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A CONCEPTUAL MODEL OF SOIL MASS MOVEMENT, SURFACE SOIL EROSION, AND STREAM CHANNEL EROSION PROCESSES

Erosion Modeling Group

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ABSTRACT

The conceptual framework of an erosion model has been designed to link processes of mass wasting, surface erosion, and channel storage and transport. A program to stimulate mass wasting will be based on a variation of the factor of safety approach which balances forces tending to drive mass movement against those resisting it. Surface erosion will be treated by using a form of the universal soil loss equation adapted to account for dry ravel processes as well as precipitation generated surface erosion. These processes move material eroded from hillslope landscape areas into the stream channel. Channel erosion may occur either as bedload and suspension load transport or in episodic debris torrents, triggered by debris dam failure or by mass movement from a hillslope.

The model will be driven primarily by hydrologic processes and will also receive key inputs from vegetation components of the general ecosystem model. Model development will aim at producing a computer model which will have sufficient realism and predictive capability to be useful to land managers.

INTRODUCTION

Scientists interested in nutrient cycling as well as those charged with the management of forested lands are becoming increasingly concerned with gaining a better understanding of long-term consequences of erosion processes. Typical questions might include the following:

What is the magnitude of nutrient losses due to soil erosion?

How do rates of erosion compare with regional rates of soil formation?

What is the ultimate fate of transported particulate matter?

How do disturbances such as logging or fire, influence long-term erosion rates?

How do vegetation patterns, productivity, and nutrient cycling relate to geomorphic history?

Progress has been made in gaining a rather complete understanding of the actual mechanisms of both surface erosion and mass soil movement. However, we are still unable to predict with an acceptable degree of accuracy long-term erosion rates from forested uplands. Despite the availability of such tools as factor of safety analysis in landslide engineering and the universal soil loss equation for predicting surface erosion rates in the central and eastern U.S., no one has attempted to devise an erosion model for the Pacific Northwest which takes into account all forms of soil movement and couples these with stream channel dynamics. In this paper we present a preliminary, conceptual outline of such a model.

The proposed erosion model includes three subsystem models which attempt to describe the three principle classes of sediment transfer: surface processes (rainfall and nonrainfall-caused surface erosion), subsurface processes (mass soil movements), and channel dynamics (storage and transport of mineral and organic debris in stream channels). It is unrealistic to consider these processes separately, as has been done in the past, since all three are obviously so closely interrelated. For example, much surface erosion occurs as a direct result of the exposure of bare mineral soil due to landslide occurrence. Therefore, an important aspect of our model is a description of the way in which these processes influence each other and the results of such interactions.

When completed and running an erosion model similar to the one proposed here holds great promise to improve our understanding of the functioning of coniferous forest ecosystems--both in theoretical and practical ways. To begin with, it will fill a significant gap in our knowledge of nutrient cycling in forest ecosystems which commonly occur on steep, unstable terrain. Such an erosion model would also supply the land manager with a valuable means of estimating long-term erosional consequences of a variety of management options. Despite extensive research efforts directed toward the problem, such a predictive tool is, as yet, unavailable to land managers, but would be one of the hoped for benefits from the Coniferous Forest Biome Program.

CURRENT RESEARCH RELATIVE TO MODEL DEVELOPMENT

A number of interrelated field research programs are providing the types of information necessary for both the development and especially the application of the erosion model. On going geology and geomorphology studies in the Andrews Forest are designed to correlate data on bedrock geology, geomorphology (including alluvial, glacial, and deep-seated mass movement histories during the past few tens of thousands of years), and the occurrence of shallow soil mass movements during the period of land management (since the early 1950's). Preliminary results of this study and the work of Dyrness (1967) show close, predictable relationships among rock type associations, geomorphic history, and shallow mass movements, which are often affected by man's activities, and are therefore a principal concern in our erosion modeling effort. The coordinated program of erosion monitoring being carried out by Fredriksen, Glenn, and Swanston will yield a better understanding of the relative importance of creep, deep-seated earth flow, stream channel storage, and other processes in the overall picture of erosion. The combined output from these research programs should enable us to develop a realistic, predictive erosion model.

In addition, similar studies being initiated by U. S. Geological Survey and Forest Service personnel will offer the overview necessary for application of the erosion model to the diverse geological and geomorphic terrains of the coniferous biome region. Study sites now in planning stages include Drift Creek (Oregon, Coast Range), Elk and Sixes River drainages (Oregon, Klamath Mountains), Happy Camp area (California, Klamath Mountains), Redwood Creek (Northern California Coast Range), Cedar River (Washington, Cascades).

GENERAL EROSION AND SOIL MASS MOVEMENT MODEL

The conceptual framework of the erosion model, shown in Figs. 1 & 2, describes the flow of particulate organic and mineral matter from the slopes of a watershed into the stream channel and eventually out of the watershed. The general structure of the model is outlined in Fig. 1, which emphasizes the linkages among various areas of the landscape as well as among the vertical strata (vegetation, slope surface, and slope subsurface) within hillslope landscape areas. Fig. 2 shows the detail of informational inputs and relationships among processes within a hillslope unit. Submodels of surface erosion and mass movements account for the slope processes. Material transported by these processes into the stream channel at the base of the slope is stored there until it is transported downstream by annual high stream flow events or by catastrophic debris torrents which occur perhaps once a century.

An initial step in modeling a given landscape is to divide the area into units, or compartments, within which the types and relative significance of various erosional processes are rather homogeneous. We expect that these compartments will exhibit fairly uniform vegetation and soil surface and subsurface conditions and should therefore correspond to soil and plant mapping units. Landscape units may be arranged so that material is moved downstream from one compartment to the next until it reaches the stream. The stream channel may be divided into units based on channel parameters and the boundaries of adjacent hillslope mapping units. In this way the channel submodel is closely integrated with the slope processes submodels.

Further internal integration of the erosion model is shown by the dotted lines in Fig. 1, which represent important information feedback loops. If, for example, a shallow soil mass movement occurs, the vegetation and soil surface conditions of the area are adjusted to remove plant cover and expose bare mineral soil. As a result surface erosion would probably increase until the area is revegetated.

It should be emphasized that the arrows between compartments of this model are designed to show "connectivity" in the modeling sense. This implies some temporal relationship in the transfer of materials and/or information between compartments. Information flow may either assess the status of a storage compartment to test for initiation of a transfer process or send new information to change compartment status. Since the erosion model is event oriented, connectivity here does not necessarily represent continuous interdepartmental transfer. The arrows shown in the concenptual models in Fig. 1, 2, and 4 were used with these generalities in mind.

The erosion model will receive key imputs from other elements of the general ecosystem model. The hydrology model (Riley and Shih 1973) generated flow of water on the surface and in the subsurface and stream channels. These flows are the principle driving forces of erosional processes. In fact, hydrology is so entwined with the erosion model that the critical paths of water movement are traced through the system in Fig. 1 and 2 up to the point where erosion occurs. Vegetation models, including primary production and succession, may be useful in developing estimates of organic sediment supply to slope and channel areas and to index the factors of rooting strength and ground cover which tend to retard erosion.

MASS MOVEMENT SUBMODEL

The mass movement subprogram of the general erosion model will be emphasized both in this report and during early phases of our modeling effort. We do this because mass movement is a dominant geomorphic agent in steep forested terrain and because to this date models of sediment yield from small watersheds (Li et al. 1973) have virtually ignored this group of processes.

In the development of a general model of erosion on mountainous terrain, it is essential that subsurface movement or soil mass wasting be adequately assessed and described in terms of controlling and contributing factors. This requires, first of all, an identification of important parameters; synthesis of a mathematical model which adequately describes the operation of the process; and final quantification of the identified parameters to allow effective evaluation of the impact of mass wasting on the total erosion cycle.

A review of soil mechanics literature (Taylor 1948; Terzaghi 1950, 1963; Terzaghi and Peck 1962; Zaruba and Mencl 1969) and recent investigations of slope stability problems on forested lands (Swanston 1969, 1970a, 1970b; Swanston and Dyrness 1973; Dyrness 1967; Fredriksen 1965) have provided sufficient insight into the basic problem of soil mass movements to allow identification of major controlling parameters. Using these parameters, an index of mass erosion potential (I) of a forested slope can be developed.

$$I = f\ (\gamma,\ \beta,\ \phi,\ C,\ F,\ R) \qquad (1)$$

where:

- (I) is some index expressing the degree of probability of a mass movement occurrence.
- (γ) unit weight of soil.
- (β) gradient of the failure surface.
- (ϕ) internal friction angle of soil.
- (C) cohesive forces within the soil mass.
- (F) seepage forces within the soil mass.
- (R) tensile forces developed in the soil mass by roots.

With some basic simplifications and assumptions these factors can be synthesized into a working equation.

The first step is to assume a mode of sliding and the operating mechanism. A planar slide on a uniform slope is the simplest mode and can be described mathematically by a simple variation of the classical Mohr-Coulomb Theory of earth failure. In this case an element of slope material is taken as a free body and the forces acting on it analyzed. To do this the following additional assumptions must be made:

1) The slope is very long with respect to the depth (Z) to a potential sliding surface. This is an acceptable assumption for shallow failures of the type which directly contribute to nutrient losses during major storm events; 2) the slope is uniform; and 3) the soil materials

1) The slope is very long with respect to the depth (Z) to a potential sliding surface. This is an acceptable assumption for shallow failures of the type which directly contribute to nutrient losses during major storm events; 2) the slope is uniform; and 3) the soil materials are homogeneous. The first assumption eliminates any end effects due to slope loading and underc utting. The latter two define a slope in which all elements are identical and the stability of each element is the same as all others.

Bell (J. R. Bell, Oregon State University, personal communication) has worked out an equation based on these assumptions which is directly applicable to modeling mass movements. In this equation, the forces acting on a single element in the soil mass are defined as the seepage force (F), the weight (W), the cohesive force developed along the potential sliding surface (C), the normal force transmitted across the potential sliding surface (N), and the tension force in the root system normal to the sliding surface (R) (Fig. 3). At equilibrium, the resultant of these forces is zero. The forces acting on the vertical sides of the soil element are neglected since all elements on the slope are considered identical and the forces transmitted across these surfaces by the soil skeleton are equal and opposite, canceling each other.

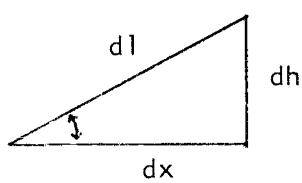
The seepage force (F) acts in the direction of flow and is equal to the hydraulic gradient (i) times the unit weight of water (γ_w) times the volume of soil through which it flows.

$$F = i \gamma_w M Z \, dx \, dy \qquad (2)$$

Where (M) is the portion of the element occupied by the water table or relative position of the water table above the failure surface; (Z) is the depth of soil to the failure surface; and (dx dy) represents the cross-sectional area of the element.

For the uniform flow field, the hydraulic gradient is everywhere equal in the element and is defined as the rate of change of hydraulic head (dh) with respect to distance along the flow path (dl).

$$i = \frac{dh}{dl} \qquad (3)$$



Since velocity head is negligible and at the surface, pressure head is zero, then total hydraulic head is equal to position head.

Therefore,

$$i = \frac{dh}{dl} = \sin \beta \quad (4)$$

and the equation for (F) becomes:

$$F = (\sin \beta) \gamma_w M (Z\, dxdy) \quad (5)$$

Seepage produces the buoyancy effect caused by a rising water table and the development of active pore-water pressures. Thus, the weight force (W) becomes an effective weight (W') and uses the buoyant unit weight of the soil below the water table. Buoyant unit weight (γ') is the mass unit weight (γ) minus the unit weight of water (γ_w).

$$\gamma' = \gamma - \gamma_w \quad (6)$$

W' is thus defined as:

$$W' = \gamma (1 - M) Z\, dxdy + \gamma' (M) Z\, dxdy \quad (7)$$

The strength of the soil is due to a combination of friction and cohesion. Thus, the shearing strength of the soil available (Sa) along the potential sliding surface is equal to the total effective cohesive force (C') plus the effective normal force (N') times the tangent of the effective angle of internal friction (ϕ').

$$Sa = C' + N' \tan\phi' \quad (8)$$

If we let $C' = \bar{c}$ area

Where $\bar{c}$ is the cohesion developed per square foot along the potential sliding surface, then:

$$C' = \bar{c} \frac{dy\, dx}{\cos \beta} \quad (9)$$

If the factor of safety (FS) against sliding is an index of mass erosion potential and defined as the ratio of the shearing strength available (Sa) to the shearing stress required (Sr) to cause failure:

$$FS = \frac{Sa}{Sr} \quad (10)$$

Then the shearing stress required for failure is:

$$Sr = \frac{Sa}{FS} = \frac{C' + N' \tan\phi'}{FS} \quad (11)$$

Summing forces normal to the potential sliding surface it is apparent that:

$$N' = W' \cos \beta + R \qquad (12)$$

This includes the normal component of effective weight ($W' \cos \beta$) and the total tensile force transmitted across the potential sliding surface by the roots (R).

If we let R = r area,

where (r) is the tension developed in the roots per square foot of area along the sliding surface, then:

$$R = r \frac{dx\,dy}{\cos \beta} \qquad (13)$$

Forces producing stress parallel to the potential sliding surface, assuming that the roots have zero bending resistance, include the downslope component of effective weight ($W' \sin \beta$) and the seepage force (F).

Thus:

$$Sr = W' \sin \beta + F \qquad (14)$$

Substituting equations (5) through (13) into equation (14),

$$\frac{C' + N' \tan\phi'}{FS} = W' \sin \beta + F$$

$$\frac{\frac{\bar{c}\,dx\,dy}{\cos \beta} + \left[W' \cos \beta + r \frac{dx\,dy}{\cos \beta}\right] \tan\phi'}{FS} = W' \sin \beta + (\gamma_w \sin \beta\, M\, Z\, dx\, dy)$$

Solving for the factor of safety yields:

$$FS = \frac{\bar{c}\,dx\,dy + [\gamma\,(1-M)\,Z\,dx\,dy + \gamma'\,M\,Z\,dx\,dy] \cos^2 \beta \tan\phi' + r\,dx\,dy \tan\phi}{[\gamma\,(1-M)\,Z\,dx\,dy + \gamma'\,M\,Z\,dx\,dy] \sin \beta \cos \beta + \gamma\,Z\,dx\,dy \sin \beta \cos \beta}$$

$$FS = \frac{\frac{\bar{c}}{\gamma\,Z \cos^2 \beta} + \left[(1-M) + \frac{\gamma'}{\gamma} M + \frac{r}{\gamma\,Z \cos^2 \beta}\right] \tan\phi'}{\left[(1-M) + \frac{\gamma'}{\gamma} M + \frac{\gamma w}{\gamma}\right] \tan \beta} \qquad (15)$$

During major storm periods the water table may reach the surface (M= 1), and the unit weight above the water table (γ) is nearly equal to the unit weight below (γ').

The equation for the factor of safety then becomes:

$$FS = \frac{\dfrac{\bar{c}}{\gamma\ Z\ \cos^2\beta} + \left[1 + \dfrac{r}{\gamma\ Z\ \cos^2\beta}\right]\tan\phi'}{\tan\beta} \qquad (16)$$

When roots are absent (r = 0):

$$FS = \frac{\dfrac{\bar{c}}{\gamma\ Z\ \cos^2\beta} + \tan\phi'}{\tan\beta} \qquad (17)$$

When cohesionless soils are being considered (c = 0):

$$FS = \frac{\tan\phi'}{\tan\beta} \qquad (18)$$

Since γ' and γ are not independent, that is:

$$\gamma' = \gamma - \gamma w;$$

and γw is a constant (unit weight of water), seven variables control stability:

1) cohesion ($\bar{c}$)
2) slope gradient (β)
3) soil friction angle (ϕ)
4) soil unit weight (γ)
5) root strength (r)
6) depth of soil to failure surface (Z)
7) relative position of the water table (M)

Most of these variables can be readily quantified using available data or measured directly using established techniques. Cohesion ($\bar{c}$), the ability of a soil to resist shearing through cementation and clay bonding, and the angle of internal friction (ϕ), a measure of the interlocking of individual soil grains, are both engineering properties obtainable from independent and related standard shear tests performed in the laboratory and field. Slope angle (β) can be readily measured on the site, from air photos or from topographic maps. Soil unit weights are available through local soil surveys or can be measured at the site using simple tests. Depth of soil to a potential failure surface (Z) is a bit more difficult to obtain but can be estimated from drill logs, bore hole monitoring or direct measurement of adjacent landslide scars.

Relative water table position during storm periods (M) and the tensile strength of roots (r) are the most difficult factors to evaluate based on our current state of knowledge. Root strength is probably directly dependent on such variables as species, size and degree of deterioration (Swanston and Walkotten 1969, O'Loughlin 1973). At the present time there is little quantitative data showing how these variables relate to total soil strength. Recently, Wu (1973) has measured the tensile strength of Sitka spruce and western hemlock roots along potential failure surfaces in southeast Alaska and reports an increase in shear strength resulting, equivalent to a cohesion of at least 100 psf, a significant increase.

Water table fluctuations during storm periods are controlled largely by storm intensity, hydraulic conductivity of the soils, geographic and elevational position and surface and subsurface topographic configuration. Local conditions control such variations and an adequate evaluation of this factor requires monitoring of soil water movement and distribution at potential mass movement sites. Eventually some of these parameters may be estimated by adapting and possibly refining the hydrology model to output information on soil moisture status.

SURFACE SOIL EROSION

Surface erosion in forested terrains involves a complex family of sediment transport processes as diverse as dry ravel, needle ice, and overland flow. These processes can be broadly grouped into precipitation and nonprecipitation related categories. The combined effects of surface erosion by raindrop impact and runoff from agricultural lands have received a great deal of study since the early 1940's. The result has been a series of equations relating soil loss to a number of parameters such as soil texture and slope angle and length. Perhaps the best known surface erosion index is Wischmeier's universal soil loss equation for croplands (Wischmeier and Smith 1965):

$$A = RKLSCP,$$

where A is soil loss per unit area, R is a measure of the erosive force of rainfall, K is the soil erodability factor, L is a slope length factor, S equals a slope gradient factor, and C and P are factors related to management procedures. The equation may be simplified to the form (Simons and Stevens 1973):

$$q_s \propto \beta L^a S^b$$

in which q_s is a measure of soil loss per unit length of slope, β indexes soil erodability, L and S are slope length and gradient factors, and a and b are empirically determined exponents. Amplifying on the basic relationships, Meyer and Wischmeier (1969) have developed a working mathematical model for surface erosion.

These equations have been developed by observation and theory to deal specifically with soil loss from fallow fields by overland flow transport. Observations in western Oregon indicate that overland flow almost never occurs on undisturbed soils. Surface erosion generally takes place from sites which have been disturbed by either natural processes or man's activities. These situations include exposure of bare mineral soil by mass movements, severe burning, logging, and road construction. In the latter two cases compaction may also lead to decreased infiltration rates and a consequent increased probability of overland flow and runoff generated erosion. It will therefore be necessary to include disturbance history as an aspect of the erodability or management procedure factors used in our modeling of surface erosion. Pertinent information on the recovery of disturbed sites is available through Dyrness' observations of secondary succession on mass movement scars, cut banks, and logged and severely burned areas for the past 5 to 10 years.

An additional factor not incorporated in classical soil loss studies is that on steep slopes (80 percent) of bare mineral soil surface erosion occurs largely as dry ravel (Mersereau and Dyrness 1972). Although quantitative features of the published soil loss equations are not directly applicable to the mountainous terrain of the western states, the basic sense of relationships among parameters in the equations will hold true in all regions and for both wet and dry processes of surface erosion. We expect that data reported by Mersereau and Dyrness and collected in current erosion monitoring studies by Glenn, Dyrness, and Sedell will allow us to adapt Meyer and Wischmeiers' (1969) model to simulate nonprecipitation related surface erosion.

Input data to the surface erosion submodel will include slope gradient and length, soil properties (infiltration rate, water stable aggregation), vegetation and soil disturbance history, and vegetation cover. Link ups with other models include generation of overland flow in the hydrology model, percent vegetative cover from manipulation or succession models, and the occurrence of mass movements from that subprogram of the erosion model.

STREAM CHANNEL EROSION

The preliminary conceptualization of the stream channel submodel is presented to stimulate interest and input from related modeling groups. The stream channel is considered as a storage area for organic and mineral debris derived from upstream channel areas, adjacent hillslopes, and in the case of organic matter, by direct litterfall and blowdown into the channel. The fate of organic residues in first- and second-order streams is also of critical importance biologically, since these stream systems are essentially heterotrophic ones dependent upon organic residue input for nutrients (J. R. Sedell, J. D. Hall, and F. J. Triska, Oregon State University, personal communication). These relationships are shown in Fig. 4.

The figure also indicates that the channel may be divided into segments so that sediment transport can be visualized as a downstream cascade from one channel unit to the next. Channel segment boundaries are set at confluences, points of change in channel geometry (gradient and cross-sectional profile) and/or at the boundaries between hillslope mapping units. A tight linkage between hillslope and channel areas is extremely important in situations where mass wasting events can greatly influence channel conditions either instantaneously or by the processes of slow earthflow and creep.

Organic and mineral debris are divided into coarse and fine fractions to distinguish fine material transported by annual high discharge events from sediment which is so coarse that it can be flushed from the channel only by catastrophic debris torrents. For first- and second-order streams the cut-off point is assumed to be an intermediate diameter of about 10 to 30 cm. Both organic and mineral matter can be transferred from coarse to fine categories by various in situ processes of breakdown, including organic matter decomposition and desiccation and freeze-thaw fragmentation of large stones, especially altered tuffs.

Fine material in the channel is transported downstream in suspension and as bedload by high streamflow events which occur on an annual basis. These processes have been modeled by Riley et al (1971), Simons and Stevens (1973) and others, necessarily using some rather restrictive assumptions. However, there is an important complicating factor in the steep forested watersheds of the Pacific Northwest. In this region the transportability of fine sediment and, therefore, the storage capacity of a channel segment are greatly dependent upon the amount of coarse organic matter (logs, large limbs, roots) available for construction of natural debris dams in the channel. Debris dams tend to grow and accumulate fine and coarse sediment until they are cleared from the channel by a debris torrent. It is unlikely that individual debris dams can be modeled, but it should be equally useful to account for debris accumulation on the basis of volume and/or mass per 100 meters of channel length. Froehlich et al (1972) and Lammel (1972) have collected this type of data on a number of streams in the Lookout Creek drainage and elsewhere in western Oregon.

All categories of material which have accumulated in a channel may be removed by debris torrent events during periods of extremely high flows. Debris torrents can be triggered by failure of debris dams which have accumulated in the channel over long periods of time or formed rapidly as the result of a mass movement from a hillslope area. For the purposes of modeling debris torrents can be treated on a probability basis. Field observations indicate that the probability of occurrence increases with increasing hillslope instability, amounts of stored sediment and peak discharge. Sediment age also may be significant if logs are decomposed to the point of losing strength. Recurrence intervals of debris torrents are therefore related in a complex way to hydrologic, geomorphic and vegetative factors within a watershed.

The stream channel submodel will draw information from several other sectors of the general ecosystem model. The hydrology model can supply discharge data for whole watersheds or portions of them. Rates of organic matter accumulation may be estimated from vegetation models. The stream model described by the Stream Systems Group (1972) deals with the decomposition transfer in the erosion-channel submodel. Froehlich's work on the status of debris in the stream environment will also form an important input to the channel erosion model.

MODEL USES

Application of the model to "real world" situations will be guided by the practical questions of (1) the predictive strengths and weaknesses of the model, which depend on our ability to determine critical parameters, and (2) the types of uses to which the model will be put.

At this time the expected uses of the model are limited only by our imaginations. We can foresee academic experiments to examine sediment routing through watersheds under various vegetation and landform conditions, especially those situations involving the effects of land management practices. Such experimentation and the data base collected during model development should add substantially to our overall understanding of erosion from forested watersheds. This knowledge is needed for the evaluation of relative rates of soil formation by rock weathering and soil loss by erosion.

It is also apparent that a greater appreciation for interconnection among nutrient cycling, soil formation and soil loss is needed if there is to be an ecologically and geologically integrated approach to sustained yield forestry, the control of stream pollution, and other land management problems. For example, concern with water quality only as an evaluation of nutrient losses from watershed ecosystems may overlook the geomorphological context in which streams are situated, and explicitly tends to ignore adequate long-term management strategies for forest soils. In particular, successful sustained yield management is predicated on the assumption that soil loss is not accelerated beyond the rate of soil formation. The present erosion model is designed to integrate various soil erosion and mass wasting processes in an open ended context, which, combined with concurrent nutrient cycling studies, will allow us to evaluate such assumptions. This synthesis should be of use to federal and state agencies such as the U. S. Forest Service, Bureau of Land Management, Soil Conservation Service and Environmental Protection Agency as they develop comprehensive approach to the great diversity of land management and stream pollution problems.

Model output for land management purposes may take several forms. Maps may be developed to show surface erosion and mass movement susceptibility of various areas within the landscape under study. With information mapping of this type it will be possible to test the effects of various roading and logging schemes.

It also may be worthwhile to do probabilistic model studies of episodic events to examine the consequences of storm events of known probability of occurrence on manipulated areas in various stages of revegetation. On a regional scale, such studies may be used to predict environmental degradation by mass wasting on the basis of storm frequency and period of cutting rotation. Management practices are an important consideration because there is increased susceptibility to mass movements during the period of minimum rooting strength about five to fifteen years after clearcutting (Swanston 1969, Nakano 1971). For a cutting rotation of Y years this means that at any one time $\left(\frac{10}{Y} \times 100\right)$ percent of an area under sustained yield management will be especially sensitive to shallow soil mass movements. Therefore, if extreme storm events of reasonable probability of occurrence would create a severe erosion problem under a Y year cutting rotation, it may be necessary to extend the period of time between cutting of a given site.

Model studies are expected to facilitate management decisions concerning areas ranging in size from individual logging units to a regional scale and over temporal dimensions ranging from the first few years of early succession to the time scale of cutting rotations or the course of several natural successional sequences.

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FIG 1 EROSION MODEL
Showing essential linkages among landscape compartments and among the vertical strata (vegetation, slope surface, slope subsurface) within a compartment.

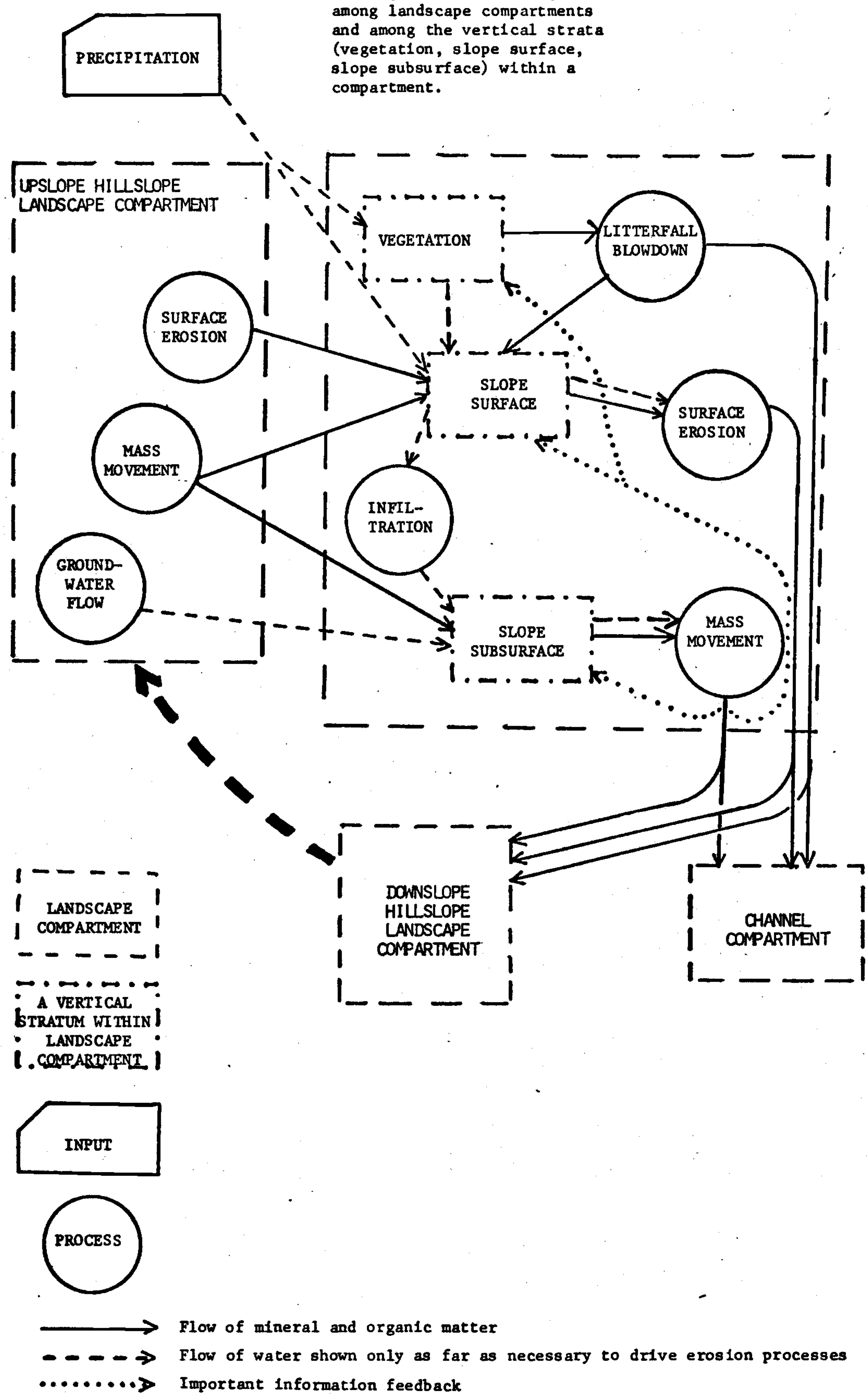
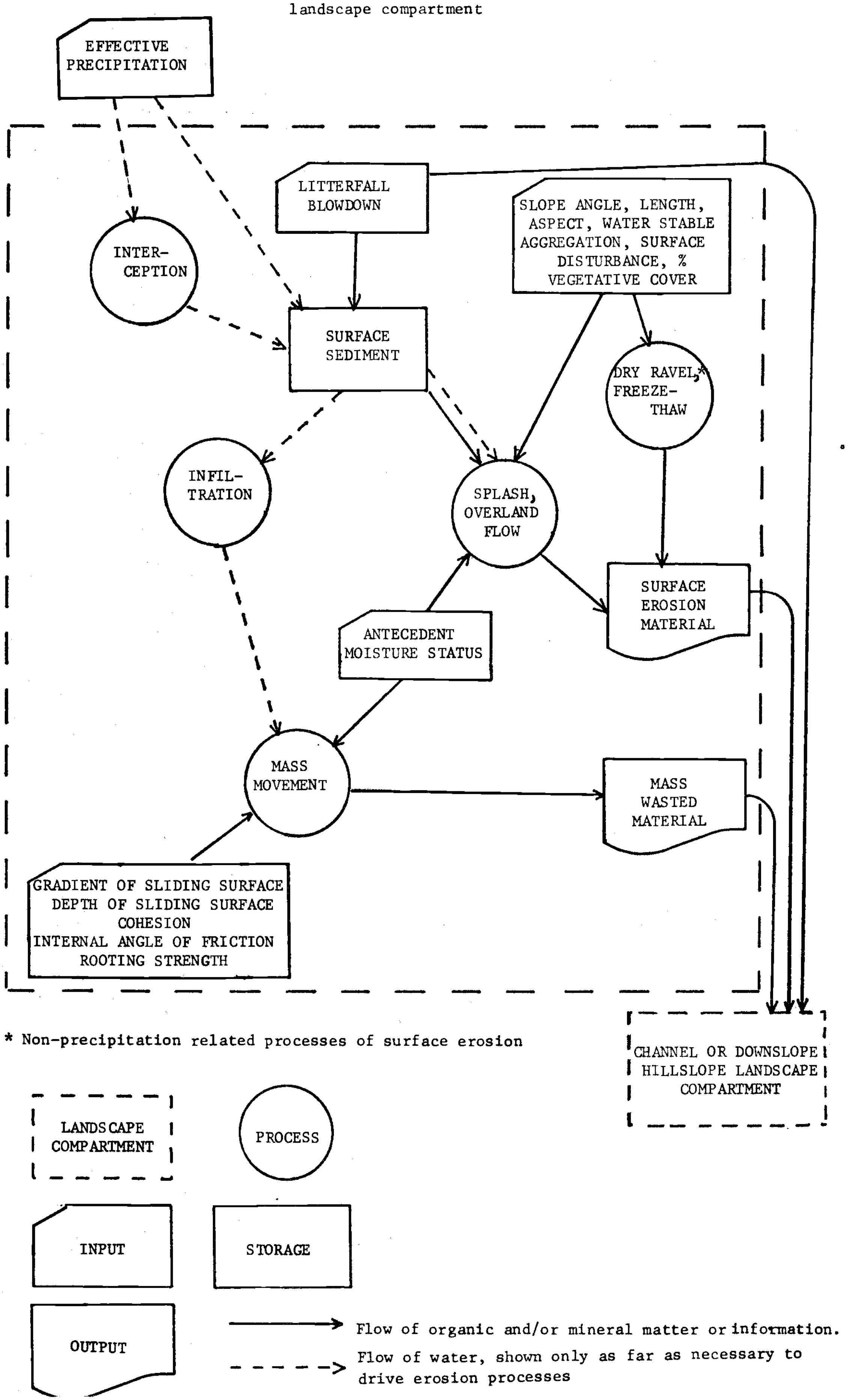


FIG. 2 EROSION MODEL
Showing detail of inputs
and processes within a
landscape compartment



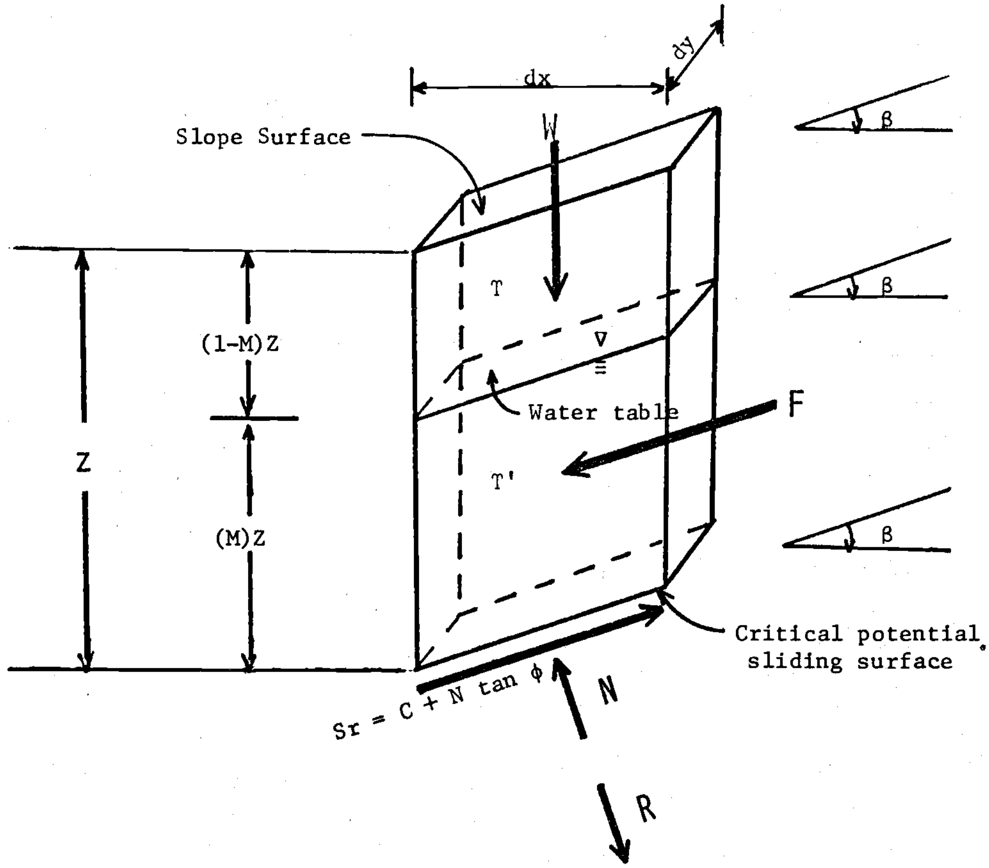
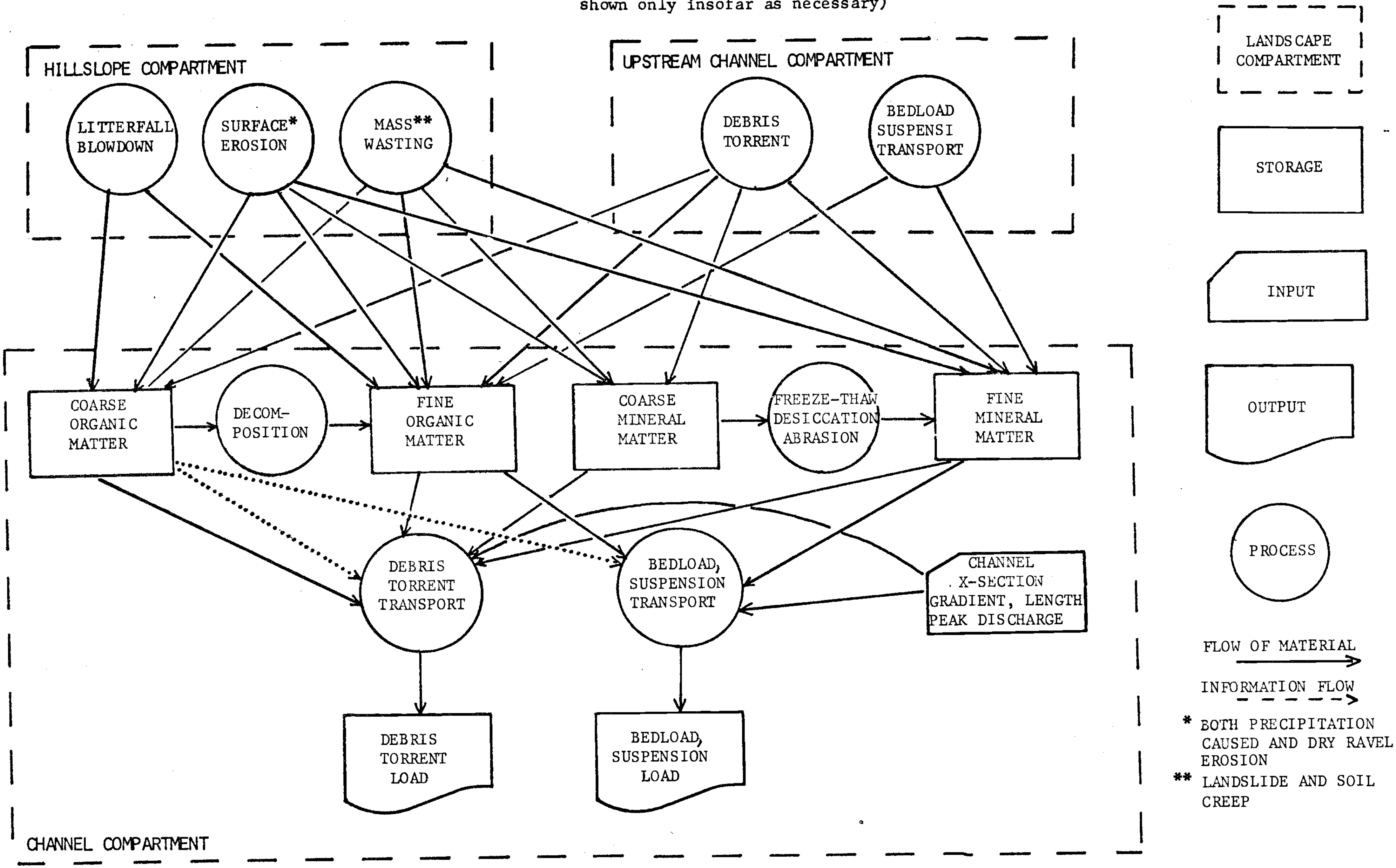


FIG. 3 SLOPE ELEMENT FREE BODY DIAGRAM, where (W) is the weight of the element; (N) is the normal force transmitted across the potential slide surface; (R) is the tension force in the root system normal to the sliding surface; (F) is the seepage force; and (C) is the cohesive force developed along the sliding surface. The slope gradient is defined by (β) while (ϕ) represents the angle of internal friction of the soil. The depth of the soil element (Z) is divided into two units described as (M) and (1-M), where (M) represents the portion of the element occupied by the water table. The equation: $Sr = C + N \tan \phi$, defines the shearing resistance required in the soil along the sliding surface to maintain the soil in place.

FIG. 4 STREAM CHANNEL MODEL

(Detail of input landscape compartment shown only insofar as necessary)



Oct. 3, 1973