WORKING PAPER 438

A SOIL EROSION MODEL INCORPORATING SEASONAL FACTORS

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Although there has been substantial further work on soil erosion, primarily sponsored by the US Department of Agriculture (e.g. Foster, 1977, 1982), the large part of it related to the USLE has almost entirely failed to come to terrms with its fundamental limitations: that it cannot provide useful forecasts of hillslope flow generation and that it fails to distinguish between the soil and surface properties which are separately relevant to hydrology, hydraulic resistance and aggregate transport. By simply embodying generalized regressions over time and space without any view of the physical basis of the erosion processes, USLE cannot realistically forecast the frequency, severity and spatial distribution of the relatively limited number of erosion events at a given site, especially under changing conditions. It is therefore an insensitive tool at best.

The second area of active research into erosion forecasting has been concerned with the development of distributed hydrological models to give detailed patterns of overland flow and sediment yield during the course of individual storm events (e.g. Alonso *et al*, 1978; Li, 1979). This group of approaches to erosion forecasting, although fruitful, requires very large amounts of field data to parameterize the models, and very substantial computer run times to forecast erosion rates for a significant period of,say, a decade. It is therefore not, at present, thought to be readily applicable to more generalised forecasting at present, particularly at the low cost per unit area required for many problem areas in the world's semi arid lands. It may also be criticized for not giving sufficient weight to recent developments in partial area models of hillslope hydrology. Despite these reservations, the application of hydrological principles to soil erosion forecasting is seen as an important step in the direction of removing the objections to USLE stated above.

The third area of relevant models in concerned with vegetation biomass and morphology. Despite its importance in controlling erosion, vegetation is normally only included in current erosion models as one or more parameters, not as an interacting component of the model. Vegetation models may either describe the distribution of gross morphological types/ plant assemblages as an empirical function of climate (e.g. Box, 1981); or may forecast the productivity or growth rate of individual species or communities. The latter type of model is most relevant to the needs of erosion forecasting, because it allows seasonal variations in plant community and therefore hydrological and erosion responses. Recent advances in general vegetation production ecology have been based largely on the detailed case studies of production and biomass in representative terrestrial biomes, conducted under the International Biological Programme (IBP). Global regressions of the resulting data on climatic variables have been attempted (e.g. Lieth and Whittaker, 1975; Lieth and Box, 1977), and have met with some success despite the range of species responses and non climatic controls influencing growth.

Improved understanding of plant metabolism in general and the physiology of certain well studied crop species in particular has led to the development of specific growth models for crops or other individual species which realistically simulate physiological and growth responses to climate in the growing season (e.g. Hanks and Rasmussen, 1982). However most are only applicable over a very restricted range of conditions. These limitations also generally apply to empirical yield models developed for agronomic forecasting.

Because vegetation models have been developed primarily by botanists, ecologists and agronomists, their hydrological implications have not generally been considered. Vegetation acts through intercepting precipitation and influencing total evapo-transpiration and water balance. It also influences crusting of the soil surface and soil moisture retention, both of which profoundly influence infiltration capacity. Forecasting the nature of the vegetation cover at a site, and its development over the year in response to seasonal elements of the climate, or the weather of a particular year, is seen as perhaps the most significant need in improving the hydrological basis of soil erosion forecasts.

2. Structure of proposed model

The model presented here is conceived as part of a larger model, with somewhat more ambitious aims. Figure 1 outlines the main sub-systems considered in the model. Those in parentheses or with thinner arrows and/or box margins in the figure are intended to be part of the final model, but have not been included in the version reported in detail here. The most important interactions controlling erosion transport on partially vegetated surfaces are thought to be (1) the environmental and hydrological control of plant and soil biomass, (2) the control of soil hydrological properties by soil biomass and (3) the control of the various erosion processes by overland flow (for wash) and by the combined action of vegetation cover and rainfall intensity (for splash). Also of considerable importance, although not yet incorporated into the model are (4) the detailed mechanics of erosion transport processes, including their distribution and interactions downslope, and (5) the factors influencing soil erodibility and its dynamic adjustment in response to biological and erosional processes. It may be seen that the current model is intended to advance soil erosion forecasts chiefly through its improved handling of hillslope hydrology and of vegetation interacting with it. In this section, each sub-system of the current model is discussed in some detail.

The approach adopted in the model is intended to be flexible in its use of available input data. In the form presented here, an absolute minimum data level is used. This not only serves to simplify the model to bring out its main principles, but also allows it to be used here to generate erosion forecasts on a world wide scale. This scale of operation is helpful in defining default parameter values, which can be used in any particular context where local values are not available. Where good local data are available on any aspect of the model, these can be used to improve local forecasts without re-writing the model as a whole. For example, the current model forecasts potential evapo-transpiration from temperature data, but this can be replaced either by direct data values, or by a Penman Monteith or other sub-model where the relevant data exist. Similarly, in most particular applications, the global vegetation sub-model can be replaced or improved in the light of local data. This flexibility should be borne in mind in considering the 'global default' model outlined here.

Figure 2 lists the equations used in computing the system relationships shown in figure 1 and described below. The sequence shows the order in which they are calculated, and the arrows show the logical precursor(s) to each equation. These expressions give the current implementation of each relationships discussed for the global model, using parameter values either derived directly from other studies, or modified from them on the basis of empirical data.

Minimum climatic inputs are of monthly values for total precipitation and number of rain-days; and of monthly mean temperatures. Rainfall intensity distributions are generated on a daily basis, using an inverse exponential distribution. These distributions may then be used to provide either mean runoff and erosion values, summed over the distribution, or else a stochastic rainfall sequence. Temperature data are used to estimate potential evapo-transpiration (in the absence of better data), and to control unit rates for the decomposition of organic soil.

The hydrological model used is a simple version of a one-store hydrological model, 'TOPMODEL', originally proposed by Beven and Kirkby (1978), and subsequently developed by both co-authors. It is based on an exponential (as opposed to a linear) store with a scale depth parameter m, which provides an explicit expression for flow distribution over the relevant sub-catchment, while retaining the simplicity of a lumped model. It provides values, for any site in a sub-catchment, of soil mositure deficit below saturation, and of overland and sub-surface flows. A topographic parameter depending on the ratio of local unit catchment area to local gradient, relates the hydrology at any particular site to the average for the sub-catchment as a whole. Local overland flow is estimated using this parameter to provide the local saturation deficit which must be satisfied before flow occurs. The model may, if desired, be used in a fully or partially distributed form where great detail is required. In its original version, flows were forecast over time increments of 1/2 to 3 hours, but an aggregated version has been developed to give monthly flows (and their distributions) in response to monthly rainfall inputs.

TOPMODEL provides an estimate of overland flow, by summing, over their frequency distribution for each month, the rainfall in excess of that required to fill soil water storage. This expression (4) includes a correction term for the change in sub-surface flow during the storm, and a term to correct the average sub-catchmeent values to the local site of interest. Rainfall, less overland flow and actual evapo-tranpiration, is then used to estimate the change of soil water storage and total sub-surface flow for the month (equation 7 to 10), using the relationship (8) from TOPMODEL to integrate the net change.

Potential evapo-transpiration is currently (though not necessarily) estimated in equation (5) from monthly temperatures. This expression approximates to Thornthwaite's estimates, but is simpler in form and provides a better fit over the whole range. Actual evapotranspiration is constrained to lie between zero and the potential value. Within this range, it falls as a linear function of soil moisture deficit, reaching zero for a rooting constant which is related, through the soil hydrological parameter *, to the organic soil biomass. This estimate is made in equation (6).

On the global scale, net productivity of the plant community is calculated as the difference between a gross, or unstressed productivity which is proportional to actual evapo-transpiration less an allowance for bare ground evaporation (equation 12); and a temperature dependent loss term representing respiration etc (equation 13). The gross productivity term is based on data from Larcher (1975). The combined effect of these two terms is to produce a net primary productivity which closely follows the equation (based on a different estimator of actual evapo-tranpiration) of Lieth and Box (1977). It differs in order to provide the best available estimator for the published data of Whittaker and Likens (1975) from gross environmental parameters. This may be replaced by a more detailed model, like those for crop species, or by direct data at a local scale.

In assessing plant growth, net productivity is set against losses which may collectively be termed 'leaf fall', though including death of all parts of the plant, at a total rate which increases with plant biomass (equation 14). The increase is initially more or less linear, and decreases in rate for communities with large standing biomass, corresponding to their greater proportion of woody and other non-shedding tissues. The form used follows the data of Whittaker and Likens (1975) and O'Neill and De Angelis (1981). Allowance can be made for cropping of parts of the living plant, for example through grazing; and for removal of some of the litter, for example for firewood. Both of thse losses are scaled to the leaf fall rate, as a measure of sustainable production. They influence the living plant biomass (equation 15) and the addition of material to the organic soil (equation 17). One important element of the global erosion model is that the estimates of vegetation biomass obtained from it can be compared with a large body of ecological literature, which provides significant independent validation both of the vegetation model itself and also of the hydrological model which is used to 'grow' it through controlling evapo-transpiration.

The organic soil biomass receives material from 'leaf fall', and loses material through decomposition to CO_2 and inorganic soil nutrients. The former is controllled by the plants as described above. The latter (equation 16) is directly proportional to soil biomass and to a rate constant which is thought to depend mainly on temperature, through its control on the population density of decomposer organisms. The temperature dependence of the rate constant gives values which are in reasonable agreement with data by Singh and Gupta (1977). In the current model, good soil aeration is assumed, so that no account is taken of the considerable depression of decomposition rates by waterlogged conditions. Low soil moisture, litter composition and its pH are also known to influence decomposition rates. These features could readily be included, either by reducing parameter values or in response to forecast soil water deficits. Neither has any distinction yet been made between litter layers and organic material admixed with the mineral soil.

A third property of the vegetation cover which is also estimated independently is the total crown cover. For a non-seasonal climate, it is estimated simply as the ratio of actual to potential evapo-transpiration. The basis for using an estimate of this kind is the assumption that plant root systems spread out to intercept available rainfall over the whole of the ground surface, whereas their crown cover is restricted; in one of their most direct strategies for limiting actual transpiration losses. For a seasonal climate, the ratio of actual to potential evapo-transpiration is used in a first order Markov model (equation 11) with a persistence of *PCOV* = 0.75. It then provides a crude estimate of cover, as it changes gradually over the year, which is used in the model to forecast exposure of the soil to splash and crusting processes. The ratio of mean plant biomass to mean cover may also be treated as a rough indicator of height for the plant community, though not of its seasonal variations, helping to give a better picture of the types of community modelled, although this measure is not used in the model. The calculated cover may also be used to provide an approximate estimate of Leaf Area Index (LAI), if this is needed by the Penman Monteith or other evapo-transpiration sub-model. On an assumption of stochastic leaf overlap with a Poisson distribution, LAI is equal to −ln(proportion bare area). This expression is not however used in the model at present.

Soil hydrological properties provide the key feedback from vegetation characteristics to the hydrological model. At a global level, no assumptions have been made about mineral soil differences, even though some consistent differences and trends with climate are known to exist. Soil parameters, particularly the key parameter ■ of the subsurface hydrological store, are instead forecast solely from the vegetation and organic biomass values, principally the latter. The basis in reason for this linkage is that soil organic matter provides one of the major reservoirs of readily reversible soil water storage. High soil organic biomass therefore bestows a good soil structure for moisture storage and a high surface permeability: qualities which are known to have a profound influence on the parameter ■ from experience with TOPMODEL. This linkage is used in two ways. First to forecast the parameter ■ as a linear function (equation 1) of the organic soil biomass (from the previous month), together with a constant term representing the mineral soil. The second expression of this linkage, in equation (2), forecasts the monthly sub-surface runoff at the start-of-month soil water level. This term, which is used in calculating the total sub-surface runoff for the month (equation 8), includes an estimate of saturated hydraulic conductivity at the soil surface, which is taken to be directly proportional to the parameter ■.

Vegetation also influences hydrological forecasts through a term in equation (3) which represents crusting and sealing of the soil surface. The available storage capacity which must be filled before overland flow can begin is assumed to be equal to the local saturation deficit in the proportion of the area covered by vegetation, and to a low constant value (of 2-5mm) for the bare part of the area. Under high canopies, this term may need correcting to allow full or partial crusting beneath the canopy.

The core of the current model is concerned with forecasting hillslope hydrology, and its interaction with vegetation cover. At present the forecast of erosion losses is relatively crude, and is intended to illustrate the implications of the hydrological forecasts rather than to provide a final basis for forecasting erosion, which will be the subject of further work.

The wash erosion forecast uses an estimate of overland flow derived from the hydrological sub-model. This estimate, either for an individual storm or as a monthly mean on the basis of the rainfall distribution, has considerable indirect dependence on vegetation, particularly through the moisture retention of the organic soil, but also through the influence of bare area on crusting of the soil surface. The values generated are based on empirical estimates previously used by Kirkby (1976, 1980), but do not yet include any detailed analysis of the relative significance of rill and inter-rill contributions such as those monitored by Meyer *et al* (1975). The forecast of equation (20) nominally relates to average denudation from a 10 metre long convex slope, falling from a divide. It may readily be adjusted to other configurations by adjusting the sediment transport rate constant, which is proportional to slope length squared multiplied by basal gradient; and by adjusting the hydrological parameter which relates the local site to the average for the sub-catchment (*ASRAT* in equation 3).

Splash erosion forecasts are related to local gradient and to storm rainfall (equation 19). The process is assumed to be effective only where the ground is bare of vegetation, although there is scope for revising this assumption where there is known to be little canopy cover within 5-10 metres of the ground. Both splash and wash expressions contain a correction for the relative roughness of the surface in terms of the spread of surface stone sizes (equation 18), but there is not at present any forecast of progressive armouring as erosion proceeds.

The set of equations in figure 2 is calculated in order from (1) to (20) for each month, and values for next month calculated on the basis of the previous month's storage, vegetation etc. The thrust of the model is currently concerned with the interaction of hydrology with vegetation in response to climate. There is no doubt that there is a second major set of interactions concerned with hydrological and strength properties of the mineral soil which merits similar exploration.

Model performance

The equations listed in figure 2 form the core of a computer simulation model, which calculates values of saturation deficit, flows and erosion based on averages over the distributions of rainfall for each month of the year. It is currently implemented on the University of Leeds AMDAHL mainframe computer in the FORTRAN 77 language, although its requirements are well within the scope of most microcomputers. The model, in its current 'global default' form, uses monthly data for precipitation, number of rain-days and mean temperature as its sole explicit inputs, although there are also a number of implicit inputs representing the constants in the governing equations.

To initialize the model, arbitrary values may be taken for living and organic soil biomasses. Over a wide range of assumed values, the simulation converges on a stable annual cycle of values if the monthly climatic means are input repeatedly. The time for effective convergence depends on the initial values chosen and their difference from the final values. A period of twenty to eighty simulation years is generally needed to reach stability. The runs reported here reflect the values of biomass, mean erosion etc. for the stable pattern obtained in this way. Simulations may however continue from this stable state to examine a historical climatic sequence, either as represented by mean values or for the particular sequence of storms. They may also examine the response to a stochastic sequence of storms generated from the mean monthly distributions, and so gain some insight into the expected variability in erosion rates over time.

The performance of the model is illustrated in a series of figures (3 to 7) which illustrate its behaviour for the set of parameter values shown in figure 2. Figure 3 shows the course of the main variables of interest for Almeria, a fairly arid Mediterranean climate, that is with maximum rainfall in the winter (coolest) months. (a) shows the march of rainfall, temperature and forecast overland flow: most of the remaining rainfall contributes to the actual evapo-transpiration. It may be seen that the proportion, as well as the total amount of overland flow is greatest in the months of greatest (and most intense) rainfall, and that there is more overland flow in the autumn, when vegeation is thin, than at similar rainfall levels in the spring.

In figure (3b), it may be seen that the forecast vegetation biomass is greatest in the spring, at the end of the rainy season, and least in the autumn, growing in the winter rainy season which is warm enough not to inhibit growth. The vegetation of southern Spain consists largely of low perennial shrubs, so that the persistence of a substantial proportion of the biomass through the summer is an accurate reflection of the true conditions. The organic soil biomass peaks even later, in May/June, depending as it does on leaf fall from the spring growth to sustain it. (c) shows the forecast for the erosion components. Wash erosion peaks strongly in the winter months in association with overland flow, and more or less in phase with it, and has a very pronounced minimum during the summer months. For splash the variation over the year, while present, is less extreme, and there is some tendency for relatively greater erosion in the autumn than the spring, when rain acts on a minimum vegetation cover. The overall pattern shown in figure 3 is of erosion and overland flow tending to peak a little in advance of the rainfall maximum, and for vegetation and organic soil biomasses to lag behind the rainfall peak. The effect of the strongly seasonal climate is to provide a time of year when vegetation is sparse and rainfall intense, so that totoal erosion is notably greater than for a climate in which the same rainfall is equably distributed over the twelve months of the year.

Figures 4 to 6 all refer to a range of mean annual temperatures and rainfalls; with superimposed variations in the degree of seasonality of rainfall and temperature, and in the mean rain per rain-day, allowing the diagrams to show many commonly ocurring combinations of global climates with summer rainfall maxima. The diagrams are thus intended to show a reasonably realistic pattern of world-wide variations in climate.

Figure 4 shows the forecast values for equilibrium biomass of living plants (a) and organic soil (b). It may be seen to forecast the broad pattern of world ecotypes. The range of values for standing biomass follows mean values reported by Whittaker and Likens (1975), with a maximum of 45 kg m^{-2} in the humid tropics, declining to 0.15 kg m^{-2} for tundra, and virtually to zero in extreme desert conditions. Within this overall range, estimates for boreal forest are on the low side, and for savanna somewhat too high (although savanna ecosystems almost certainly reflect many factors beside direct hydrological control). Soil organic matter peaks in cool-temperate and boreal areas, conforming well to the data of Basilevich and Rodin (1975). Both living and organic soil biomass distributions show a primary dependence on temperature at high rainfalls, when growth is limited by potential evapo-transpiration; and a joint dependence on rainfall and temperature for semi-arid climates, tending towards zero values for very hot, dry climates. The forecast behaviour thus provides a fair summary of world-wide values, especially when it is noted that no assumptions are made about vegetation form (e.g. grass, shrubs or trees etc) or deciduous/ evergreen habit. The model can therefore be considerably improved if parameter values are allowed to take even such broad categories of local cover into account. If estimates of plant 'height' are made as living biomass ÷ cover, then the pattern is of tallest vegetation (more than 40 kg m^{-2} per unit cover) for the tropical rain forest, dropping to about 2 kg m^{-2} for hot deserts, and 0.2 kg m^{-2} for tundra conditions. The resulting forecast pattern is one of tundra with a total cover of ground hugging vegetation; of deserts with widely spaced large shrubs or cacti; and of complete cover of increasing height, from temperate to tropical forests. As with biomass, the overall pattern is satisfactory, though with local anomalies.

These vegetation estimates are an important half-way house in building up erosion forecasts. They provide a readily checked set of values and ranges, as well as representing important controls on erosion rates. By validating the gross estimates shown in figure 4, we may have some confidence in estimates both of regular seasonal change and of responses to particular weather sequences or agricultural and conservation practises which influence vegetation type or cover. With suitable parameter changes, adaptations of the global model may also serve as a stable model for particular plant communities where no special purpose growth model is available.

Figure 5 shows, for the same range of climates as the previous figure, the forecast levels of total erosion for the chosen 10°, 10 m slope. The area for which denudation by splash is faster than by wash is also indicated. The forecasts for low-temperature areas are thought to be too large. Although these cold areas are known to be subject to severe wash erosion because of their sparse vegetation cover, the forecast makes no allowance for snow or ice, and so over-estimates the effect of overland flow. The temperate zone, except at very high rainfall levels, is seen as one of minimal erosion. At almost all but the lowest rainfalls, a temperature transect for erosion from this forecast, holding rainfall constant, consists of high erosion in sub-freezing climates; a rapid drop to low values above about 5°C; and then a progressive increase to high tropical erosion rates.

Constant temperature transects for the erosion forecast are more familiar, following the pattern of Langbein and Schumm's paper (1958) on sediment yields for catchments and reservoirs in the southern USA. Examples, from the same data as figure 5, are drawn in figure 6 for a series of temperatures. It may be seen that forecasts for wash alone show a simple peak of erosion rate, at rainfall values which increase with temperature. Except at low temperatures (6°C and below), increased rainfall is associated with a well defined zone of very low erosion, followed by a second zone of increasing erosion. The exact form of this rising limb for high rainfalls is strongly influenced by the hydraulic conductivity of the near-surface soils; high conductivities giving a more subdued rise. The addition of splash somewhat confuses the pattern of total erosion at low temperatures. Splash gives the curve a 'shoulder' on the right of the semi-arid wash erosion peak, which at lower temperatures gives a secondary peak of total erosion. At high temperatures, the influence of splash is proportionately less.

In figure 7, the effect of seasonality has been explicitly separated out in the forecasts of erosion. Five curves are shown here, all for the variation of wash and splash erosion with rainfall along a 21°C transect. The basic curve is for zero seasonality, with every month at equal rainfall and temperature. The 50% curves have rainfall ranging as a sine wave from 50% of the annual mean to 150% of the mean; and temperature varying sinusoidally over 5°C either side of the mean. On the +50% curve, these changes are in phase, so that rainfall peaks in the summer (i.e. hot season). On the -50% curve, the changes are out of phase, giving winter rainfall (i.e. a Mediterranean climate). The other two curves are for +/-90% changes in rainfall, with a temperature fluctuation of +/-10°C. Increasing seasonality can be seen to have a strong influence on the erosion forecasts. Greater seasonality always increases erosion, as has been noted above, but its greatest impact is in reducing the depth of the temperate erosion minimum. This effect is seen to be a great deal more marked for the case of winter rainfall minima. For the strongest seasonality (-90% curve), which is for a climatic transect similar to that along the Spanish coast from Almeria to Gibraltar, the temperate minimum of erosion has almost completely disappeared. It is clear that, at the very least, more attention should be paid to seasonality in collating erosion data, and that Fournier's (1960) expression for seasonality should be given due credit, but should not be the last word on the subject.

4. Conclusions and prospects

The forecasts for soil erosion, overland flow, living biomass and organic soil have been explored here to demostrate the relevance of a model which in primarily concerned with the relationship between vegetation and slope hydrology. At present many of the relationships, especially those used to estimate soil hydrological properties from organic soil biomass, are experimental, without direct evidence for their form. It is clear too, that other inter-relationships, especially those including the mineral soil, are also important; and that the present model fails badly for sub-freezing regimes. Despite these shortcomings, the model presented is well founded in empirical data at many points, and in our understanding of detailed hydrological and geomorphological processes. It represents one important conceptual step towards a better physical basis for erosion forecasting.

At the global scale of the model presented, there has not been time here to explore all the dimensions of interest. There is, for example scope for attempting to place cropping and conservation practice on a more rational basis. There is also scope for using the estimates of sub-surface flow, in conjunction with vegetation and soil organic matter, to generate a parallel model for solution rates, taking account of the influence of vegetation not only in controlling hydrology, but also in controlling soil CO_2 levels.

The prospect for better detailed erosion forecasting is seen to rest on the global model presented here, in the sense that it provides a default basis for any parameters which are not better defined in each local context. Many parameters are however known in any local forecasting context, generally including the type of vegetation cover. The overall framework is still thought to be highly relevant however, in allowing forecasts to respond, through vegetation growth (for the known species of the site) to the weather of particular years or runs of years; or to changes in land use or conservation practise.

Current soil conservation practise aims at limiting erosion at a level which, while sustainable in the short term, cannot be replaced by natural rates of bedrock and soil weathering. To improve our control of the land for agriculture without degrading our soil resources in this way, we must aim at a better knowledge of the whole erosional system, and not simply those parts which are seen as amenable to straightforward physical analysis. The role of vegetation as a major control on erosion is unquestioned. We must intensify our study of erosional systems, going beyond the normally accepted bounds of physical hydrology by including the vegetation as a dynamic part of that system.

References cited.

Alonso, C.Y. *et al*, 1978. Field test of a distributed sediment yield model, in *Verification of mathematical and physical models in hydraulic engineering*. American Society of Civil Engineering, Hydralics Division.
Basilevich, N.I. and Rodin, L.Y., 1971. Goegraphical regularities in productivity and circulation of chemical elements in the earth's main vegetation types, in *Soviet Geography*, (Rev. and Trans.) American Geographical Society, New York.
Beven, K.J. and Kirkby, M.J., 1978. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24(1), 43-69.
Foster, G.R. (Editor), 1977. *Soil erosion: prediction and control*. Soil Conservation Society of America.
Foster, G.R.,1982. Modelling the erosion process, in *Hydrologic modelling of small watersheds* (ed. C.T. Haan), American Society of Agricultural Engineering, Monograph 5.
Fournier, F., 1960. *Climat et erosion: la relation entre l'erosion du sol par l'eau et les precipitations atmospheriques*. Presses Universitaire de France, Paris, 201pp.
Hanks, R.J. and Rasmussen,V.P., 1982. Predicting crop production as related to plant water stores. *Advances in Agronomy*, 35, 193-215.
Langbein, W.B. and Schumm, S.A., 1958. Yield of sediment in relation to mean annual precipitation. *Transactions, American Geophyscial Union*, 39, 1076-1084.
Larcher, W., 1975. *Physiological plant ecology*. Springer Verlag.
Li, R.M., 1979. Water and sediment routing from watersheds, in *Modelling in Rivers* (edited H.W. Shen). John Wiley, pp 9.1-9.88
Lieth, H. and Box, E.O., 1977. The gross primary productivity of land vegetation: a first attempt. *Tropical Ecology*, 18, 109-115.
Lieth, H. and Whittaker, R.H. (Editors), 1975. *The primary production of the biosphere*.
O, Neill, R.V. andDe Angelis, D.L., 1981. Comparative productivity and biomass relations of forest ecosystems, in *Dynamic properties of forest systems* (ed. D.E. Reichle), IBP Publication 23.
Singh, J.S. and Gupta, S.R., 1977. Plant decomposition and soil respiration in terrestrial ecosystems. *Botanical Review*, 43, 449-528.
Whittaker, R.H., and Likens, G.E., 1975. The biosphere and man, in *The primary production of the biosphere* (ed. H. Lieth and R.H. Whittaker).
Wischmeier, W.H. and Smith, D.D., 1958. Rainfall energy and its relationship to soil loss. *Transactions, American Geophysical Union*, 39, 285-291.

List of figure captions.

1. Systems diagram showing the main processes and interactions included in the current erosion model (Heavy lines); and in prospective versions of it (Light lines and parentheses).

2. List of equations used in current model, in order of calculation, showing logical precursor(s) of each.

3. The annual march of climate and forecasts of vegetation and erosion for Almeria, S.E. Spain.

   (a) Input monthly rainfall (mm) and temperature (°C), with forecast overland flow (mm).

   (b) Forecast vegetation biomass (kg m^{-2}), organic soil biomass (kg m^{-2}) and vegetation cover (%).

   (c) Forecast denudation by wash and splash in μm yr^{-1}, for a 10 m convex slope, falling from a level divide to 10° at base of plot.

4. Forecast distribution of biomass in kg m^{-2} for a range of rainfalls(logarithmic scale) and temperatures, with assumed 'realistic' variations in seasonality and numbers of raindays.

   (a) Living plant biomass

   (b) Organic soil biomass

5. Forecast distribution of total erosion loss in mm yr^{-1} over same ranges as in figure 4. Shaded area is that for which forecast splash exceeds forecast wash erosion. Note that the relative importance of splash declines with slope length.

6. Transects across data set of figure 5, for constant temperatures of 6°C to 30°C (with 'realistic' seasonality and numbers of rain days). Solid curves show combined effect of splash and wash: broken lines are for wash alone.

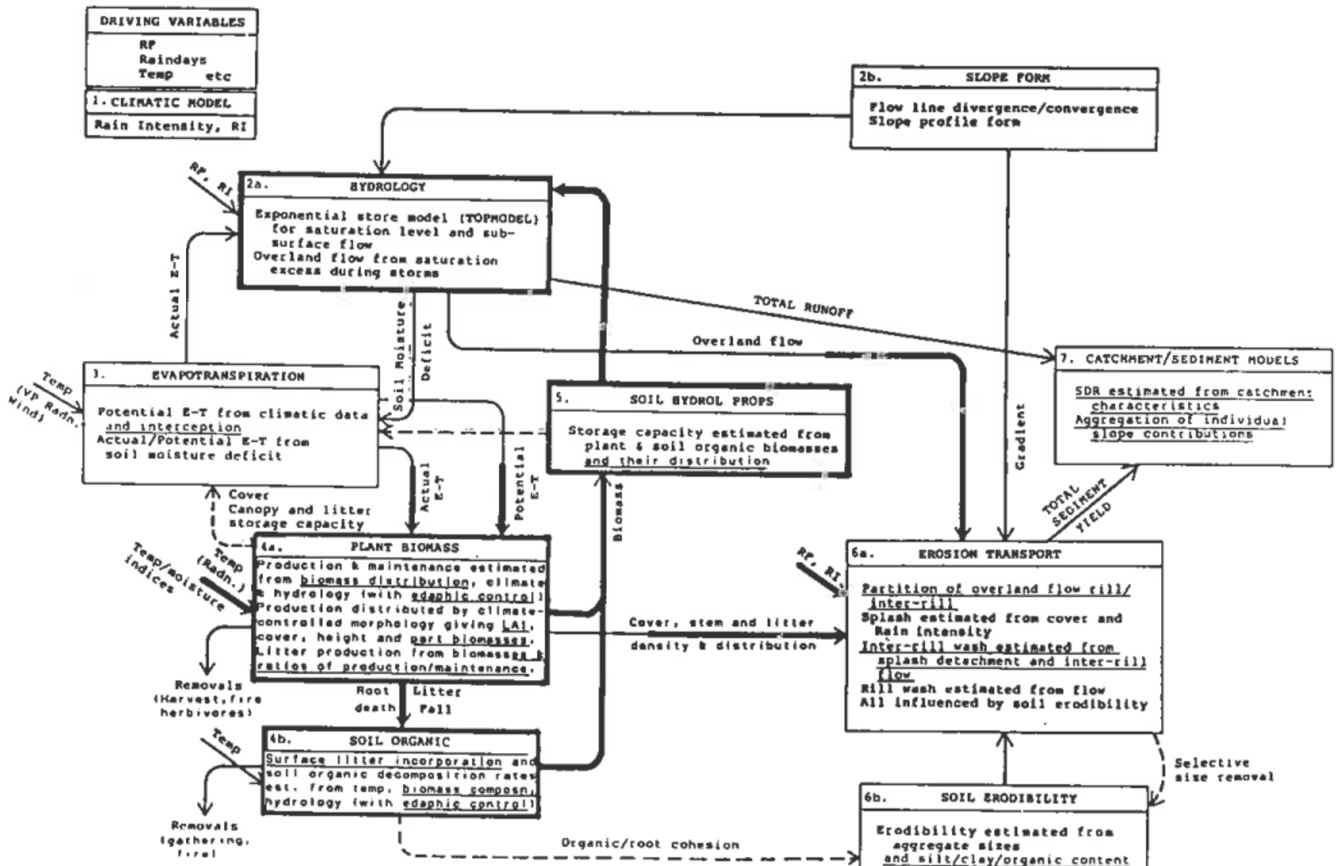
7. Forecast variations in total erosion rates in mm yr^{-1} as rainfall is varied at a mean temperature of 21°C. Values refer to degree of seasonality:

   For 50% curves, monthly rainfall ranges from 50% to 150% of mean, and temperature by +/- 5°C.

   For 90% curves, monthly rainfall ranges from 10% to 190% of mean, and temperature by +/- 10°C.

   Sign (e.g. +/- 50%, 90%) indicates whether rainfall peak is in phase with temperature (+: summer rainfall peak) or out of phase (-: winter rainfall peak).

FIG. 1



<14> Soil Erosion Model [illegible] mjk

FIGURE 2

(1) $M = MBASE + 5\ MH_{t-1}$ (Soil storage parameter in mm)

(2) $RJ = 1\ M^2 + \exp(ST_{t-1}/M)$ (Saturated soil flow)

(3) $RC = 5\ (1-C_{t-1}) - C_{t-1}(ST_{t-1} + M\ ASRAT)$ (Critical storage to initiate overland flow in mm)

(4) $OF = RF_t/[\exp(RC/R\emptyset_t\ (1 + M/R\emptyset_t)]$ (Overland flow in mm)

(5) $PE = 0.12\ (T_t + 6)^2$ (Potential evapo-transpiration mm)

(6) $0 <= AE = ST_{t-1} + RF_{t-1} - OF + 7\ M <= PE$ (Actual E-T)

(7) $F = RF_t - AE - OF$ if $>= 0$: otherwise 0 (mm Infiltration)

(8) $DS = M \ln [RJ/F + (1-RJ/F) \exp(-F/M)]$ if $F>0$

$= M \ln (1 + RJ/M$ if $F=0$ (Increased deficit over month)

(9) $ST_t = ST_{t-1} - DS$ (Updated soil water storage in mm)

(10) $SF = F - DS$ (Total sub-surface flow for month in mm)

(11) $C_t = PCOV\ C_{t-1} + (1 - PCOV)\ AE/PE$ (Vegetation cover %)

(12) $GPP = 0.0033\ [AE - 3\ (1 - C_t)\ RF_t/R\emptyset_t]$ (Gross production)

(13) $RES = 0.0005 \exp(-T_t/12)\ MV_{t-1}$ (Respiration etc)

(14) $LF = MV_{t-1} / [72.8 \ln(MV_{t-1} + 1.4)]$ (Leaf fall etc)

(15) $MV_t = MV_{t-1} + GPP - RES - LF\ (1 + VCROP)$ (Updated living biomass in kg m^{-2})

(16) $DEC = MH_{t-1}\exp(0.12\ T_t - 5.75)$ (Organic soil decomposition)

(17) $MH_t = MH_{t-1} + LF\ (1 - HCROP) - DEC$ (Updated organic soil biomass in kg m^{-2})

(18) $TAN\phi = 0.2 + 0.5\ DRAT$ (Surface roughness)

(19) $SPL = 0.00084(1-C_t)\ RF_t\ GRAD/[LEN\ GRSIZE(TAN\phi)^2]$ ($\mu m\ yr^{-1}$)

(20) $WASH = 8 \times 10^{-4}\ OF^2\ LEN\ GRAD\ /(GRSIZE\ TAN\phi)$ ($\mu m\ yr^{-1}$)

<u>Additional notation in order of use above</u>

MBASE	Basal value of *M* for mineral soil
RF	Mean precipitation for month
T	Mean temperature for month
$_{t,t-1}$	Suffices referring to current and previous month
λ	Parameter linking saturated hydraulic conductivity at surface to *M*. λ should be inversely proportional to sub-catchment mean of topographic ratio a/*GRAD*. λ = 8 (mm.month)$^{-1}$ currently.
ASRAT	Ratio of local value of topographic parameter a/*GRAD* to average for sub-catchment.
a	Area drained at point per unit contour length
GRAD	Local surface gradient (tangent slope)
RØ	Mean rainfall per rain-day for month
PCOV	Persistence of cover parameter (currently 0.75 to indicate 75% surviving next month if *AE* = 0.
VCROP	Proportion of annual leaf fall which is cropped from plant, *in addition* to any removal of normally shed material.
HCROP	Proportion of annual leaf fall cropped, and therefore not added to litter.
DRAT	Ratio of grain sizes of Roughness elements (D_{84}) to Mean size, *DM*
DM	Mean grain size of surface aggregates carries.
LEN	Length of slope plot for erosion estimates.

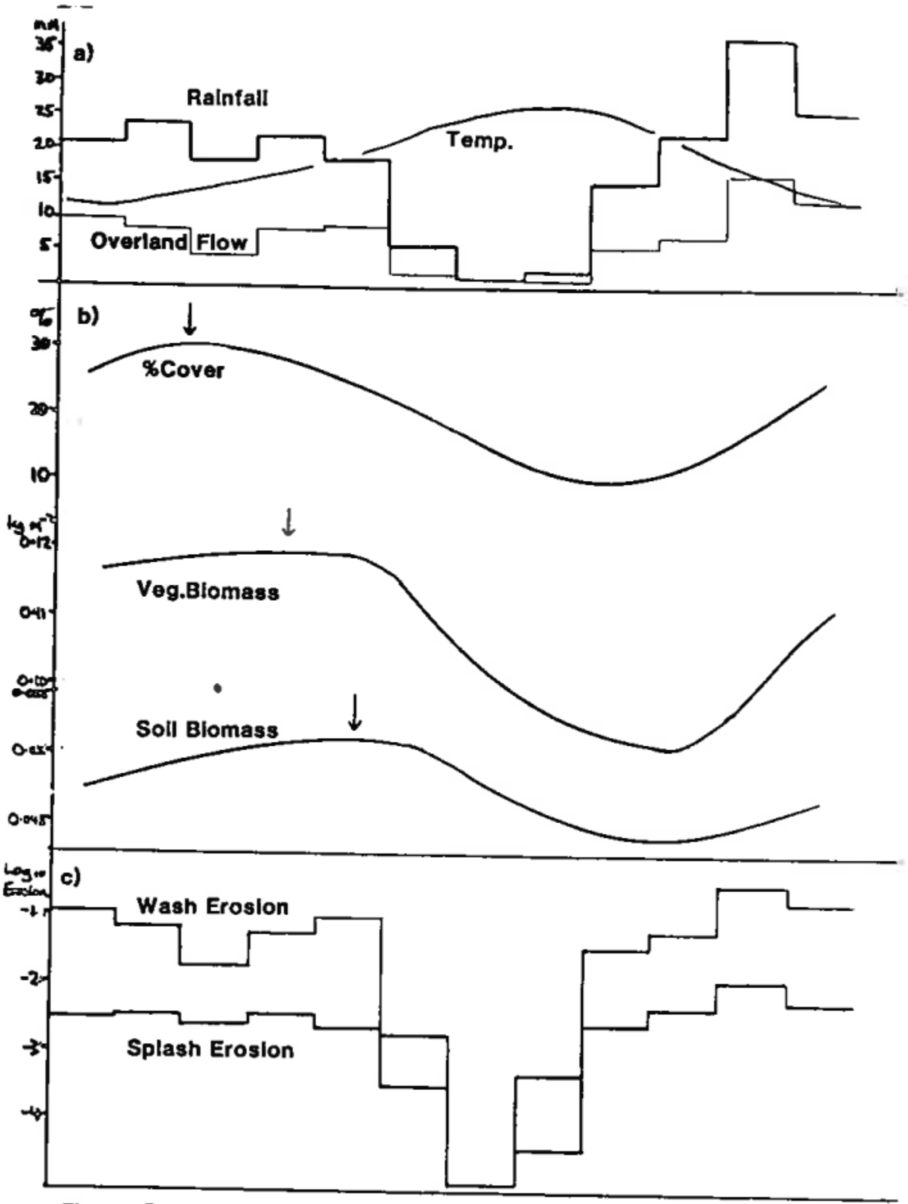
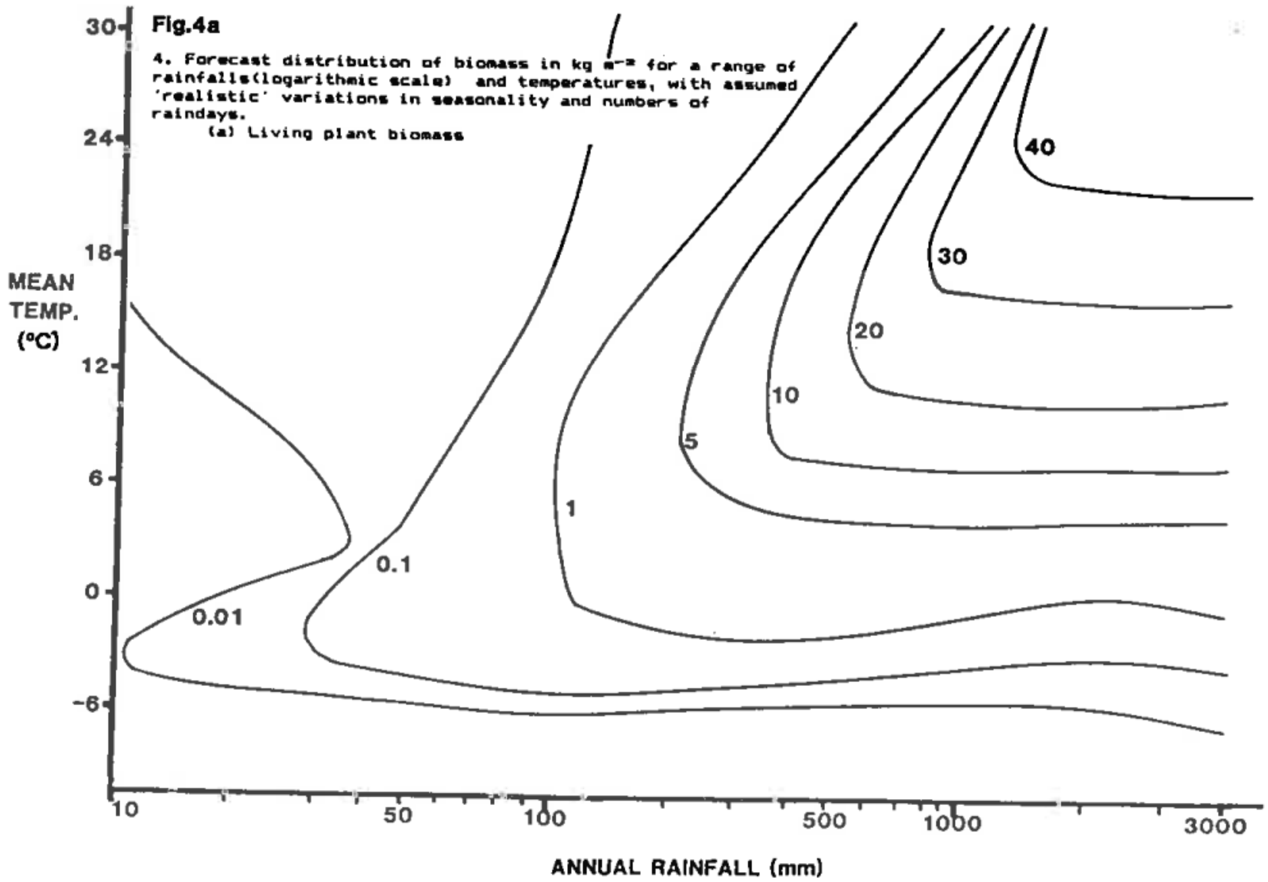


Fig.3 3. The annual march of climate and forecasts of vegetation and erosion for Almeria, S.E. Spain.

(a) Input monthly rainfall (mm) and temperature (°C), with forecast overland flow (mm).

(b) Forecast vegetation biomass (kg m^{-2}), organic soil biomass (kg m^{-2}) and vegetation cover (%).

(c) Forecast denudation by wash and splash in µm yr^{-1}, for a 10 m convex slope, falling from a level divide to 10° at base of plot.

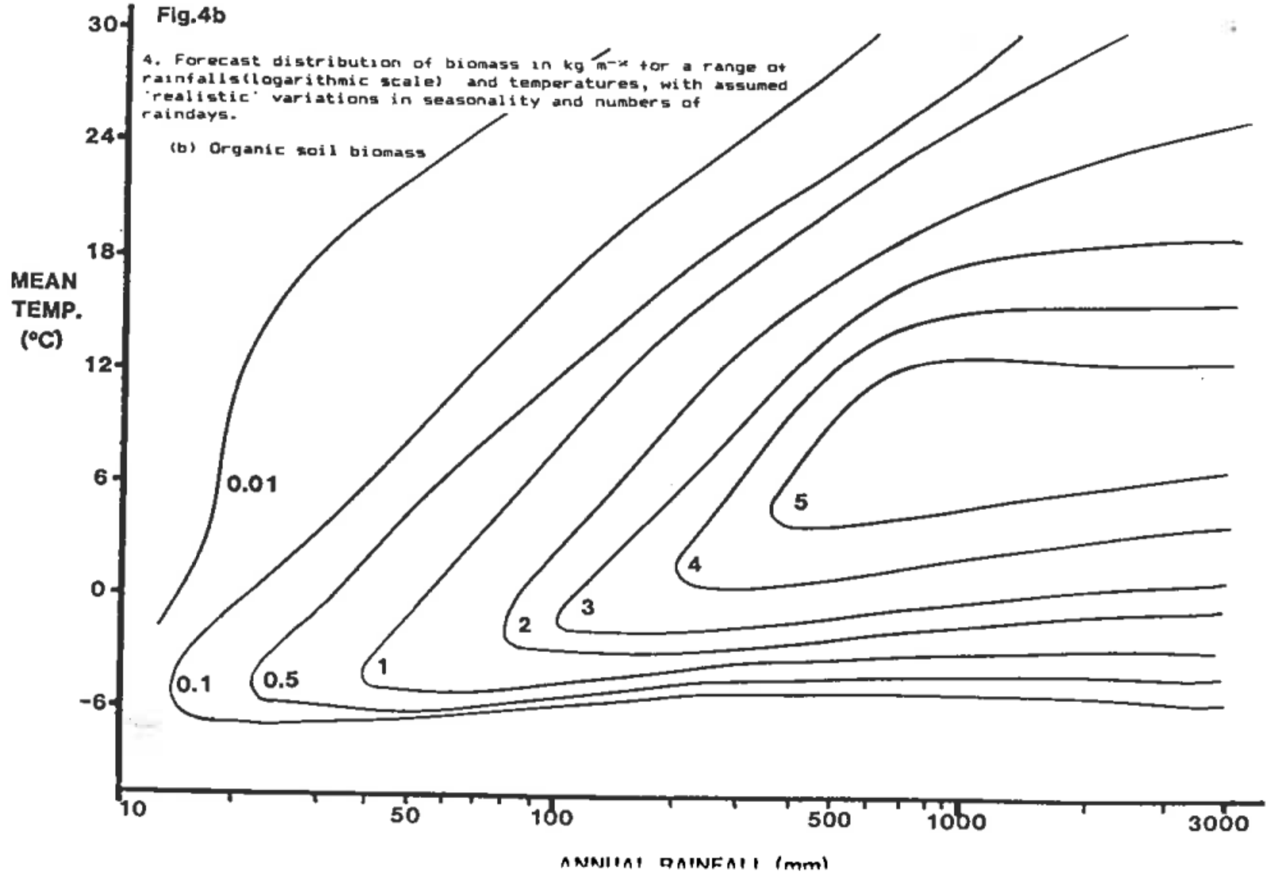


4. Forecast distribution of biomass in kg m^{-2} for a range of rainfalls (logarithmic scale) and temperatures, with assumed 'realistic' variations in seasonality and numbers of raindays.
(a) Living plant biomass

Fig.4b

4. Forecast distribution of biomass in kg m^{-2} for a range of rainfalls(logarithmic scale) and temperatures, with assumed 'realistic' variations in seasonality and numbers of raindays.

(b) Organic soil biomass



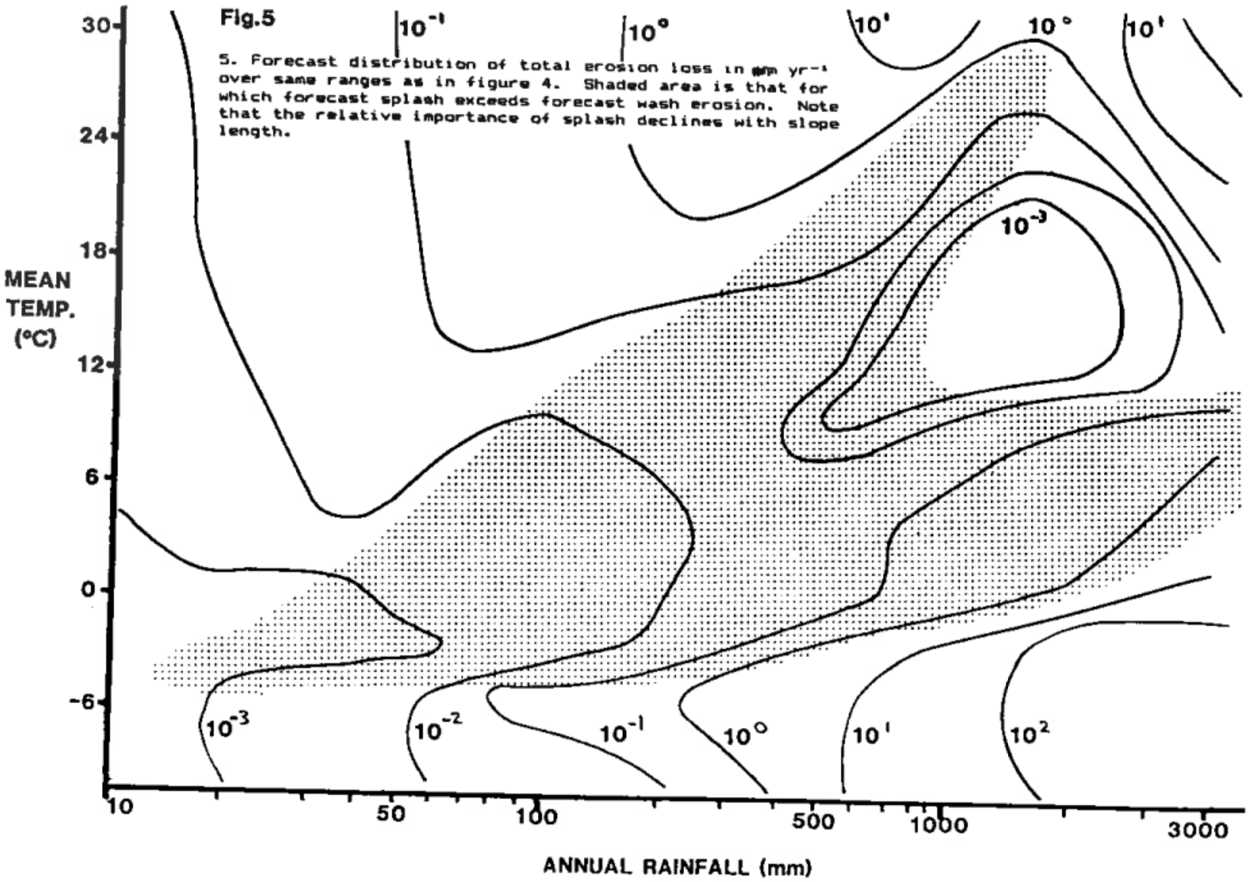
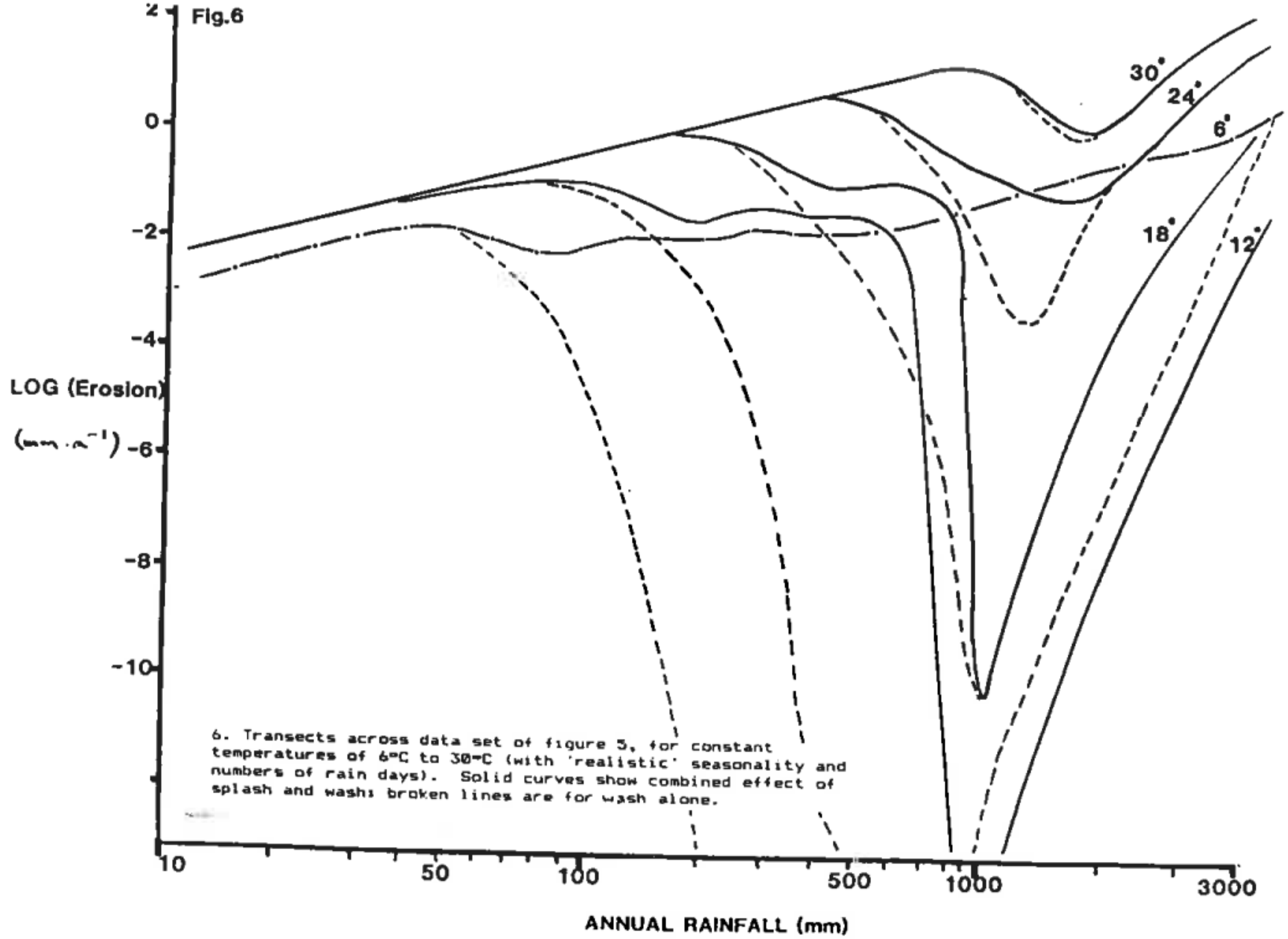
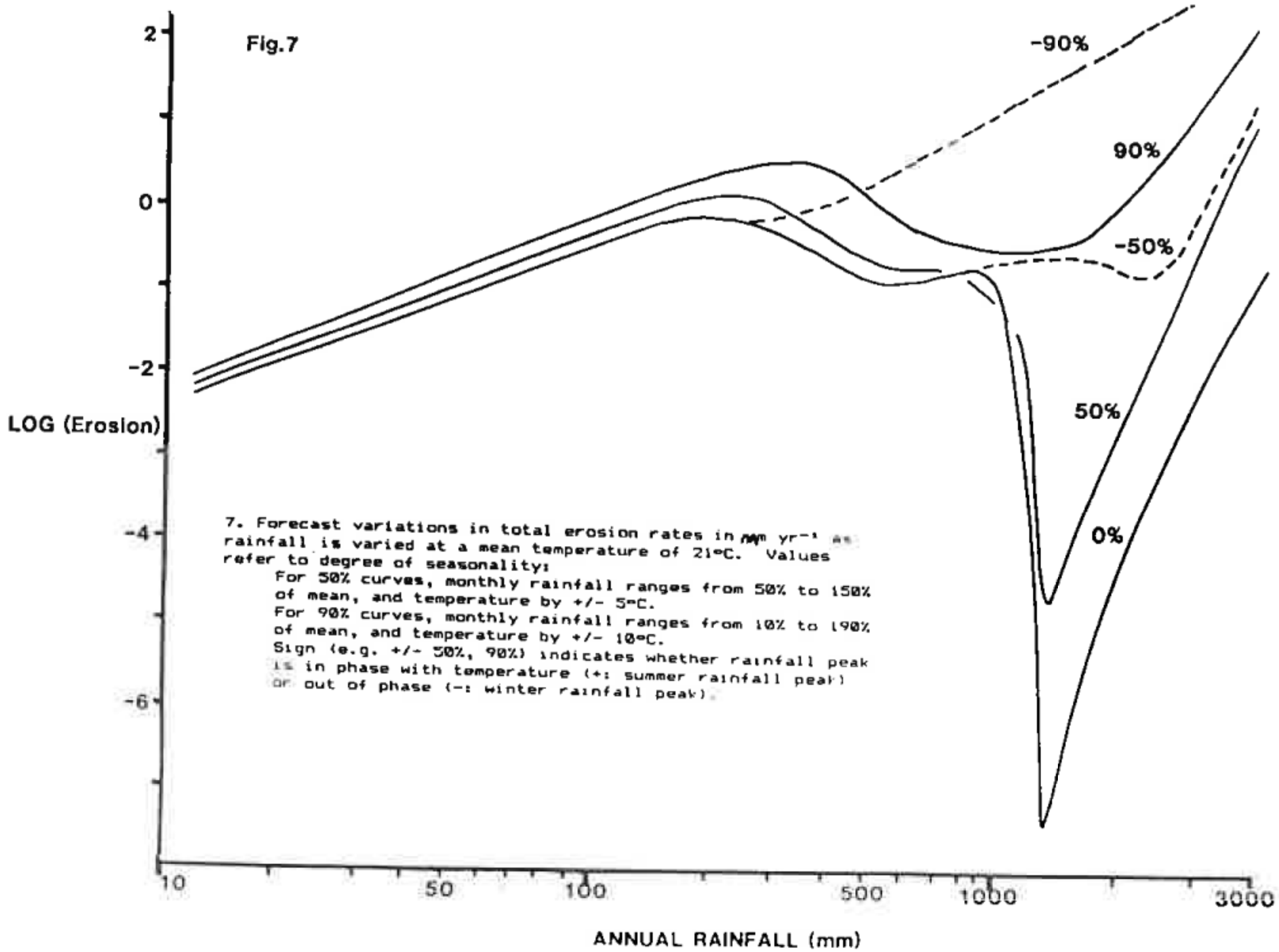


Fig.5

5. Forecast distribution of total erosion loss in mm yr^{-1} over same ranges as in figure 4. Shaded area is that for which forecast splash exceeds forecast wash erosion. Note that the relative importance of splash declines with slope length.



6. Transects across data set of figure 5, for constant temperatures of 6°C to 30°C (with 'realistic' seasonality and numbers of rain days). Solid curves show combined effect of splash and wash; broken lines are for wash alone.



7. Forecast variations in total erosion rates in mm yr⁻¹ as rainfall is varied at a mean temperature of 21°C. Values refer to degree of seasonality:

For 50% curves, monthly rainfall ranges from 50% to 150% of mean, and temperature by +/- 5°C.

For 90% curves, monthly rainfall ranges from 10% to 190% of mean, and temperature by +/- 10°C.

Sign (e.g. +/- 50%, 90%) indicates whether rainfall peak is in phase with temperature (+: summer rainfall peak) or out of phase (-: winter rainfall peak).