(loop)=in(p$,x,ll,ul,row,0)
26450 IF ((f7>0) AND ((x<>xdat(loop)) OR (not_first=0))): OPEN #3,ser: PRINT
      #3,p$;' = ';xdat(loop): CLOSE #3
26460 END IF
26470 IF ((xdat(13)=0) AND (loop=13)):loop=17
26480 END FOR loop: no_slides=(xdat(13)=0)
26490 not_first=1
26500 AT #0,24,0: CLS #0, 3:PRINT #0, 'Is Data OK ? ';:IF yes: EXIT test
26510 IF f7>0: OPEN #3,ser: PRINT #3,\'with corrections as follows:': CLOSE #3
26520 END REPeat test
26530 F1_flag=0: n$(1 TO 3)=' ': IF NOT fresh: scr 2: gr_win 0: f_title
26540 new_times: ASSIGN_VALUES: END DEFine indata
26550 REMark ================================
26560 DEFine FuNction yes
26570 LOCal a: a=0: PRINT #0,' (Y/N) ? ';
26580 REPeat a:a=(INKEY$(-1) INSTR CHR$(255)&'ny'): IF a>1: EXIT a
26590 CLS #0,3:RETurn a-2: END DEFine yes
26600 REMark ================================
26610 DEFine PROCedure new_times
26620 LOCal x,ll,ul,p$(48),I:_base=Built_Wndo(#9,348,40,82,64): INK #9,0: PAPER
      #9,4: CLS #9
26630 PRINT #9,'ENTER TIMES to plot and alter/quit': FOR I=27 TO 28
26640 ll=ldat(I): ul=udat(I): x=xdat(I): IF I=27
26650 IF time>ll: ll=time*1E-3
26660 IF x<ll: x=ll
26670 IF ll>=ul: ul=ul+ul
26680 END IF : p$=cudat$(I)&' ('&ll&' to '&ul&'): '
26690 REPeat loop:AT #9,I-25,0:PRINT #9,p$;: x=EDITF(#9,x,6): IF (x>=ll) AND
      (x<=ul): EXIT loop
26700 xdat(I)=x
26710 END FOR I: Close_Wndo #9,_base: IF f7>0
```

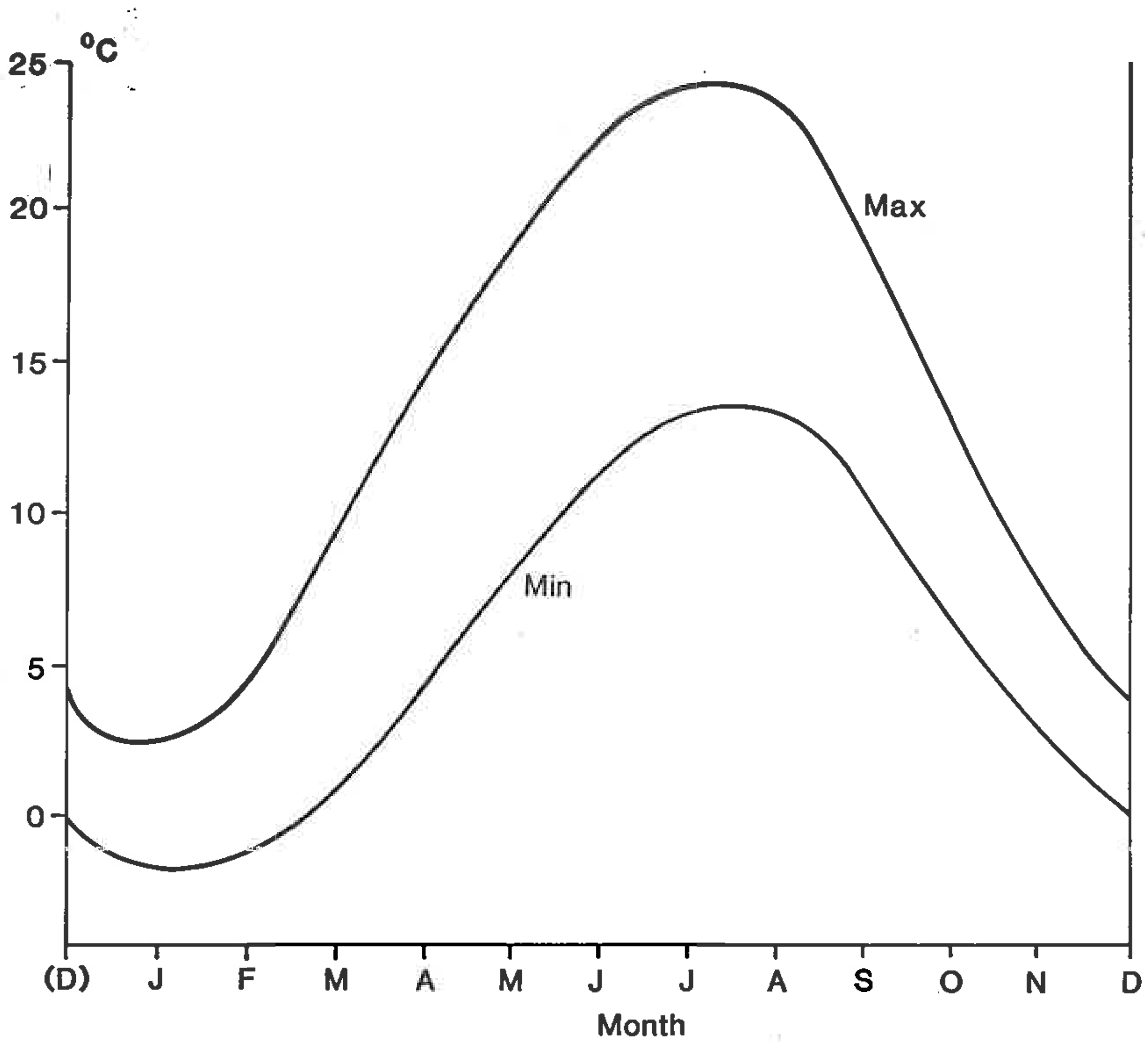
```
26720 OPEN #3,ser: FOR I=27 TO 28: PRINT #3,cudat$(I);' = ';xdat(I)
26730 CLOSE #3: END IF : tprint=xdat(28)*1000:
     next_print=-INT(-time/tprint)*tprint:
     next_print=next_print+tprint*(time==next_print)
26740 tfinal=xdat(27)*1000: t_flag=0: n$(10 TO 15)=' ': END DEFine new_times
26750 REMark ===============================
27340 DEFine FuNction Built_Wndo(ch%,a%,b%,c%,d%)
27520 DEFine PROCedure Close_Wndo(ch%, _base)
27630 DEFine PROCedure Move_RAM(srce,dest,step1,step2,bytes%,lines%)
27730 DEFine FuNction FORMAT_FP$(val,fld_width%,dec_places%)
```



1. The main interrelationships included in the model.



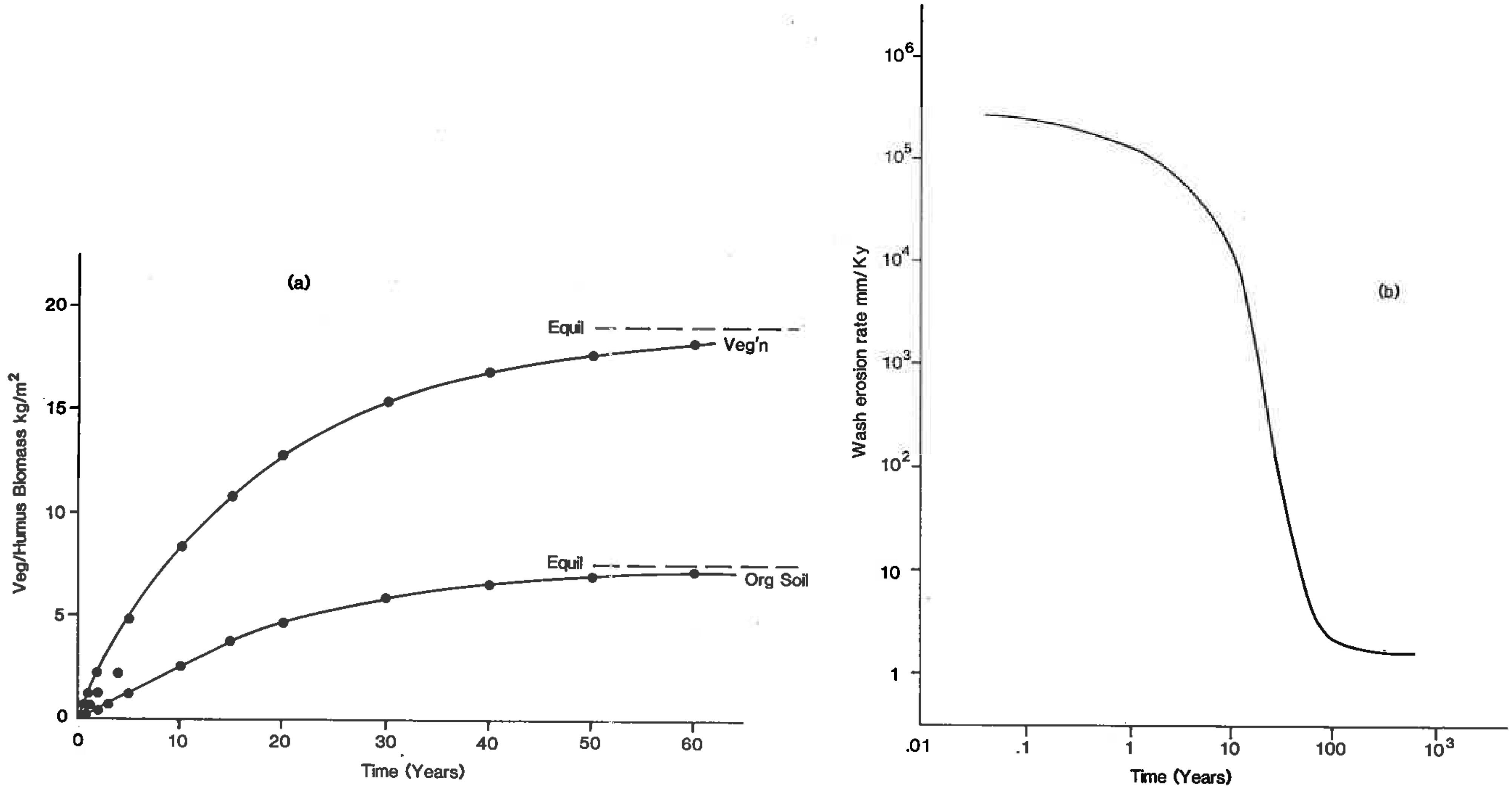
2. Interactions included between vegetation and erosion rates.

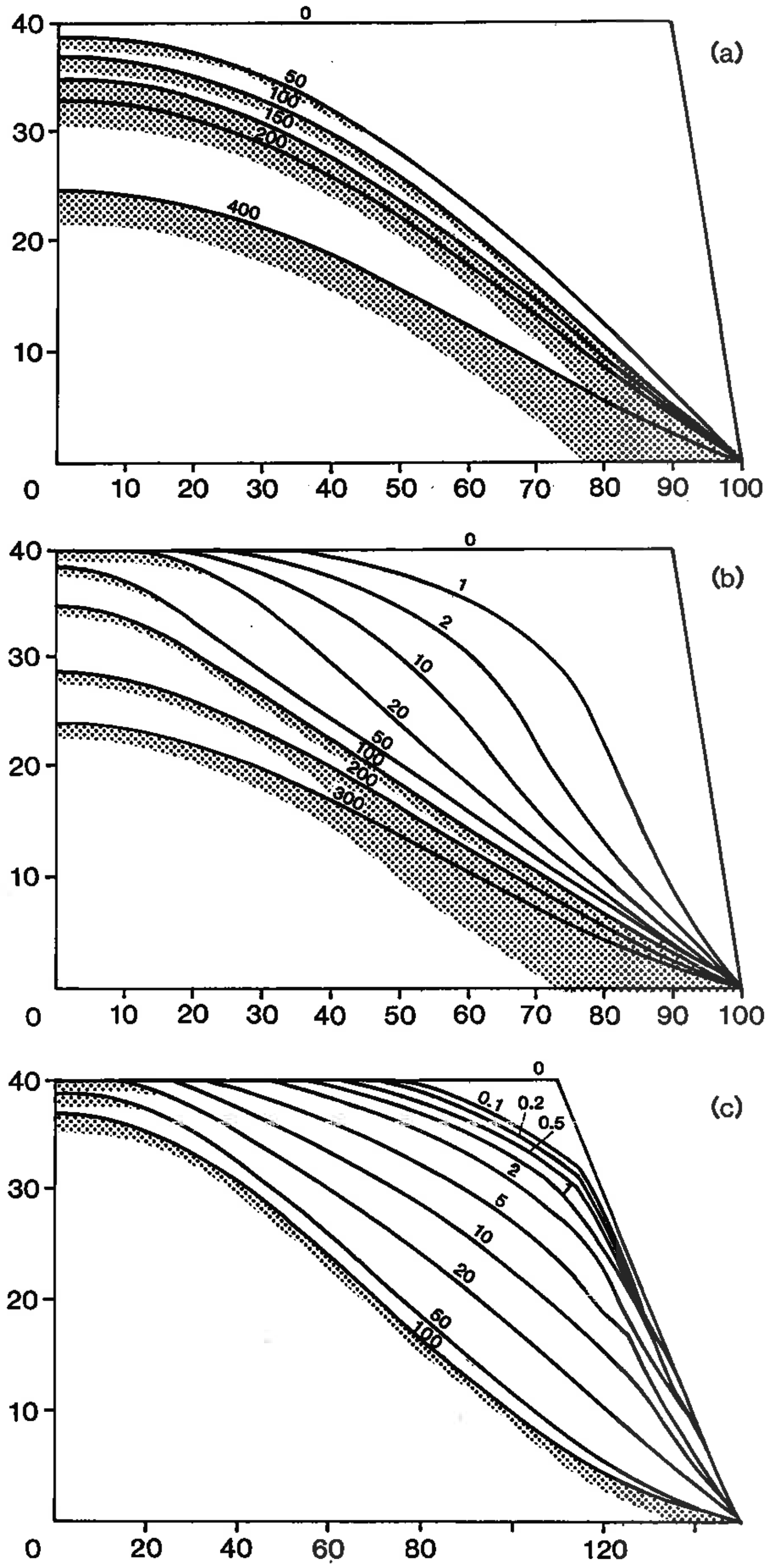


3. Assumed annual march of temperature for Luxembourg.

4a. The approach of vegetation and organic soil to equilibrium for current Luxembourg parameters.

b. The initial fall in erosion forecast as vegetation becomes established on a bare inorganic regolith.



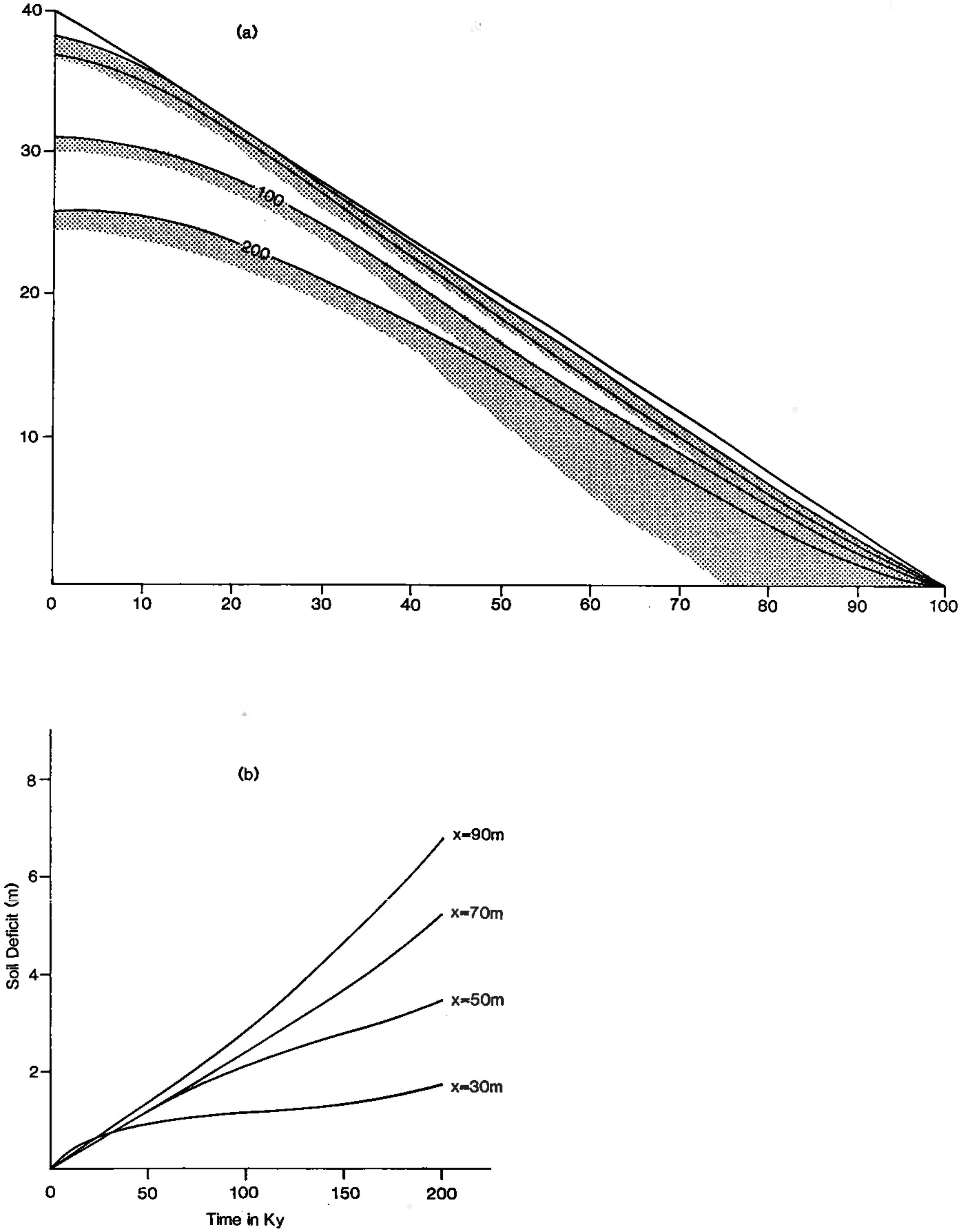


5. Examples showing the influence of initial slope form:

a. 100m plateau: no landslides

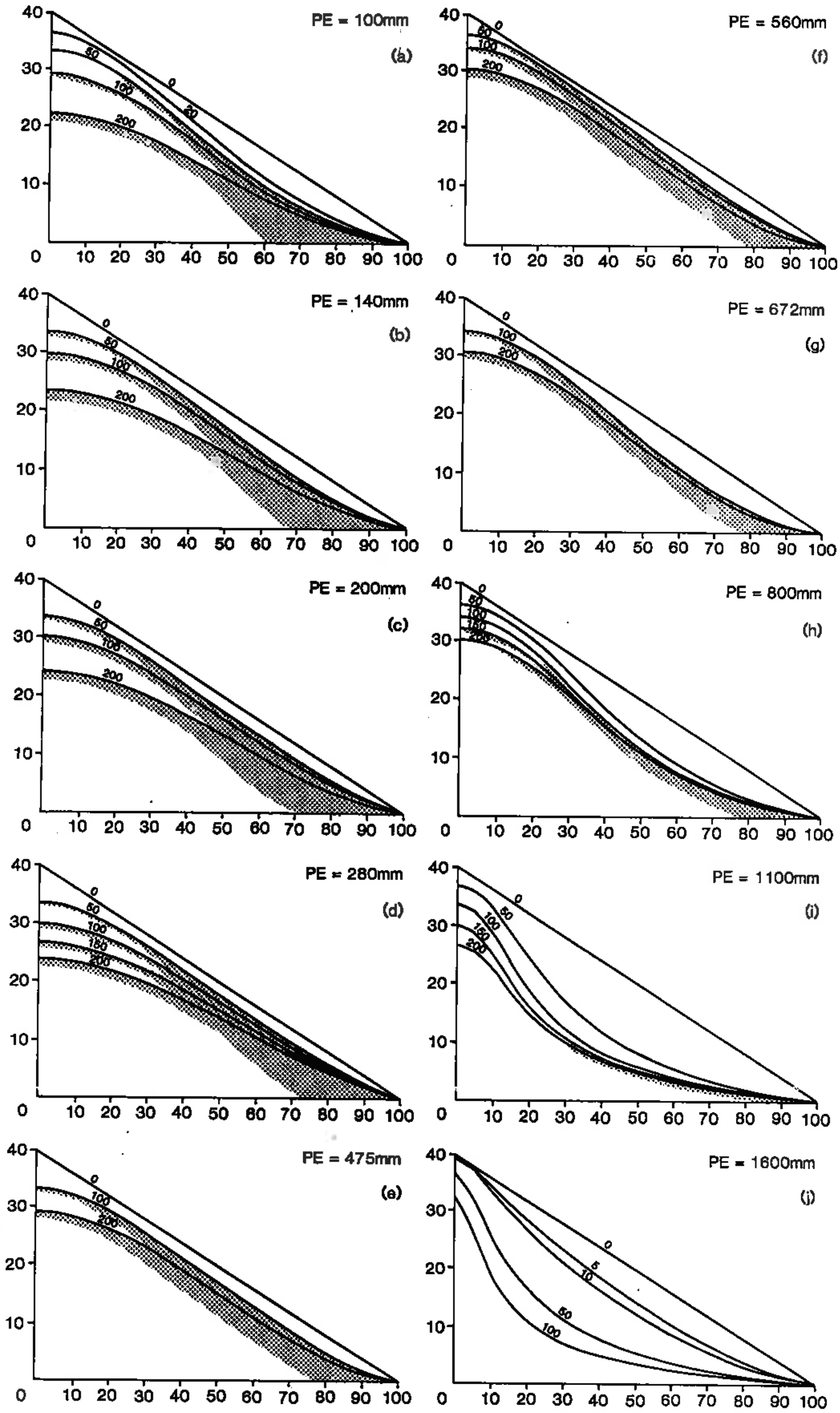
b. 100m plateau: with landslides

c. 150m plateau: with landslides



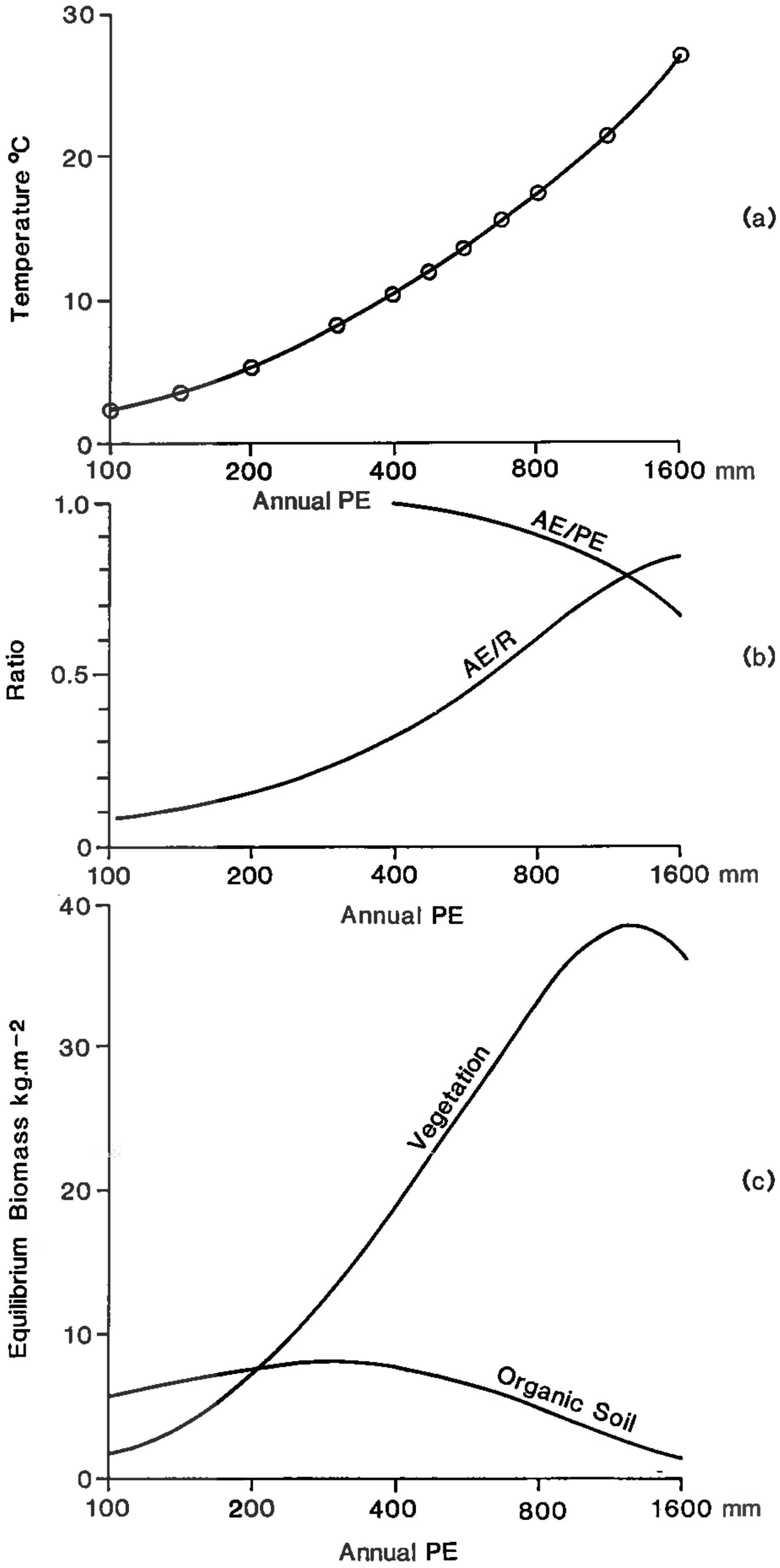
6a. Evolution of the slope form, starting from 'standard' parameters and initial form, for current Luxembourg conditions. Soil deficit is shown to scale.

b. The evolution of soil deficit at different locations downslope.



7. Slope evolution forecast for a range of conditions, differing only in temperature.

a. 100mm PE (2.4°C)	b. 140mm PE (3.6°C)
c. 200mm PE (5.6°C)	d. 300mm PE (8.4°C)
e. 475mm PE (12.0°C)	f. 560mm PE (13.5°C)
g. 672mm PE (15.8°C)	h. 800mm PE (17.4°C)
i. 1100mm PE (21.5°C)	j. 1600mm PE (27.2°C)

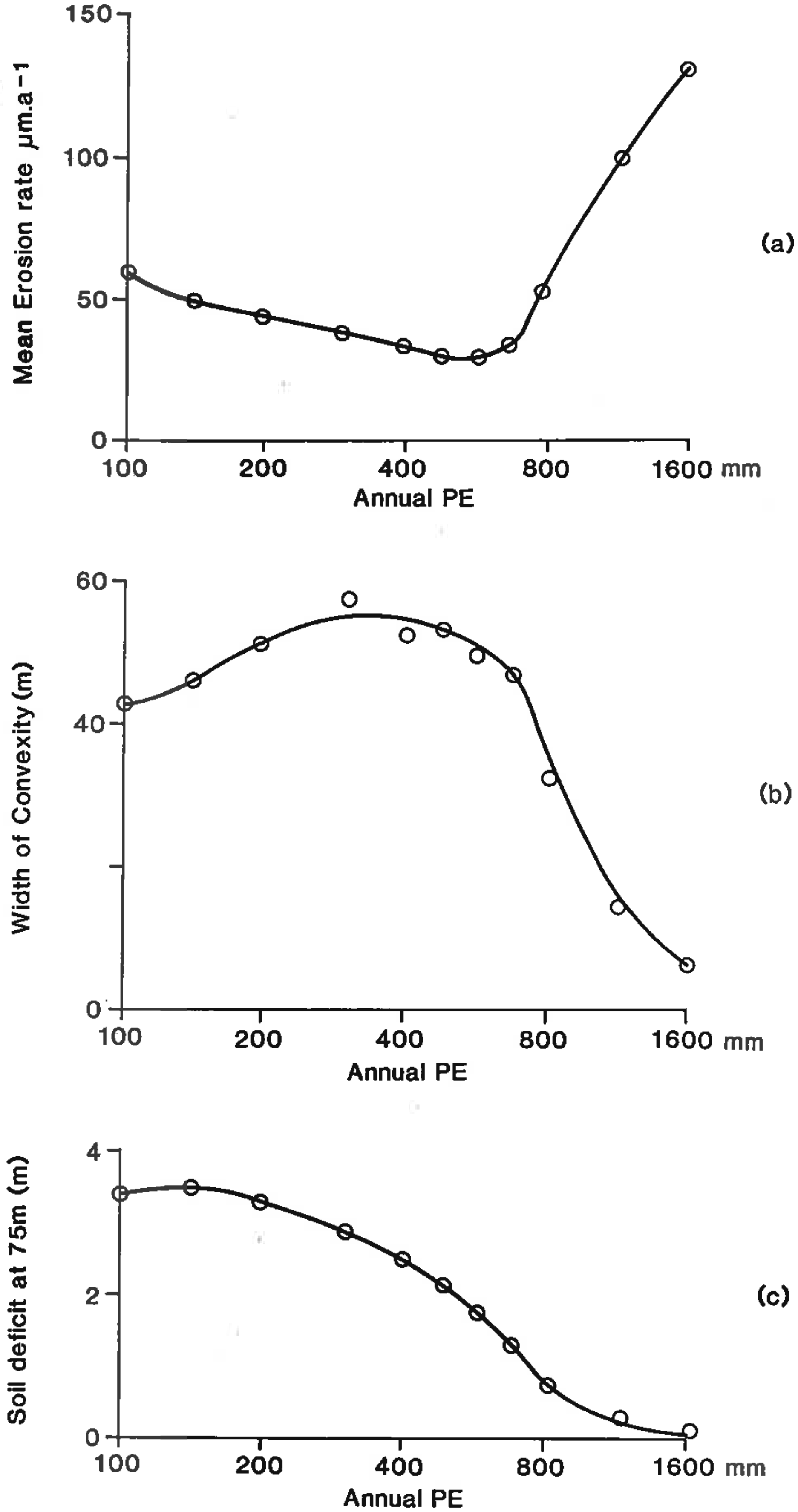


8. Forecasts of short term responses to climatic differences.

a. Temperature

b. Actual evapotranspiration as a fraction of rainfall and PE

c. Equilibrium biomass for vegetation and organic soil

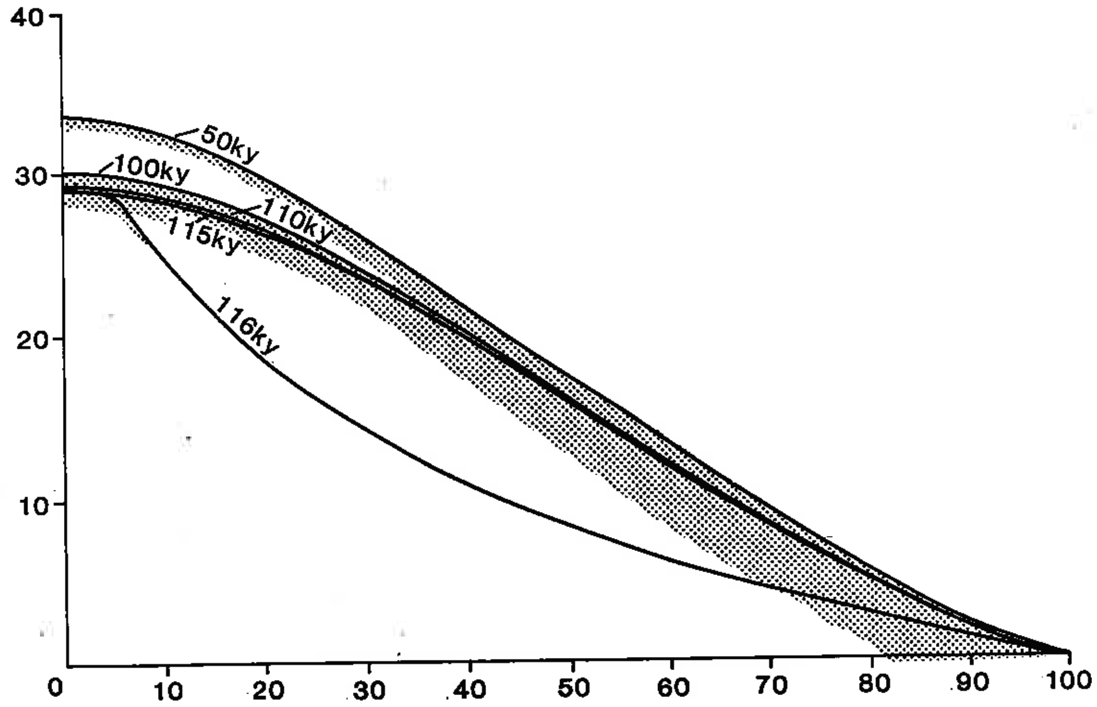


9. Forecasts of long term responses to climatic differences, for slopes shown in figure 7.

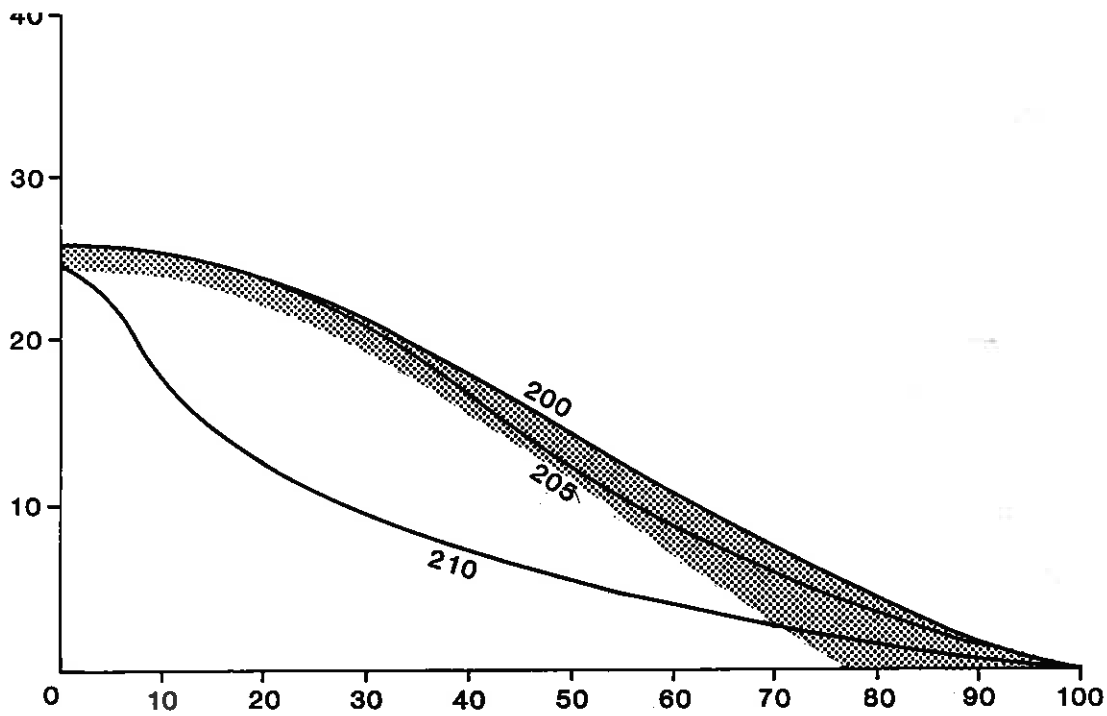
a. Mean erosion rate over 100,000 years

b. Soil deficit at 75m after 100,000 years

c. Width of summit convexity after 100,000 years.



10. Forecast response to the following example sequence:
(i) 200,000 years of current conditions (as in Fig 6)
(ii) 10,000 years with same climate, but with 90% removal of leaf fall as a crop.



11. Forecast response to the following example sequence:
(i) 100,000 years with temperature 5°C cooler than at present, and no cropping.
(ii) 10,000 years with temperature as at present, and no cropping.
(iii) 5,000 years with 50% cropping, at same temperature.
(iv) 1,000 years with 90% cropping, at same temperature.