MAKERERE UNIVERSITY

COLLEGE OF AGRICULTURAL AND ENVIRONMENTAL SCIENCES,

SCHOOL OF FORESTRY, ENVIRONMENTAL AND GEOGRAPHICAL SCIENCES

DEPARTMENT OF GEOGRAPHY GEO-INFORMATICS AND CLIMATIC SCIENCES

GEO 3204

ADVANCED GEOMORPHOLOGY

STUDY GUIDE

COURSE INSTRUCTOR
Nseka Denis Galende

MARCH 2023

Welcome to this course

I greet you all and hope that you are doing well. I take this opportunity to welcome you to this course of Advanced Geomorphology (GEO 3201). This course is intended to equip you with more advanced knowledge and applications of geomorphology discipline in land resource assessment, land use design and environmental management. The course therefore aims at rigorous applications of geomorphology to contemporary problems in environmental management and natural resource utilization. This is aimed at skilling you to be an elicit environmental expert, land use planner and designer, disaster and hazard management expert, landscape ecosystem and biodiversity expert, water resource expert, soil and water conservation expert, landscape expert, etc. The course builds on the knowledge and skills you acquired from Geomorphology course (GEO 2101) during your second year of study. In this course, we will put more attention on slope and fluvial geomorphic landforms and processes operating thereof, to capture the dynamics of human-environmental relationships and geomorphic challenges and opportunities of natural resource utilization on such landscapes. In order for you to understand how landforms and landscapes evolve, modern approaches to geomorphological study will be mostly used. As you will notice, there will be significant departure from evolutionary approach to a dominantly process-response approach.

The final grade in the course will be made up of discussions, individual and group assignments, tests and a final exam at the end of the course. In order to pass this course, you will need to participate in the discussion topics by posting in the course forums to fulfil the requirements for the course. There are discussion activities that provide learners opportunities to learn from the work of their peers and discuss issues in working with their assignment. There are both group and individual assignments that generally require learners to examine a range of aspects of Advanced Geomorphology. This study guide will be followed throughout the entire course. The study guide provides participants with detailed learning outcomes, tasks, activities, time plan and learning resources.

As you can see from the study guide, much emphasis is put on your ability to collaborate in groups. Collaboration is much easier when everyone has an online identity. For that matter, Unit 0 has been designed in which you will be required to introduce yourself to others and also add a photo of yourself for your group members to see you. You will be in groups for effective participation. You will also be required to have a personal folder. This is where you will be uploading your individual hand-ins.

Contact the tutor(s) if you have any questions.
Enjoy the course

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Course overview

Aims

The aim of this course is to introduce you to the application of geomorphology in land use planning and environmental management. This course is intended to equip you with more advanced knowledge and applications of geomorphology discipline in land resource assessment, land use design and use and environmental management. The course therefore aims at rigorous applications of geomorphology to contemporary problems in environmental management and natural resource utilization. This is aimed at preparing you to be an environmental manager, land use planner and designer, disaster and hazard management expert, landscape ecosystem and biodiversity expert, water resource expert, soil and water conservation expert, landscape expert, etc.

Learning Outcomes

By the end of this course you should be able to;

- Demonstrate the role of models and theories in geomorphic processes, slope morphology and landscape development.
- Apply geomorphological knowledge in natural resource and environmental management as well as mitigation of natural hazards and disasters.
- Analyze the applicability of land use planning in relation to geomorphic landforms and processes.
- Measure geomorphological and environmental process.
- Develop land capability and suitability classifications

Course assessment

- The course assessment comprises both coursework assessment and final examination.
- Coursework assessment will be given as from the following alternatives.

a) An essay on a pertinent geomorphological issue based on library research and other sources of information and experience will be done.

b) Fieldwork excursion. A compulsory and guided fieldwork will be conducted in the highland geomorphological landscapes of southern and south western Uganda. The fieldwork excursion will cover the peneplains or erosional surfaces of Uganda as described by Wayland (1935). Specifically the landscapes of Buganda, Masaka-Kooki, Ankole and Kigezi highlands will form the basis of this field excursion. The study will focus on structural morphology, fluvial processes, erosion processes, landslide hazard ch aracterization, drainage patterns, stream and channel dynamics, the impacts environmental change and many other geomorphological aspects of the region. The cost for fieldwork (Transport, accommodation and meals) will be met by the students. A group fieldwork report will be written after the exercise.

(c)A coursework examination lasting for 1 and ½ hours.

A written examination will be given during the last 3 weeks of the semester. Coursework and examination will account for 30% and 70 % of the final grade respectively. Pass mark is 50%.

COURSE CONTENT

1. MODERN APPROACHES TO SLOPE STUDIES

1.1 Concepts in modern slope studies- slope morphology and processes

1.2 Weathering limited and transport limited slopes; applications of the concepts.

1.3 The influence of soil depth on bedrock weathering and slope development.

2. MODELS OF SOIL COVERED SLOPES.

2.1 Models of slope development- Evolutionary, analogue and mathematical models e.g., analytical and simulation approaches; and the nine unit hypothetical land-surface model.

2.2 The equilibrium theory of slope development, negative feedback mechanism and processes response model.

3. ENERGY SOURCES FOR DEBRIS TRANSPORTATION ON SLOPES

3.1Gravity derived energy:-the downslope and perpendicular components

3.2 Climate derived energy, and evaluation of the role of water on slopes.

4. DEEP CHEMICAL WEATHERING OF THE TROPICAL REGIONS AND LATERIZATION

4.1 Dominant weathering and erosion processes under high temperatures and humidity and their environmental and development implications.

4.2 Weathering and erosion processes in dry sub-humid, semi-arid and arid lands and environmental implications, resulting landscapes,

4.3 Weathering products such as sand, gravel, and clays.

4.4. The concept and implications of deep weathering in tropical regions, laterization and laterites in the humid tropical regions and resulting landscapes; occurrence and significance of laterites with special reference to the East African region.

5. SLOPE STABILITY ANALYSIS

5.1 Slope material strength and slope stability analysis: Analysis of occurrence of slope instability and classification.

5.2. Mass- movement processes and slope instability-

Landslides and related phenomena (landslips, soil slips, mudflows, rockslides, ground subsidence) controls and mechanics of the processes; implications to environmental design and management.

5.3. Disastrous Geomorphological processes (natural hazards), types of natural hazards; slope failure and subsidence, assessment, detection and prediction of impending geomorphologic hazards, prevention of occurrence and protection from occurrence.

5.4 Safety factor analysis: Computation of the safety factor (Fs) on slopes: Interpretation and application of safety factor values for land use planning, Natural resource and environmental management

6. HYDRO-GEOMORPHOLOGY OF DRAINAGE BASINS AND SLOPES.

6.1. The concept of drainage basin; definition and structure, the unity of the drainage basin and applications to modern ecosystems study and environmental management, assessment, prediction of processes and impacts.

6.2 The historical, modern and economic perspectives/ importance of drainage basins.

7. QUANTITATIVE ANALYSIS OF DRAINAGE BASIN PROCESSES

7.1 The process of infiltration; its operations and mechanics

7.2 Characterizing the controls of infiltration processes

7.3 Examination of the Infiltration Curve/Equations

7.4 Measurements of infiltration using infiltrometers

7.5 Runoff processes and mechanics

7.6 Characterizing the processes that produce storm runoff including; Horton overland flow; Subsurface flow; Return flow; Direct precipitation onto saturated area.

7.7 Analyzing the controls of runoff processes, implications and management.

7.8 Runoff in Regions of High Infiltration and its implications

8. SOIL EROSION PROCESSES, CONSERVATION AND SLOPE DEVELOPMENT

8.1 The processes of soil erosion on slopes, types of erosion (inter-rill, rill and gully erosion)-factor controls and dynamics; measurements of soil erosion.

8.2 Soil conservation techniques and practices; impact of soil erosion/ slope erosion on slopes, agriculture and infrastructure; soil erosion control in environmental management.

9. TECHNIQUES IN GEOMORPHOLOGICAL AND ENVIRONMENTAL PROCESS INVESTIGATIONS

9.1 Techniques in slope morphology measurements e.g. slope gradient, length, direction measurements and geomorphological mapping.

9.2 Measurements of slope material strength and slope stability (e.g. soil creep, landslides)

9.3 Measurements of channel processes e.g. sediment transport, flow velocity and hydraulic variables.

9.4 Hydrological and energy balance measurements; infiltration and runoff measurements, soil erosion measurements (indices of rainfall erosivity and soil erodibility, sheet and gully erosion measurements) stream flow and erosion measurements.

Topic 1a: Modern Approaches to Slope Studies

Topic learning outcomes

Upon completion of this topic, you should be able to:

1. Understand the different slope morphologies and processes commonly found on slopes.
2. Apply the relevancy of weathering and transport limited conditions in the transportation and accumulation of materials along the slope profile

1.1 Introduction to the topic

Dear reader, in this first lecture I will introduce you to landforms that occupy our earth's surface. A landform is a distinctive feature on the earth's surface which can be of whatever size. Landforms may vary from very small ones (e.g. anthills) to larger ones like mountains. In this course, however, particular attention will be given to one landform called a slope or hillslope. The reason as to why we shall focus on slopes is because they are the most numerous landforms found almost everywhere. Whereas certain landforms e.g. mountains, escarpments, gorges, cliffs etc., may only be found in specific areas and therefore not easy to see every day, slopes are found everywhere including where you live, farm and work.

Now; what is a slope? For simplicity, a slope can be considered as any landform with one part or section raised higher than the other. In other words, a slope has a higher section and a lower section. It can also be considered as any landform which allows water to flow from one section to another. A slope can also be regarded as a feature or landform with a gradient or an angle of inclination. You can also consider a slope a measure of steepness or elevation of the earth's surface relative to the base level. Therefore, any feature for which you can measure its gradient or angle of inclination can be considered as a slope.

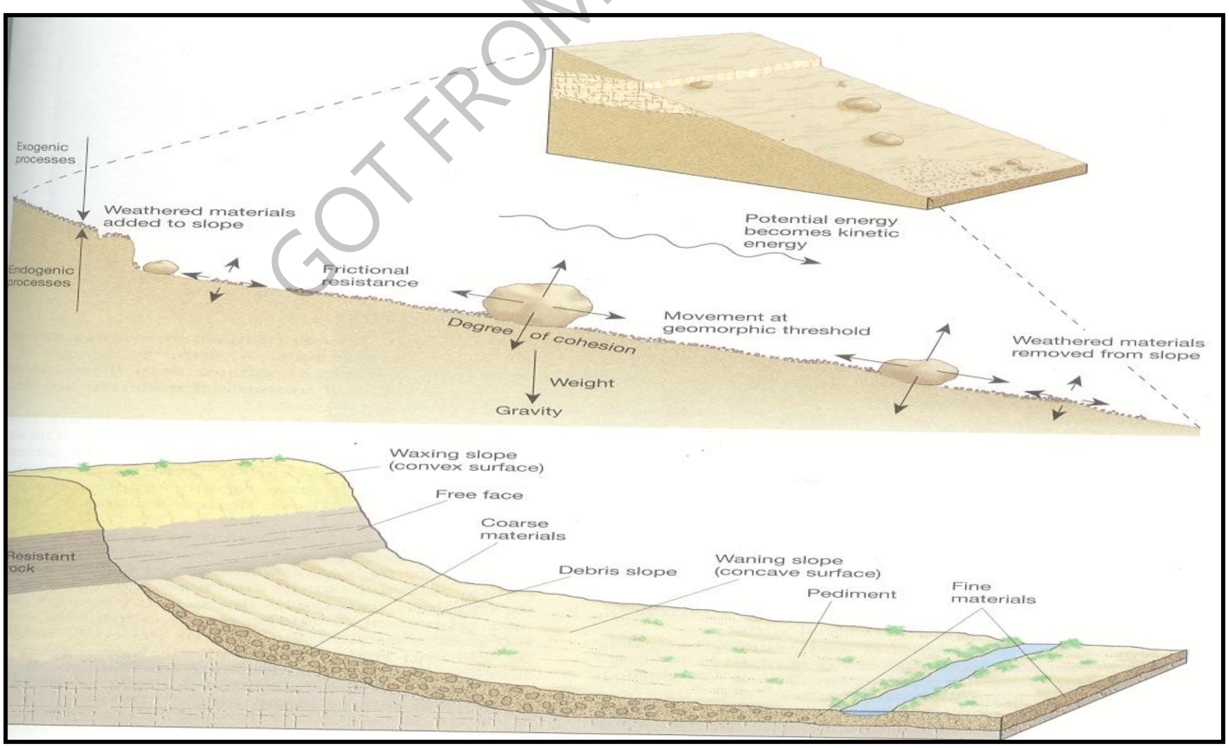
This clearly shows that everywhere on the earth's surface, there are slopes. In the same token, all landforms on the earth's surface can be considered as slopes. We can therefore classify the slopes into 3 categories based on their altitude, size and gradient and these can be; steep, gentle and low lying slopes. Conclusively therefore, if you look around where you are, you will notice that you are on slope or even between slopes. So, in which class is your slope? Is it a steep slope? Or a gentle slope? Or is it a low lying slope? And why do you think so?

I. 2 Slope morphology and processes

Having introduced ourselves to the concept of a slope, and having considered a slope as a surface that lies at an angle to the horizontal such that some parts on it are higher than others, let us now consider the morphology of the slope. Slope morphology refers to the structure, appearance, nature or shape of the slope.

If you consider a slope from the valley bottom to the ridge top, what appearance do you get? Or how does it look like? In simple terms, slope morphology describes how a given slope or landform looks like or appears from the lower sections to the upper most sections. Slope morphology reflects the nature of the slope-forming materials, the environmental factors that govern processes on inclined surfaces, and the history of specific landscapes.

Slopes come in a variety of morphologies that reflect the processes shaping them. In profile, hillslopes may be convex, straight, or concave. When you consider a slope from the valley bottom to the top most parts, a slope can be convex, concave or remnant and terraced or with benches. Slopes or hillslopes are curved, inclined surfaces that bound landforms. Slope forms vary with conditions of rock structure and climate. Slopes generally feature an upper waxing slope near the top. This convex surface curves downward and grades into the free face below. The presence of a free face indicates an outcrop of resistant rock that forms a steep scarp or cliff.



There is a large amount of evidence to suggest that even if not all, slopes possess round convex summits and are separated from the stream channels at their bases by shallow concave elements.

Convex slope segments commonly occur in the upper parts of soil-mantled slopes, as near the drainage divide. The processes of soil creep and raindrop splash erode soil on the upper parts of slopes. Since soil eroded from the upper slope must pass each point below it, the volume of soil moved increases with distance from the divide. Since the transport rate for creep and rain splash is proportional to the slope angle, the slope angle must also increase from the divide, resulting in the slope convexity.

Straight slope segments are dominated by mass movement processes. Talus slopes are a type in which debris piles up to a characteristic angle of repose. When new debris is added to the slope, thereby locally increasing the angle, the slope adjusts by movement of the debris to re-establish the angle. Again, the result is a dynamic equilibrium in which the landform adjusts to processes acting upon it.

Concave slopes are especially common where overland-flow runoff transports sediment derived from upper slopes. In addition, the size of particles being transported decreases downslope because of weathering and abrasion, because the finer particles are easier to transport, slope angles can be reduced in the downslope direction. The result is a concave shape to the slope profile.

In tropical humid regions, soil-mantled slopes generally steepen downslope from convex ridge tops at drainage divides. They also typically have a planar midslope segment with a constant angle, and a concave basal zone at the bottom of the slope. Straight portions of slope profiles are typically more pronounced in steep terrain where frequent landslides plane off topography in the mid-slope zone.

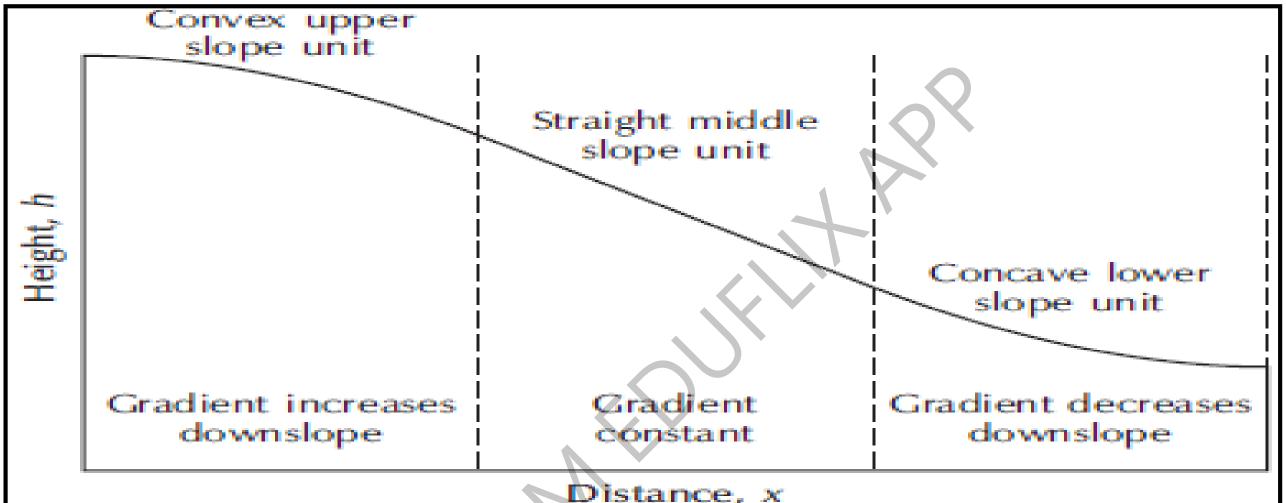
In map view, slopes are described as convergent, divergent, or planar. On convergent slopes, flow lines converge downslope, and divergent slopes are those where flow lines diverge downslope.

The general topographic form of soil-mantled slopes reflects the processes acting to shape them. Slope processes generate divergent, planar, or convergent topography, depending on the predominant erosional and depositional mechanisms.

The diffusion-like action of creep and sheet wash creates zones of hilltop convexity and divergent noses on soil-covered hillsides. Long, planar slope segments common in steep, rapidly eroding terrain reflect the influence of landslides, but landslides also create relief where they incise mountain sides and excavate new valleys.

The main slope can be anything e.g., (i) a vertical cliff, (ii) a debris-mantled slope; or (iii) a smoothly concave, rill-dissected scar. It is considered as that slope section between the upper and lower concave slope zones

The mix of convergent, planar, and divergent terrain in a landscape reflects aspects of its geomorphic setting. Narrow hilltop convexities and long planar slopes are typical in rapidly uplifting and eroding terrain. Broad, rolling hills generally reflect slower uplift and erosion rates.



Processes on slope sections

The upslope convexity and the concave base are both products of processes that are essentially ***transport-limited.*** Here creep and depositional processes are most important. The upslope convexity stems from a combination of weathering, creep and rain splash. Most materials that are splashed at the top are convex in nature.

On a flat surface water takes vertical movement into the soil and at the top of the slope this soil saturated with water begin to creep downwards forming a convex shape. It is the weathered materials on the top that creeps and not the rocks. And when they creep, they form a convex shape.

Soil creep is the downslope movement of soil and sediment under the influence of gravity by processes that are too slow to see without instrumental measurements or other indicators of long-term movement. The term incorporates a wide range of processes that include; seasonal heave from ice or expanding clays, downslope movement of soil from the burrowing activity of animals and material displaced downhill by uprooted trees.

Downslope creep rates are quite variable, and depend on slope angle, climate, soil moisture content and particle size, but they rarely exceed a few millimeters per year. Creep rates typically decrease with depth below the ground surface and most displacement happens within about a half meter of the surface.

Evidence of active soil creep often includes such indicators of net downslope movement as tilted fence posts, pistol-butted trees, cracked building foundations and accumulation of soil on the upslope side of fixed obstructions.

The concave base is from retreat, surface wash and solution. It may also be a depositional feature. The remnant is a result of limited weathering processes. If transport is more rapid than weathering, a thin soil is left and movement is said to be weathering limited. If weathering is faster than transport, then it is transport limited.

The concave base appears to result from retreat (not necessarily at unchanged angle) of the valley side slope, through surface wash and solution. It may also be partly or even wholly a depositional feature.

The remnant part of the slope profile between the upslope convexity and the concave base on the other hand, is primarily a reflection of ***weathering limited*** processes, particularly instability movements. The term **main slope** is used for this part between upslope convexity and the basal concavity.

Using a deductive procedure, one can argue that slope development is perhaps most profitably approached by separate analysis of: (a) the form; (b) the behavior of the main slope. The moment there is a steep slope, it induces movement of materials on the top. The materials down the slope have a relationship with those on the top.

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TOPIC1b: Transport-limited and weathering limited processes and slopes

Slopes or landforms are never static but constantly changing over time. Whenever, they change, we say they have developed. Slopes can change through an increase or a reduction in size. The change in size or appearance is brought about by the removal or addition of materials onto a given slope section. A slope section can either gain or lose materials depending on the availability of energy to transport materials from it.

On some slope sections, there is a lot of energy available to move materials by running water or gravitation forces, while on some slope sections, the energy is low. This energy ultimately depends on the gradient or slope angle which determines the speed and power of running water and the forces of gravity.

Sections with steep slope angles will normally experience high energy levels both from running water as well as gravity. Such sections will experience a lot of material removal due to high transportation rates. On the other hand, sections with low gradient normally have low energy levels from both running water as well as gravity. They experience less removal of materials due to low transportation rates.

On a slope therefore, there are sections which experience high transportation rates due to the steep gradient (e.g., along the main slope). On such sections, every available material is transported as soon as it is weathered down. They limit weathering processes and are thus referred to as weathering limited.

On the flat or gentle sections (e.g., the bottom valley with concave shape and the upper top most section with convex shape), however, there is less energy to transport materials due to low gradient. Such sections experience less transportation of materials and are thus referred to as transport limited sections.

On weathering-limited slopes, transport processes are so efficient that debris is removed more quickly than it can be generated by further weathering. Such hillslopes develop a faceted or angular morphology in which an upper free face, or cliff, contributes debris to a lower slope of accumulation. Slopes of this sort are especially common on bare rock where the profile of the slope is determined by the resistance of the rock, not by the erosional processes acting on it.

One consequence of this is that many rock slopes retreat parallel to themselves in order to preserve the characteristic slope angle for a rock type of given strength. If the features of the rock change with depth into the slope, however, the characteristic angle of the slope will change. Rock slopes develop where weathering and soil erosion are slow (as in arid regions) and where rock resistance is high.

Transport-limited slopes occur where weathering processes are efficient at producing debris but where transport processes are inefficient at removing it from the slope. Such slopes lack free faces and faceted appearances, and they are generally covered with a soil mantle. The profile of this type of slope generally has a sigmoid appearance, with convex, straight, and concave segments. The shape of the slope is an expression of the process acting upon it.

The main difference between the weathering and transport limited slopes is soil or sediment cover. Areas with an abundance of weathered material just laying around are transport limited surfaces whereas areas with no sediment laying around are weathering-limited. On the weathering limited areas (see figure), the rock is too steep for the weathered material (sand grains) to collect.

The sand that weathers away from the rock face falls or is somehow transported down to the transport limited area. Here (in the valley floor and along the base of the scarp), the rate of erosion is less than the rate of sediment production. Erosive processes (running water, wind) can't keep the sand "swept away" in the flat topographic Hollows (valley floor) like it can on the steeper rock surfaces (along the steep faces of rock).

These two slope conditions are further explained below using the following statements;

(1) Processes have most commonly been classified by the way in which the debris moves, and their names reflect this classification. For landscape development, however, a more important distinction is based on immediate source of moving debris.
(2) Material is loosened from the hillslope bedrock by weathering, and moved downslope by transport processes. Where transportation processes are potentially more rapid than weathering, only a thin soil cover is able to develop because debris is removed as fast as it weathers loose. Movement is then said to be weathering limited. However, if instead, weathering rates are potentially more rapid than transport processes, a soil cover develops and the movement is said to be transport limited. This dichotomy is basic to understanding of hillslope development, and was first described by Gilbert in 1887.
(3) Where removal is transport-limited, then the hillslope development depends on the transport capacity of the relevant processes and the rate of weathering is reduced to an equilibrium value which is less than its potential maximum by an increase in soil thickness.
(4) Where the removal is weathering-limited, the hillslope development depends on the variations in weathering rate, and the rate of transport is reduced to the rate at which fresh material weather.
(5) These quite different sets of clouds lead to quite different sequences of slope development, and there is a general association between weathering-limited slopes, relatively thin soils, the existence of important threshold slope angles; and between transport-limited slopes, a well-developed soil cover, and convexo-concave slopes, which become progressively less steep without significant threshold slope angles. The extent to which the explained associations occur and the causes need to be discussed individually.

If you have more materials arriving at a point than it is going away, then it becomes a transport limited slope because there is less energy. If you have fewer materials at a point than is going way, then the process is weathering limited.

Transport-limited slopes have soil production rates that equal or exceed rates of sediment transport, a condition that results in the development of a persistent soil mantle. There is enough transportable material available on these slopes than the transport capacity of erosional processes governs the rate at which sediment leaves the slope.

Transport-limited slopes are less influenced by the properties of the underlying bedrock and more strongly controlled by soil properties. Consequently, the smoothly convex to planar form of soil-mantled slopes typically masks variations in the underlying rock type as well as bedrock structures like folds, joint patterns, and fault scarps.

The distinction between weathering-limited and transport-limited slopes generally corresponds to differences between bedrock and soil-mantled slopes, respectively.

Weathering and sediment transport both affect slope morphology. At one extreme, **weathering-limited slopes** (also called production-limited slopes) have net rates of sediment transport that are determined by the rate at which weathering provides new materials.

On these slopes, soil erosion rates generally match rates of soil production, so weathered material is transported downslope about as rapidly as it is produced. These slopes tend to be bedrock slopes with thin soils. The steepness of weathering-limited slopes is generally controlled by rock mass strength, and slope morphology is often closely related to the underlying rock type.

The properties of bedrock slopes with little to no soil are strongly influenced by material and strength properties of the bedrock itself. On many bedrock hillslopes, the angle of the slope depends on the relative resistance of the underlying bedrock. Harder rocks form steeper slopes; weaker rocks form gentler slopes.

Where slopes are formed by inter-bedded strong and weak rocks (sandstone and shale, for example), variability in erosion resistance commonly produces the stair-stepped morphology typical of arid and semi-arid landscapes. Rock slopes are typical of arid and semi-arid landscapes, but are found only as steep cliffs in temperate and humid landscapes where weathering maintains a soil mantle on most slopes.

To summarize the two types of slopes,

- Weathering-Limited Slopes: Rates of soil/regolith production are less than rates of erosion
- Transport-Limited Slopes: Rates of weathering and deposition are more rapid than rates to transport

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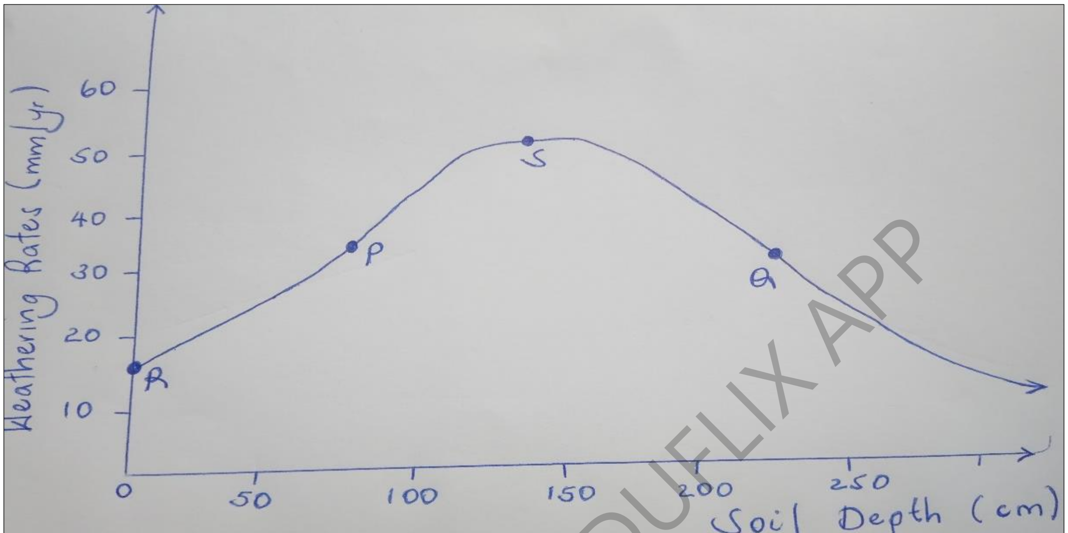
TOPIC1c: Influence of soil depth on bedrock weathering

The following is an illustration of the influence of soil depth and bedrock weathering in slope development processes.



The diagram illustrates that weathering of bedrock at the base of a soil depends mainly on the circulation of water. The following relationships apply;

(a) In very thin soils (e.g., point R), water runs off rapidly because there is insufficient pore-space in the soil to accommodate it, so that weathering rates are low;
(b) In very thick soils (e.g., at point Q) water circulates so slowly that the rates of weathering are again low. Therefore, soil weathering is at maximum at intermediate soil thickness, a concept first developed by Gilbert in 1887.
(c) In the diagrammatic illustration, the shape of the soil thickness-rate of weathering curve is very important because the behavior of soils to the left and right of the peak is quite different as follows;
(d) If a soil represented by point Q has a local increase in soil depth due to for example, animal burrowing activity, then this soil increase will cause a reduction in the rate of weathering at that point.
(e) If weathering is in balance with transport processes, then the reduction in the rate of weathering will lead to a thinning of the soil which will lead to tendency of obliteration of the original increase in soil depth. This is a stable situation in which small local irregularities tend to be eliminated.
(f) In contrast at point P, to the left of the peak of weathering curve, a small increase in the soil thickness (increase in weathering rate) and the soil situation is unstable, only reaching equilibrium at point S.
(g) Likewise, a small local decrease in soil depth will lead to instability in the opposite direction reaching equilibrium at a point R, under conditions of ***zero soil depth.***

(h) In this way, the whole of the left hand side of weathering curve, between points R and S, is unstable, and soils tend to polarize either towards no soil at point R, or else to a soil of at least a minimum depth, corresponding to the peak at point S.

The significance of this unstable range of soil thickness for hillslope development is that there is a minimal overlap between weathering-limited and transport limited.

Threshold Slopes

On slopes that have steepened to the point where landslides are the dominant erosional mechanism, it becomes increasingly difficult for river incision to further steepen slopes without triggering additional land sliding. Consequently, once slopes reach an upper, limiting angle between about 30° and 40°, depending on soil and rock strength, they become **threshold slopes** on which landslide frequency controls slope erosion rates instead of slope angle.

At slope angles above about 26°, the relationship between slope angle and hillslope erosion rate thus changes from the linear relationship common on low-gradient slopes

Slopes with gradients less than about 26°, the approximate lower limit for the initiation of most debris flows, tend to erode and evolve through slope-dependent sediment transport in which the pace of soil erosion increases linearly with slope.

The development of threshold slopes at angles close to the upper limiting angle is a major reason why mountainous topography looks remarkably similar across a wide range of climates and tectonic settings worldwide.

Slope morphology evolution

Slope morphologies change over time through three process including: slope decline, slope replacement, and parallel retreat.

Slope decline occurs as steep slopes gradually become shallower, and cause a flattening of the overall slope profile. The end result of slope decline is a profile with a convex upper slope segment above a concave lower segment that develops where material is deposited near the base of the slope.

In **slope replacement**, the gentler profile of the lower slope segment extends uphill as the steeper upper angle (or cliff face) retreats, as occurs when material shed from a cliff face is not removed at the base and talus slopes develop.

During **parallel retreat**, a slope maintains a constant angle as the slope surface cuts into the bedrock.

Slope decline generally characterizes profile evolution in temperate and humid regions with soil-mantled slopes, and slope replacement and parallel retreat are more common in arid and semi-arid regions with bedrock slopes.

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Topic 2a: Models of soil covered slopes

By the end of this topic, you should be able to:

1. Understand the different models used in explaining slope processes and development
2. Analyse the role of models in slope and landscape evolution.

Slope evolution or landscape change is a complex phenomenon which can only be well understood when simplified using models or theories. A model is viewed as anything that simplifies a complicated real situation using assumptions and prepositions. Therefore, in order for us to understand how slopes or landscapes change, we need to use certain assumptions and models. The significance of a model is that it generalizes widely recognized features or processes, arranges them in a meaningful pattern, and simplifies the components so that they may be readily understood.

For example, Consider the problem of the complex processes involved in soil erosion and mass movement on slopes; and how you would differentiate them, analyze them, and integrate the key ones to come up with generalized model to explain the situation.

There are several types of models generally classified into:

The analogue models; these are models which represent components of a landscape, and perhaps associate each component with the dominant processes acting on it.

Evolutionary models; these are models which identify a sequence of changes in a landscape, which changes are usually recognized from field evidence, e.g., Davis', L.C.King and Penck's models. The main weakness of these models is that they lack data and are too descriptive.

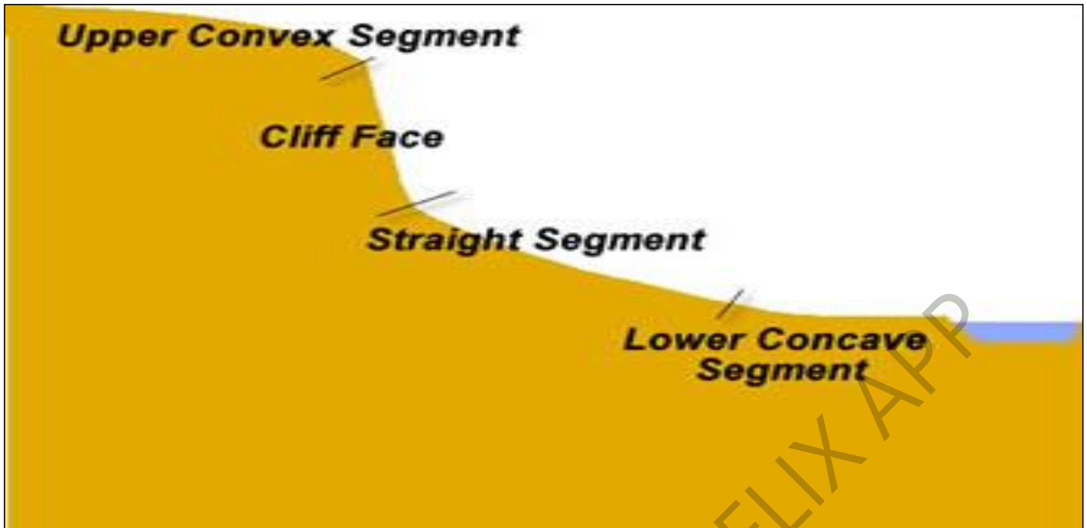
Mathematical models. These are models which are expressions of landforms and processes as equations which can be repeatedly solved, with subsequent solution being modified by the solution of its predecessor, so that step-by-step changes are calculated.

The Analogue Models

These are models in which hillslopes are traditionally considered from the ridge tops to valley floors. The approach, however, tends to neglect the complexity and variation of forms and processes across the slope, i.e., along the contours. The divergence of water and debris from convexities and their convergence upon depressions and drainage lines is, certainly as important as any process acting directly downslope.

Analogue models are the ones in which a hillslope is described from the valley bottoms to ridge tops by identifying the discrete units or sections that make up the slope. After identifying the slope units or sections that make the slope, the dominant processes on each of the units is identified.

On many hillslopes, the heads of drainage network are old landslide scars, and this emphasizes both the variation of forms and processes across a slope and the continuity of hillslopes with valley floors. On a slope profile, there is need to recognize the major types of ***unit***, which recur in the landscape. That is to say, there is need to establish the existence of ***discrete slope units***, characterized by distinct inclinations and processes. This may be done either by distinguishing flat, convex, concave, cliff or inclined units, or more usefully, by recognizing the relationship between pedological and geomorphic processes and the characteristic slope units on which they occur.



Evolutionary Models

The earliest evolutionary model was the concept of the cycle of erosion, as expounded by W. M. Davis (1909), and his disciples. Later attempts were made by W. Penck (1924), who sought to interpret the rate of crustal movement from slope morphology, and of L. C. King (1967), who was concerned with the forms of the earth, with the widespread phenomena of parallel retreat of free faces on slopes and semi-arid climatic influences.

Unfortunately, all these early evolutionary models of landscape change are entirely descriptive and untestable. The models were formulated before the complexity, universality and duration of climatic changes of the late Cenozoic was appreciated, and before many data on the rates, incidence and mechanisms of geomorphic processes were available.

Evolutionary models, usually presented as a sequence of slope profile changes or a sequence of block diagrams, still have a place in geomorphology where they are founded upon detailed field work. Most such models are ***ergodic*** hypothesis, which suggests that, under certain circumstances sampling in space can be equivalent to sampling through time, and that space-time transformations are permissible.

Therefore, the slope profile developed upon two adjacent sheets of different ages but similar composition, may be taken as representing two stages of development of one set of slopes, or slope profiles measured in the lower, middle and upper reaches of a valley may be regarded as being part of a sequence with the headwater slope profiles being young and the lower reach profile being older. In the latter case, extraneous influence such as antecedence or base level change must be absent before the model could be regarded as acceptable.

Mathematical Models

These are models which use figures and numbers. This is due to the fact that slope conditions can be quantified. Every slope variable can be quantified e.g., slope gradient in degrees, slope length e.g., in meters, soil depth in cm or meters, vegetation cover in terms of percentage cover, slope processes etc. We can also attach a figure on climatic conditions e.g., rainfall in 300mm per month. After attaching numbers or figures on slope variables, it is then possible to develop equations to solve certain problems on the slope. Therefore, mathematical models are the ones which use statistics, equations, figures or numbers to explain slope conditions.

These models were developed as a result of change in focus of attention in modern research, due to the uncertainty associated with evolutionary models. Today mathematical models are primarily concerned with studies of the resistance of material and with processes of change and their results.

Attempts are also being made to incorporate data on processes, and knowledge of mechanics of the processes into ***mathematical models***, which can be used to predict the way in which landforms will change under specified conditions of ***structure, climate, relief and time*** for the operation of the processes.

Once reliable models are produced, they may have a number of applications including prediction of the effects of land-use changes upon slope forms and rates of evolution; the formulation of research programs to provide data for the tests of models; the study of long-term effects of a single process or group of processes, a condition normally impossible under natural conditions and the explanation of geomorphological laws such as the evolution of Richter slopes.

There are two main approaches to the development of mathematical models namely; ***analytical and simulation models***

Analytical models

Analytical solutions are based upon an assumed manner of action of processes. The necessary basis for any process-response model is the continuity equation, which is a statement that;

If more material is brought into a slope section than is taken out, then the difference must be represented by accumulation; conversely, if less material is brought into a slope section than is removed the difference must come from net erosion of the section. Therefore, the rate of debris transport is a major term in the continuity equation, and the variation of the rate of transport with relief largely controls the slope form and rate of change.

For a satisfactory statement of the continuity equation, there is also need to specify the initial form of the profile, the condition at the crest (usually regarded as fixed), and the base of the slope (where constant removal of materials is the simplest condition).

Simulation models

Simulation models have been formulated by workers like Young (1967), Ahnet (1976) and Armstrong (1976). The model assumes a land surface in three dimensions represented as a matrix of unit cells, each of which has two important properties namely; *the height and the soil depth.*

The matrix of heights represents the form of the basin at any one time, and the direction of mass transfer of material is determined by the gradient at any one point, so that the form becomes an important variable which modifies the action of slope processes.

Soil depth at any point represents the total amount of materials which is potentially mobile. An initial form of landscape is specified as a map of heights and depths.

The processes operating in the model are selected; their mode of operation specified as an equation, and their magnitude is assigned a value which represents a natural rate of operation. Thus, it is possible to specify that each iteration of the model represents a set of period of time.

Today, by using a high speed computer, the evolution of slopes by denudation processes operating over tens of thousands of years or more can be calculated in a matter of minutes or a few hours. The continuity equation for the slope system can be represented as a budget, so that over a unit of time can be calculated. The following equation applies;

(i) $\delta H = I - O$

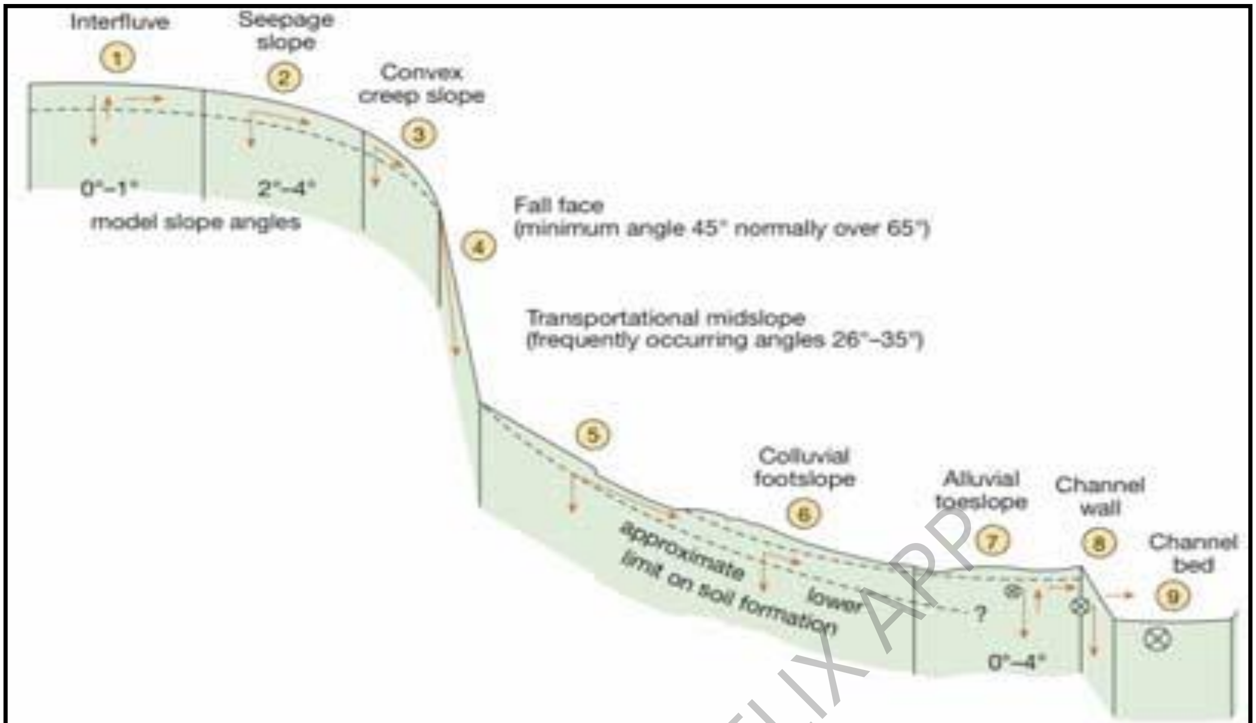
(ii) $\delta D = I - O + W$,

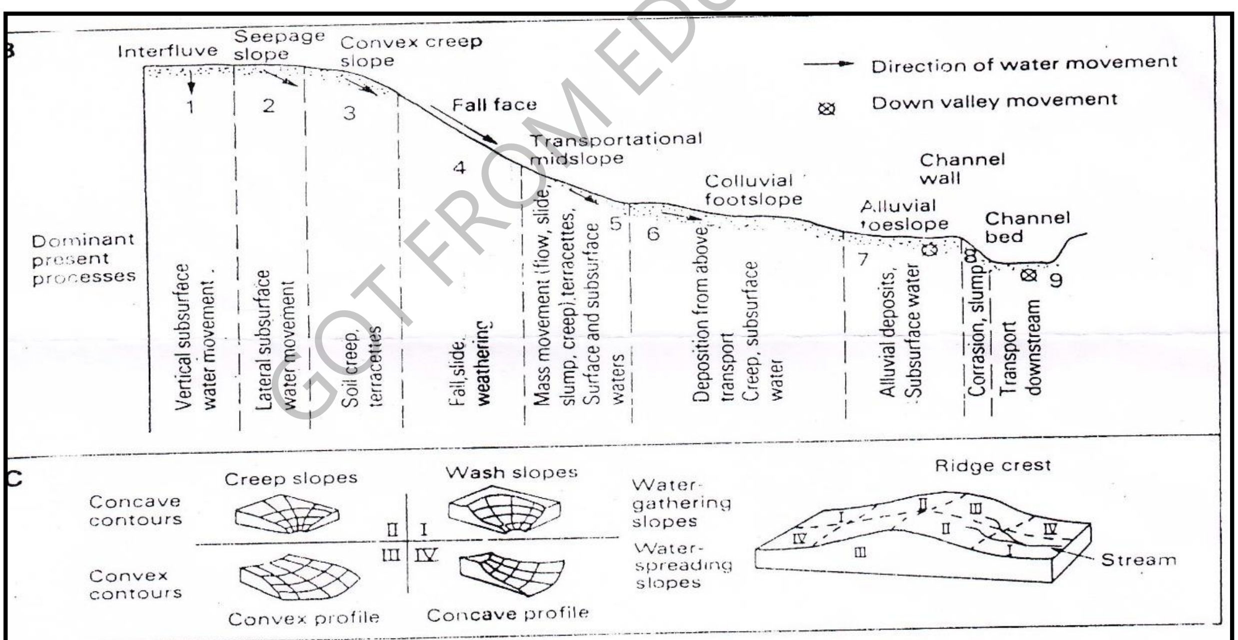
Where H= height of the ground surface above a datum, I=the inflow of material into the cell, O=the outflow of material from the cell, D= the soil depth, and w= the amount of weathering.

Therefore, in each, iteration is computed by considering the weathering component and the outflow from each cell (representing the magnitude of the transport process), which is then added to the inflow of the cell next downslope. In the model only three processes are considered; (i) weathering; (ii) slope transport; (iii) fluvial transport

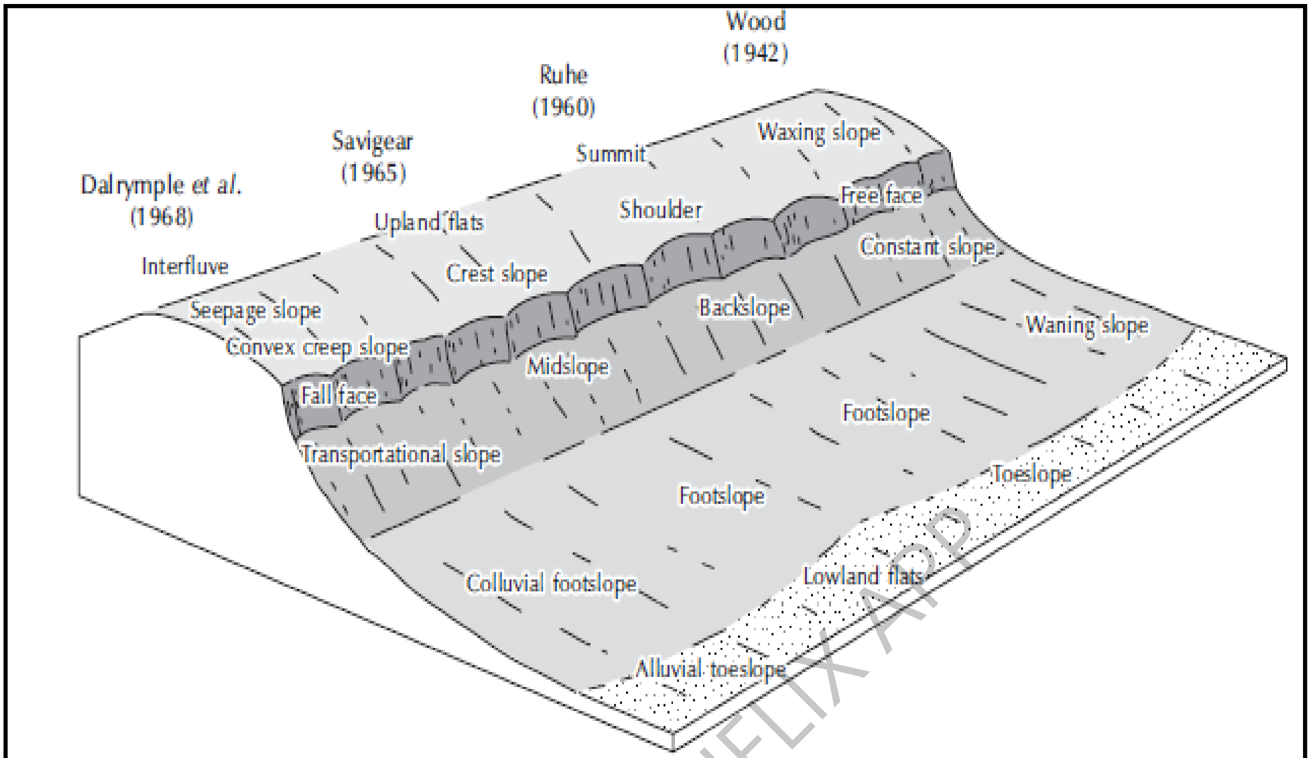
To accommodate this variety of slopes, Dalrymple et al. (1968) has developed a hypothetical 9-unit land surface model.

The following diagram illustrates A Hypothetical Nine-Unit Land Surface Model (after Dalrymple et.al. 1968), indicating the most dominant process on the various slope units.





Slope classification: a variety of schemes.
(A) Slope facets. (After King and Wood, in Young, 1972)
(B) A nine unit model (After Dalrymple, in Young, 1972)
(C) A classification of slope elements in a landscape (After Troeh, 1965, in Bloom, 1968)



The results of the simulation model are represented in the above diagrams.

The model regards the hillslope system as a three dimensional complex extending from the drainage divide to the center of the channel, and from the ground surface to the uppermost boundary of weathering bedrock.

Each of the nine slope units is defined in terms of form and dominant processes currently operating on it. In reality it is unusual to find all nine units occurring in one slope profile;

They do not necessarily occur in the order illustrated in the diagram, and the individual units may recur in a single slope profile.

A functional nine-unit sub-division of the valley side slope has been proposed, which combines their form with a statement of the contemporary geomorphological process. The following dominant processes are identified with the nine units of the slope:

1. The **interfluve**: A divide area characterized by largely pedogenic processes associated with vertical surface soil water movement.
2. The **seepage slope**: A gently dipping portion dominated by downward percolation and lateral subsurface water movement.
3. The **convex slope**: soil creep, terracet formation
4. The **fall face**: A Cliff face characterized by rapid detachment of material or bedrock (weathering limited) exposure.
5. The **transportation mid slope**: Active region characterized by transportation of material by mass movement (flow, slide, slump, creep), terracet formation, surface and subsurface water action

6. The **colluvial foot slope**: Depositional region. Material is further transported down slope by creep, slope wash and subsurface flow.
7. The **alluvial toe slope**; Region of alluvial deposition, processes from subsurface water movement.
8. The **channel wall**: removal by corrason, slumping, fall etc.
9. The **channel bed**: transportation of material down valley by surface water action, periodic aggradation and corrosion. Downstream transport of material

While slopes are of crucial significance in all landform studies, they should not be studied in isolation, but should be related to the whole morphological environment, which in humid landform areas means that slope processes and forms must be related to river processes and fluvial landforms.

Considerations of the relationship between slope angle and slope stability inevitably lead to questions of the way in which slope forms change with time.

Such changes are so slow that observational techniques can hardly provide direct evidence of the pattern of slope evolution.

The model provides a means of describing or mapping slopes to show how they vary along contours. Thus, the model relates processes to slope forms.

Starting from initial form, block diagrams represent the result of the action of the three processes namely weathering, slope transport and alluvial transport, after the calculated number of iterations.

The main features of the landscape are the overall convexity of the landforms, their smoothness and their stability. Individual slopes appear to be maintained in an equilibrium form, after first attaining convexity, with little change in slope, but a change in dimensions.

The Dalrymple et.al (1968) model has the advantage in that it can form the basis of a mathematical model of slope change in which the mode and rate of operation of processes characteristic of each slope segment are expressed in form of equations and repeated operations of the processes are simulated.

Thus the model can be adopted to the character of most areas, and local details of bedrock and soils may be added to make it relate to specific drainage basins.

It is important to note that the integrated view of form, materials and processes implied by this approach is essential to the valid interpretation of river basin characteristics, while the same approach had also been used to look for significant differences between basins of different orders.

Specific results of some simulation models which are well related to natural conditions suggest the following conclusions:

(a). processes involving downslope soil transportation tend to cause slope decline, and the slope is "transport *limited".*

(b) Processes involving direct removal of material from the slope tend to cause parallel retreat, and the slope is "*weathering limited"*

(c) Stream incision at a rate in excess of the rate of transportation on the slope produces steep basal slopes, which may then fail by land sliding.

The simplest process-response models are those which assume that only one process is operating upon a slope.

Creep processes produce an expanding upper convexity on a slope; wash produces an increasing lower convexity; uniform solution produces a parallel down wearing; and shallow land sliding on a transportational mid-slope produces parallel retreat of that slope unit and a lower concavity where deposition occurs.

GEO 3204: ADVANCED GEOMORPHOLOGY COURSE

Lecturer: Dr. Nseka Denis Galende

<u>TOPIC 2b: The Equilibrium theory of slope development</u>

By the end of this topic, you should be able to;

1. Analyze the implications of different forces within a system
2. Evaluate the role of applied forces versus the resisting forces in slope processes and development.

This model focuses on the different forces on the slope i.e., the resisting forces and the destructive forces.

1. Since about 1950, geomorphologists have increasingly emphasized the actual mechanics of landform development, focusing on the specific relationship and process in the landscape.

Most slopes can be explained in terms of ***applied force versus resistance of materials***, that is shear strength of the slope materials. When disruptive forces overcome material resistance, the material is fragmented and set in motion and erosion commences.

2. Erosion itself has an effect on the balance between stress and resistance. If erosion reduces the slope gravitational stress exerted on the material forming the slope, as well as the shear stress exerted by the erosional agent is reduced.

It should be noted; however, that reduction of slope angle by erosion is not indefinite. Certainly it will not be reduced below the steepness required for removal of the debris produced by weathering on the slope. On the other hand, an increase in slope angle will increase the downslope gravitational stress and the energy of the erosion agent.

This produces more vigorous erosion, which soon reduces the slope to the angle at which the erosional stress is just adequate to remove the specific type of material supplied by weathering. This is a good example of negative feedback- in which disturbance of a system that is in equilibrium triggers changes that tend to restore the original system.

Note that:

(a) Negative feedback is the principle means of maintaining equilibrium in physical systems and is a normal feature of most landform systems.
(b) Negative feedback makes the slope system a self-regulating area that tends to maintain a steady state through time, which changes in form occurring only as a consequence of the removal process.

The negative feedback mechanism works backwards to the original state and then repeats itself e.g. if there is an uplift of a slope, then erosion will start.

It makes a slope self-regulating; a slope uplifts itself and reduces itself. It is the process of maintaining a system at equilibrium.

The landscape keeps on being destroyed by erosion and coming back through uplift.

3. An imbalance in slope material resistance to erosion leads to varying slopes:

(i). Steep slopes occur where the material is most resistant to detachment and removal

(ii) Gentle slopes occur where the material is easily eroded.

High relief features that are assumed to be in equilibrium are underlined by more resistant rocks while those which are assumed to be in equilibrium and are low relief features are underlined by less/ weak resistant rocks.

Since slope angle tends to equate stress to resistance, it is possible for the whole landscape, whether comprising of tough or soft rocks, to wear away at approximately the same rate over a long spans of time.

4. The equilibrium theory of landform development suggests that slope forms are adjusted to geomorphic processes in a very delicate way, such that the gravitational energy provided is just adequate for the work to be done.

Any change in the energy or the nature of applied stresses causes an adjustment in the form that will re-establish the equilibrium of the form-process relationship. In the same token, any alteration in form unrelated to the normal operative stress, e.g., produced tectonically or human interference, causes an increase or decrease, in erosional energy, which in turn, tend to re-establish the original equilibrium relationship.

Hence, it is impossible to modify either landforms or geomorphic processes without triggering a reaction in the natural system, which tends to restore an equilibrium relationship between processes and form.

5. It is important to note that besides this process-form equilibrium, there is another type of equilibrium resulting in some depositional features. These ones persist because erosional removal from them is balanced by arrival of new material. Examples include beaches, river sand bars, talus cones, river deltas and volcanoes.

Such features enlarge or shrink depending upon the balance between input and erosional loss of material, although some of these (e.g., beaches) have achieved semi-permanent configurations which are for long periods in balance as far as erosional losses and arrivals of new material are concerned.

Such beaches are in a delicate state of equilibrium that is easily upset by modifications of any part of the beach system. The upset could range from the sediment source to waves and currents that act upon the beach itself and the coast at some distance from it.

6. The equilibrium concept of landform development is of great value in that it focuses on the exact relationship between geomorphic processes and surface forms, an approach to landform analysis that is indeed more rewarding in terms of understanding the development of landscape, than either the cycle of erosion concept or Penck's tectonic model of landform development.

When the forces of erosion are in equilibrium with the forces of resistance then the slope is in equilibrium and this is a steady state situation.

The steady state of deposition materials is where the rate of deposition is equal to the rate of removal of these materials and such a deposition landscape is said to be in equilibrium e.g. beaches since the amount of materials being deposited is at the same time removed and thus giving room for new materials.

Therefore, the equilibrium model has been of great contributions to understanding of geomorphology than both these earlier concepts. The equilibrium theory has particularly focused attention on landforms that may be in steady state condition, i.e., not changing progressively, though constantly being affected by erosion or deposition.

Static equilibrium is when a slope reaches equilibrium and stays there forever. This is difficult in nature due to changes which occur in nature due to catastrophism.

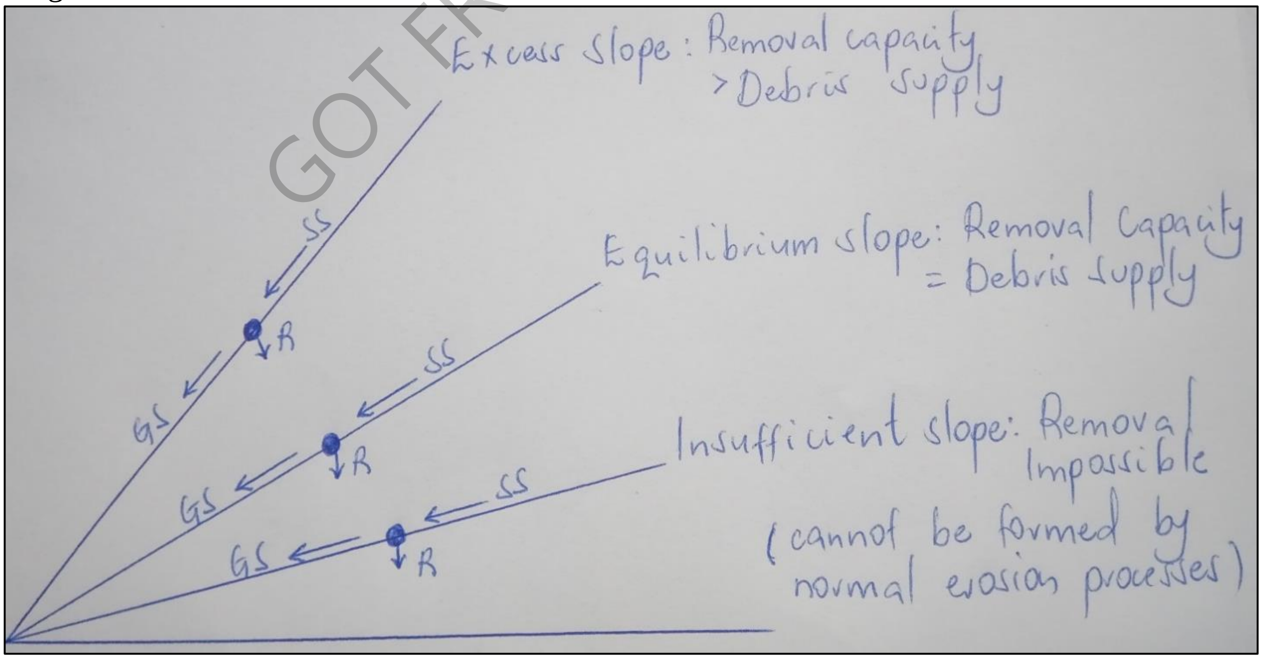
A hilly region with sharp ridge crests and narrow ravine like valleys is one of the world's most common landscapes.

If slopes reach from the ridge crest to the valley, stream down-cutting will cause removal from the entire landscape with no change in form occurring.

Downward valley erosion could go on indefinitely if landscape is slowly but continuously uplifted, resulting in a landscape steady-state that is independent of time.

Note that whenever there is a continuous input of energy or material into a geomorphic system, a time-independent landscape is the result. Diagrams (a) and (b) illustrate the varying forces on slopes that relate to equilibrium slope conditions.

Diagram a:



In the diagram (a) hypothetical slope angles indicate downslope gravitational stress (GS), shear stress (SS) exerted by the gravitationally driven erosion agent (such as slope wash), and resistance to detachment of slope particles (R). Note the following

(a) Resistance remains the same at varying slope angles, while GS and SS diminish with decrease in slope angle;

(b) The steepest slope is unstable, as the sum of GS and SS far exceed R, causing rapid erosional removal.

(c) The intermediate slope is stable, as the sum of GS and SS just balances R, so that removal can occur without changing the slope angle;

(d) The lowest slope cannot be produced by the stresses shown, as particle resistance R exceeds erosional stresses, so that erosional removal is impossible

Diagram b:

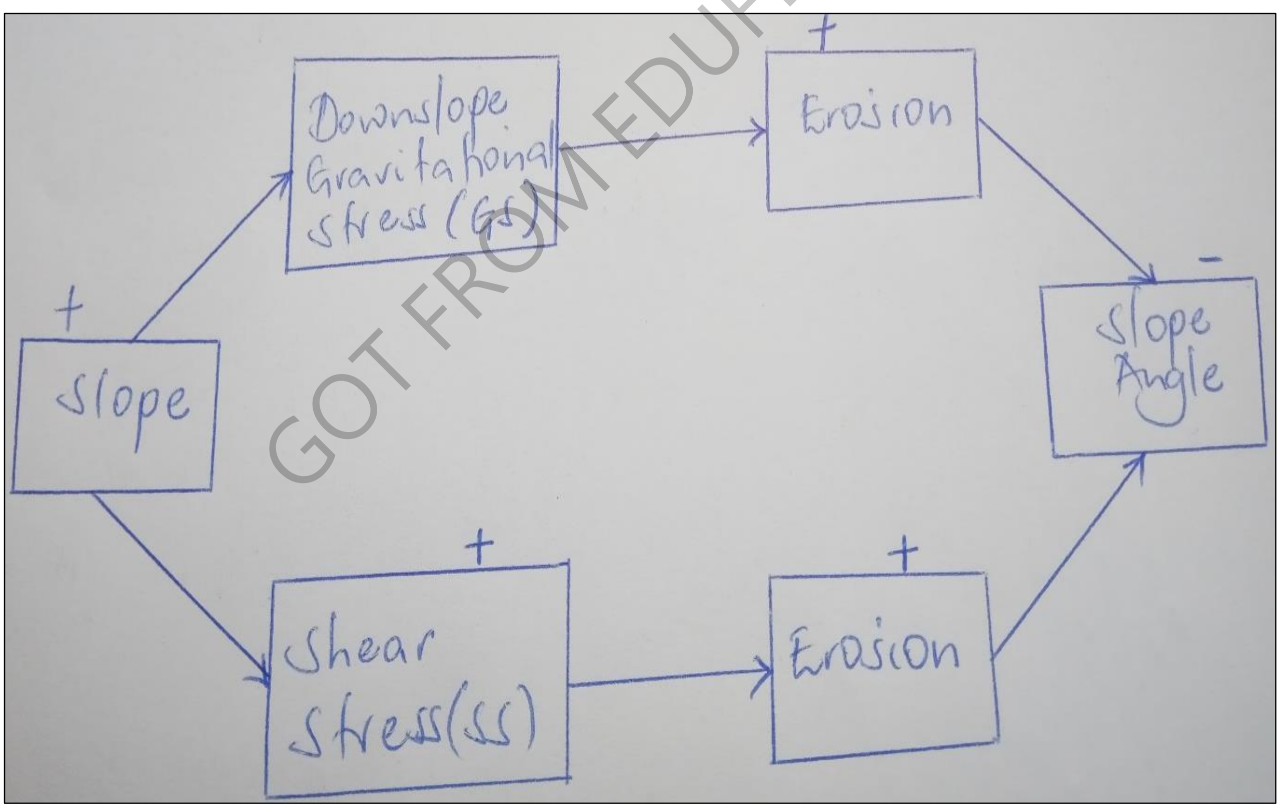


Diagram (b) is a representation of negative feedback relationship causes slope to be self-adjusting towards angles that equate stress to resistance. Any increase in slope increases the erosional stresses, which in turn, decreases the slope angle until equilibrium is established.

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Topic 3: Energy sources for debris transport on slopes

Learning outcomes for this topic

By the end of this topic, you should be able to:

1. Explain the different forms of energy responsible for transporting materials on slopes
2. Evaluate the nature of the forces on the slopes and their implications to land resource and environmental conservation as well as prediction of natural disasters.

Consider a landslide or rock fall; this is a dramatic expression of force overcoming resistance on slope. All hillslopes are, however, examples of systems in which force and resistance are continuously opposed. Debris involves all the rock materials which are mobile on a slope.

(1) For any systems in equilibrium, the forces tending to promote movement are exactly balanced by resistance opposing it, and such an equilibrium system may be either in a state of rest or undergoing movement at a uniform rate.

(2) Acceleration of the system, or part of it, is the inevitable result of the forces becoming greater than resistances. In the slope geomorphology context, equilibrium usually means a state of rest so that any acceleration of the system results in the beginning of debris movement.

(3) When the forces within a moving debris mass becomes less that the resistance to movement of the mass, then the mass will slow down and eventually stop.

In order for materials or debris to be moved from one part of the slope to another, we need energy. Where does this energy which moves or transports materials on the slope come from?

Well in geomorphic systems the energy or force to move materials is ultimately derived from either ***gravity or climate.***

I. Gravity derived energy

This is the force derived from the gravitational forces which pulls materials to lowest areas. The force provided by gravity is simply that of weight of each debris particle, which will move it downwards if it is not resisted. Therefore, the following should be noted:

Forces of gravity on an object are expressed in terms of the weight of that object, forces which act ***vertically downwards***

On a slope, the weight of an object can be resolved in two components namely, the *downslope force*, which tends to move the object downhill parallel to the surface; and a force *perpendicular to the surface* which acts to hold the material on to the slope.

The forces can be resolved into; the downslope component (D) and the perpendicular forces or normal stress (N) and, can be resolved as follows;

Because slope movements are generally along or parallel to the surface, the ***downslope component*** of weight is the most important in promoting debris transport. Some slope movements are, however, attributable to the ***perpendicular force***, for instance, movements such as ***contraction*** after frost heave and ***soil consolidation***. But the extent to which the ***perpendicular component*** actually promotes debris transport is minimal, compared to its role as a direct resistance to hydraulic lift forces and determining ***frictional resistance.***

The **downslope component** is force which moves the object downhill parallel to the force. It is a force which promotes movement of materials and thus it is a destructive force on a slope. The downslope component of the forces acting on a single particle: weight of the slope material (w), times acceleration of gravity at the earth's surface (g) times the sine of the slope angle on which the particle is resting (β).

The **perpendicular component** is the force which acts to hold materials on the slope. It is therefore a resisting or protective force to movement of materials.

The perpendicular force or normal stress: Weight of the slope material (w), times acceleration of gravity at the earth's surface (g), times the cosine of the slope on which the particle is resting (β).

The gravity force depends ultimately upon differences in slope angle or gradient, and it is the downslope component of weight which transmits this force.

The component is equal to the weight force multiplied by the **sine** of the slope gradient angle, so that it is the sequence of slope gradients, or in other words, the **slope profile** which communicates the information about elevation differences between points in the landscape. This means that the slope or river longitudinal profile serves a function as a **telephone line** which is passing the message about conditions at the foot of the slope or river, upwards to the divide.

Besides acting as a communication link, the gradient may also be thought of as the means where the ***total available energy inherent in the relie***f is distributed over the landscape, so that the gravity forces are most effective on the steepest slopes, because it is there that the downslope weight is greatest.

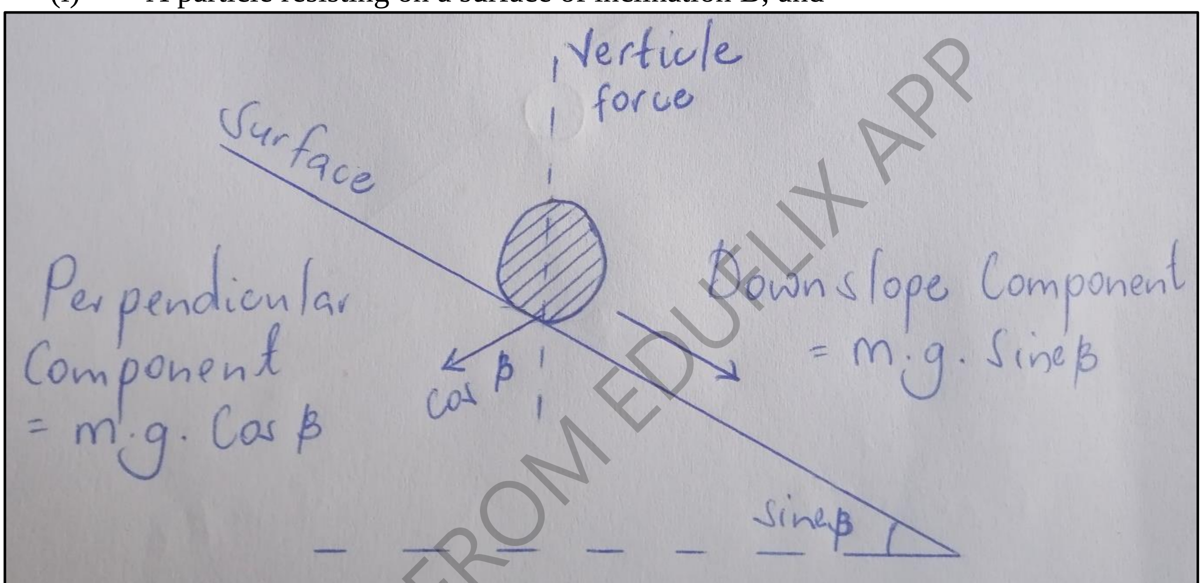
Take for example, the river; its incision or lateral migration behavior enables the system to redistribute the effective gravity forces considerably in a landscape by forming steep slopes (and thereby concentrating gravity forces near the river), or by moving the position of the steepest slopes from the hillside to the opposite one, and can achieve this without altering the total available relief.

Because the force of gravity depends on differences in elevation, the principle source of energy for gravity is ***tectonic uplift*** of landscape. Likewise, the lowering of base level by ***eustatic changes*** in sea level produces similar effect, but it does so because below sea level, the hydraulic forces dramatically change their character although they do not stop acting because the force of gravity remains unchanged.

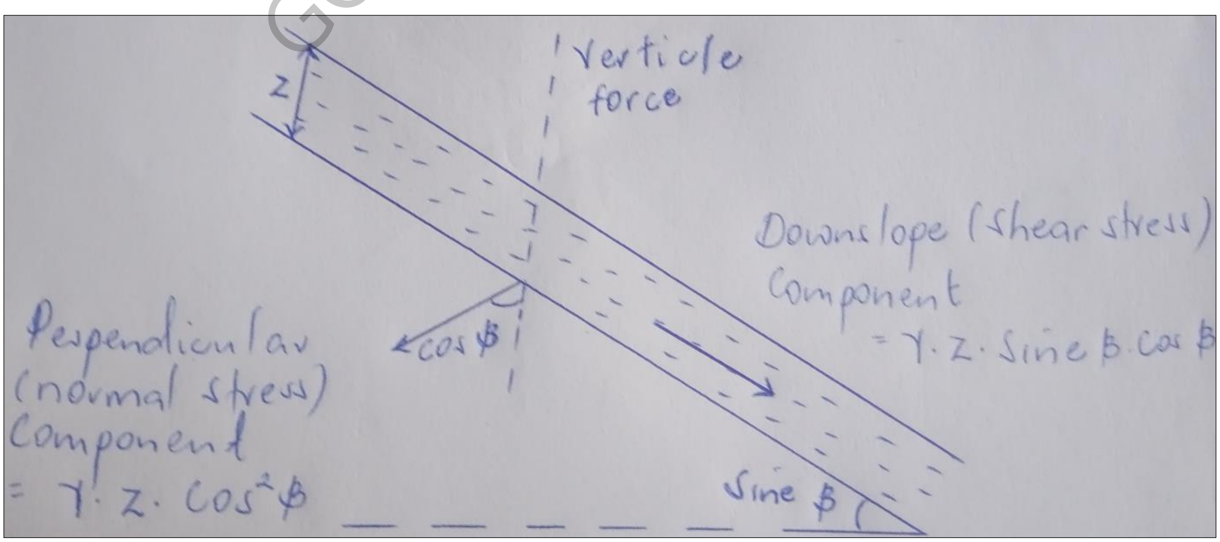
On a much smaller scale, the gravity force is constantly being removed by ***climate-derived forces*** which are lifting material e.g., in frost and moisture heaving in the upward translocation of salts in the soils, in plant growth and in the formation of worm casts, anthills etc.

The nature of the gravity forces- although the forces are similar, they are slightly different as illustrated by the following assumptions:

(i) A particle resisting on a surface of inclination B; and



(ii) A possible slip plain within the soil but parallel to the surface.



The diagram (i) illustrates that the force acting on an isolated particle is simply its own weight acting through its Centre of gravity.

Gravity forces acting on a particle of mass m resisting on a surface of slope β. If it has a mass m, then the vertical weight=m.g, where g=acceleration due to gravity ($9.81m/s^2$)

(i) The downslope component which is tending to promote movement along the surface= m.g.sine β.
(ii) The perpendicular component which is tending to promote resistance into the surface=m.g.cos β.

The diagram (ii) illustrates the relevant gravity forces acting on a possible slip plane at depth Z below the surface of a medium having a unit weight Y.

The relevant force is pressure exerted by the weight of the material resting on the plane. This overburden pressure also acts vertically downwards and equals Y.Z, where Y is the unit weight of the soil, and Z is the vertical distance between the surface and the slip plane. As in the case of the isolated particle,

(i) The downslope component= shear stress= Y.Z. sin β. Cos β;
(ii) The perpendicular component=normal stress=Y.Z. Cos^2 β.

The downslope component acting on a mass of ***soil block*** with a weight of (y) and depth of (z): Weight of slope material (y), times depth of material (z), times the sine of the slope angle on which the material block is resting (β), times the cosine of the slope (β).

The perpendicular force or normal stress (N) =w x z x $cos\beta^2$: Weight of the soil block (w), times the depth of the block (z), times the square of the cosine of the slope on which the material is resting.

II. Climate derived forces

Climate as a source of geomorphic processes is through its control on temperature and available water. These provide energy for the most important forces on hillslopes, both static and ***moving water***.

Climate also, directly controls the forces of freezing water and thermal expansion of rock materials, and indirectly affects biological and chemical forces such as those produced by plant growth and evaporate formation.

These forces vary not only in the gross amount of work done (magnitude), but also in the net result of downslope movement of materials that they achieve efficiency.

Generally, although very large amount of thermal and biochemical energy is applied to the landscape ***only minute amounts*** of these forces are actually effective in transporting debris;

Rather, it is the mechanical and hydraulic forces that move most hillslope debris, because they operate at a relatively high efficiency.

Of these forces, water flow is by far the most important, both in total energy expounded and in total debris transport achieved. Water flow itself has two components;

(i) Hillside flow (overland flow); (ii) stream flow.

Hillside flow accounts for the greatest part of the total work done by flowing water, but it is so inefficient compared to stream flow that it actually moves only a fraction of the debris that streams can transport.

GEO 3204: ADVANCED GEOMORPHOLOGY COURSE.

Lecturer: Dr. Nseka Denis Galende

<u>Topic 5: Slope Stability analysis</u>

Learning outcomes for this topic

By the end of this topic, you should be able to:

1. Evaluate the conditions responsible for slope failures
2. Prepare a land suitability and capability design for landscape utilization.

Forces on a slope

The causes of many landslides and related types of downslope movement can be analyzed by studying relationships between:

(a) The driving forces (shear stress) - those forces which tend to move the earth materials downslope. They are destructive forces on a slope.
(b) Resisting forces (shear strength) - those forces which tend to oppose such movement. The most common driving force is the "downslope component" of the weight of the slope material such as vegetation, fill material, or buildings. The most common resisting force is the shear strength of the slope material acting along potential slip planes.

Factors determining the strength of slope materials

The response of slope materials to stress is determined by their strength (shear strength) which is the ability to resist deformation and fracture without significant failure. In the context of slope materials experiencing stresses generated by gravity, the slope strength is in relation to shear stress. The strength of slope materials varies over time and space because rocks and soils are generally complex mixtures of mineral particles, water and air etc. the factors affecting strength are;

1. Frictional resistance between the constituent particles of a material
2. Cohesion

Slope stability

The stability of a slope can be expressed in terms of the relationship between those stresses tending to disturb the slope materials and cause it to move and those forces tending to resist these driving forces.

Controls of slope stability

The nature and extent of slope stability for the various types of downslope movements can generally be explained by examining forces on slopes in terms of the following somewhat interrelated variables:

(a) Type of earth materials; (b) slope (topography; (c) climate; (d) vegetation (e) water (f) time (the geological time scale) (g) human activities

There is seldom only one case of slope instability. Instability is usually the result of a sequence of events that ends with downhill movement.

Climate

Climate influences mass movement through its elements of precipitation/rainfall and temperatures. Through precipitation/rainfall water is introduced into the rock and as the rock absorbs more and more water, the rocks become heavier and unstable and hence easy and ready to move down slope.

Through temperature variations during day and night where the rocks can experience expansion and contraction process due to the extreme temperature variations, the rocks may end up breaking down and hence easy to move down.

The Role of Water in slope stability

Although water is not always directly involved as the transporting medium in mass movement processes, it does play an important role.

Water becomes important for several reasons

1. Addition of water from rainfall or snow melt adds weight to the slope. Water can seep into the soil or rock and replace the air in the pore space or fractures. Since water is heavier than air, this increases the weight of the soil. Weight is force, and force is stress divided by area, so the stress increases and this can lead to slope instability.

2. Water has the ability to change the angle of repose (the slope angle which is the stable angle for the slope). Think about building a sand castle on the beach. If the sand is totally dry, it is impossible to build a pile of sand with a steep face like a castle wall. If the sand is somewhat wet, however, one can build a vertical wall. If the sand is too wet, then it flows like a fluid and cannot remain in position as a wall.

Dry unconsolidated grains will form a pile with a slope angle determined by the ***angle of repose***. The angle of repose is the steepest angle at which a pile of unconsolidated grains remains stable, and is controlled by the frictional contact between the grains. In general, for dry materials the angle of repose increases with increasing grain size, but usually lies between about 30 and 45^o

3. Water can be absorbed or aborted by minerals in the soil. Absorption causes the electronically polar water molecule to attach itself to the surface of the

minerals. Absorption causes the minerals to take the water molecules into their structure. By adding water in this fashion, the weight of the soil or rock is increased. Furthermore, if adsorption occurs then the surface frictional contact between mineral grains could be lost resulting in a loss of cohesion, thus reducing the strength of the soil. In general, wet clays have lower strength than dry clays, and thus adsorption of water leads to reduced strength of clay-rich soils

4. Water can dissolve the mineral cements that hold grains together. If the cement is made of calcite, gypsum, or halite, all of which are very soluble in water, water entering the soil can dissolve this cement and thus reduce the cohesion between the mineral grains.

5. Water also acts as a lubricant by reducing the friction between the materials and the surface and thus facilitating on the movement of materials down slope.

6. Liquefaction -, liquefaction occurs when loose sediment becomes oversaturated with water and individual grains loose grain to grain contact with one another as water gets between them.

The amount of water necessary to transform the sediment or soil from a solid mass into a liquid mass varies with the type of material. Clay bearing sediments in general require more water because water is first absorbed onto the clay minerals, making them even more solid-like, then further water is needed to lift the individual grains away from each other.

Groundwater exists nearly everywhere beneath the surface of the earth. It is water that fills the pore spaces between grains in rock or soil or fills fractures in the rock. The water table is the surface that separates the saturated zone below.

7. Another aspect of water that affects slope stability is fluid pressure. As soil and rock get buried deeper in the earth, the grains can rearrange themselves to form a more compact structure, but the pore water is constrained to occupy the same space. This can increase the fluid pressure to a point where the water ends up supporting the weight of the overlying rock mass. When this occurs, friction is reduced, and thus the shear strength holding the material on the slope is also reduced, resulting in slope failure.

8. Water also acts as a transporting agent along slopes and therefore carries materials down slope.

9. The introduction of water will also lead to the breakdown of the rock both physically and chemically and hence making the materials available for down slope movement

Slope materials

The properties of slope-forming materials exert a profound influence on both hillslope processes and form. Slopes made of loose, unconsolidated sediment, mantled by soil, and that expose bedrock each offer substantially different resistance to erosion and gravity-induced failure.

Because of this, the material that makes up a slope strongly influences the processes that determine its evolution and morphology.

The geological makeup especially the rock units (e.g., mudstone, sandstone, limestone, greentuff es etc), tectonics, bedrock structure affects movement of materials in several ways;

Rock permeability

Permeable rocks easily shock in or absorb in water when it rains and thus becomes heavier and thus easy to move down slope. On the other hand, the impermeable rocks may remain stable for long periods as they may not allow in water.

Rock jointing

Joints and cracks with in the rocks will increase on material movement as these rocks can easily break and move down. Water can also easily find its way into the cracks where it can increase on the pressure in the rock and lead to its break down and hence movement.

- Joints & Fractures - Joints are regularly spaced fractures or cracks in rocks that show no offset across the fracture (fractures that show an offset are called faults).
- Joints form as a result of expansion due to cooling, or relief of pressure as overlying rocks are removed by erosion.
- Joints form free space in rock by which water, animals, or plants can enter to reduce the cohesion of the rock.

If the joints are parallel to the slope they may become a sliding surface. Combined with joints running perpendicular to the slope, the joint pattern results in fractures along which blocks can become loosened to slide down-slope.

Rock strength

Hard rocks try to resist movement as they are intact and therefore less affected by mass movement while the soft ones are easy to break and move down slope.

Rock is made of mineral grains that are bound together by interlocking crystal structures or interstitial cement. While it is obvious that bedrock properties directly influence the morphology of bare rock slopes, it is also true that the nature of buried bedrock also influences slope stability, soil properties, and the topography of soil-mantled slopes.

Colluvium is the unsorted, unstratified hillslope material that overlies bedrock. Hillslope soils tend to be colluvial because they are produced by weathering of underlying bedrock and are gradually transported downhill under the force of gravity. The material properties of soils and weathered rock often strongly influence the morphology of soil-mantled slopes.

In some places, hillslopes are formed of unconsolidated sediments that were deposited by rivers (alluvium), glaciers (till), or wind (loess). In such cases, the material properties of a slope may be similar to those of a soil-mantled slope, even if little to no mature soil has developed.

Strength of Rock and Soil

The rocks and soils that make up Earth's surface vary greatly in material strength and ability to resist erosion. Granite is difficult to break with a sledgehammer. A loose pile of sand at the base of a slope of weathered granite can be scooped up with a spoon. Deeply weathered saprolite in tectonically stable continental interiors or tectonically shattered bedrock in rapidly uplifting mountains may have less strength than a soil horizon. It is thus unsurprising that the material strength of slope-forming materials is a dominant influence on slope processes and topography.

The ability of material to resist applied stress is called its **shear strength**, a property that is quantified by three components, two of which are the intrinsic material properties of internal friction and cohesion. The third component, called the effective normal force, is the component of the material's unit weight that acts to hold it on the slope.

Water that fills voids, or pore spaces supports part of the weight of overlying material and thus imparts a buoyancy force that reduces the effective weight of slope-forming material.

Friction angles for both soil and rock generally fall in the range of 10-40°, but rock cohesion values are typically many orders of magnitude greater than those of most soils. There is consequently a profound discontinuity and contrast in strength on many slopes where weaker soil and weathered rock lie above much stronger bedrock. Because of the disaggregation of soil and rock particles once failure occurs, the post-failure strength of earth materials often is less than the peak strength before failure.

For most slope processes it is thus usually easier to maintain transport than to initiate it. Once it is moving, slope-forming material tends to keep going until it spreads out and achieves a gentler slope, or dissipates its kinetic energy as friction generated flowing over, through, or around whatever was in its way.

Internal Friction

The internal frictional strength of rock and soil arises from the frictional resistance to shear between mineral grains that are in contact across potential failure surfaces. Frictional strength increases in direct proportion to the normal force holding grain surfaces in contact.

The **friction angle**, or the angle of internal friction (ϕ), corresponds to the slope of the relation between shear strength and the confining force (which on a hillslope is equal to the effective normal force).

In other words, as the effective normal force increases, the shear strength of a material increases at a rate set by the friction angle.

In loose, granular materials, the friction angle is usually close to the **angle of repose**, the maximum angle at which a slope of dry material can stand.

Rock masses and granular material like sand typically have friction angles of about 30 to 40°, while clay has a lower friction angle of 10 to 20°. The great difference in strength between loose sand and rock is due to their cohesion — in contrast to mineral grains making up a rock, grains of sand are not bonded to each other.

Cohesion

Cohesion is a measure of the intrinsic strength of a material when there is no confining force. Cohesive strength arises from various types of internal bonding, including the chemical bonds between mineral grains that provide substantial strength to crystalline rocks.

Sediments compacted by the weight of now-melted glacial ice often have high cohesion. Interstitial cements like calcium carbonate (lime) also greatly increase soil cohesion.

Electrostatic bonding between the charged surfaces of clay particles and ions in interstitial water enhances the cohesion of clay-rich soils, but these electrostatic forces are much weaker than chemical bonds in rock.

In partially saturated soils, the surface tension produced by capillary stresses can increase stability through negative pore pressures to a point. But negative pore pressures are significantly reduced as a soil approaches saturation during a rainstorm. Thus, they do not contribute much, if at all, to soil strength at the time it is needed most.

Effective Normal Force

Normal forces — those oriented into the slope — help hold soil on hillslopes. On a dry slope, the normal force from the weight of dry rock or soil is supported by the contacts between grains. The normal force acts to stabilize a slope, and it is greater on gentler slopes because it is the component of the unit weight of the soil oriented into the slope, and thus is a function of the cosine of the slope angle:

Below the water table, positive pore pressures commensurately reduce the effective normal force and lower the shear strength of the soil. Landslides tend to happen during and after rainstorms because even partially saturated soils are much weaker than dry soils. A slope does not, however, need to be completely saturated to fail. Slopes fail when they become saturated enough that the resisting forces fall below the shear force, a condition that requires lower pore pressures on steeper slopes.

Effects of Weathering on Rock Strength

Weathering lowers rock strength over time through physical and chemical weathering and by altering slope hydrology. The cohesion of weathered soils and unconsolidated sediment is generally much lower than that of rock, and the development of zones of weakness as weathering proceeds also greatly reduces rock strength. As fresh rock weathers to become soil, porosity and permeability increase, sometimes by orders of magnitude.

Such changes proceed preferentially along fissures and fracture zones, and produce patterns of variable weathering intensity within the rock. Many slope failures involve sliding of the surficial soil and sediment mantle off of underlying bedrock, because unweathered or lightly weathered rock has much higher cohesion and is much stronger than soil.

In other cases, erosion of a more cohesive surficial soil layer exposes an underlying layer of deeply weathered saprolite that is highly erodible and prone to development of deep gullies.

Consequently, classifications of relative slope strength have been developed for evaluating rock mass strength based on field mapping and observations of the character, number, and density of discontinuities and zones of weakness.

In landscapes with intense chemical weathering, as is common in tropical regions, a zone of pervasively weathered, virtually cohesion less saprolite that extends deep beneath the soil may slide off a slope or erode rapidly if exposed to erosional processes through removal of surficial material**.**

Topographic parameters

The topographic parameters that influence slope stability include;

i) Elevation, which is significant in showing climate, vegetation and potential energy;

ii) Slope gradient, which is significant in showing overland and subsurface flow velocity; Steep slopes with a high slope angle have a high gravitational pull and thus it is easy for materials to move down slope. While gentle slopes have a low gravitational pull due to a low slope angle and thus movement of material down slope is limited.

iii) Slope aspect which shows solar insolation, evapo-transpiration, flora and fauna distribution and abundance;

iv) Slope length

v) Slope curvature which is significant in showing converging, diverging flow, soil water content, and soil characteristics. Curvature can be convex or concave.

vi) Complex topographic parameters such as topographic wetness index, stream power index, topographic position index, etc.

The influence of earth movements

Earthquakes and volcanic eruptions which cause vibrations and shakes with in the earth’s crust can cause the materials to be unstable and even sometimes cracks and joints may be created and thus easy for the materials to move down slope.

Vegetation cover

Vegetation cover acts as a protective layer to the surface rocks from the impacts of rain drops. Vegetation /tree roots also bind the soil materials together and hence it is not easy for materials to be movement.

The absence of vegetation cover therefore makes the slope vulnerable to mass movement processes.

The apparent cohesion that plant roots contribute to soils differs greatly among species, and changes as vegetation grows, matures, and dies. Consequently, plant succession or a change in community structure, like conversion of forest to grassland, can cause substantial changes in slope stability.

Forests generally contribute the most shear strength to soils, but roots may substantially reinforce even grassland soils. Roots die and decay following forest fires or timber harvest, and there is usually a period of at least several years during which root strength remains low as root networks re-grow.

During this window of low root reinforcement, potentially unstable slopes are particularly vulnerable to slope failure.

During periods of low root strength, more landslides occur in response to rainfall events than they would have prior to vegetation clearing, or under mature forest

Human activities

An understanding of land use practices is particularly important because changes in vegetation can conceal old landslides and cause slope instability. The major human activities on the hillslopes that affect slope stability includes; the agronomic activities, animal husbandry, settlements, infrastructural development. These affect the hydrological and pedological characteristics of the slopes and thus influence slope stability.

In addition to altering or clearing vegetation, human land use affects slope stability by changing hydrologic pathways, such as when urbanization or road construction concentrates and delivers runoff to steep slopes. The effect is even more dramatic when rainwater runoff is routed to topographic concavities, gullies, or hollows where colluvial soil accumulation and both surface and shallow subsurface runoff are focused.

Time

It takes long periods of time for slope materials to be broken down for movement down slope.

Triggering Events

A mass movement event can occur any time a slope becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is unstable all of the time and the process is continuous. But other times, triggering events can occur that cause a sudden instability to occur. Here we discuss major triggering events, but it should be noted that it if a slope is very close to instability, only a minor event may be necessary to cause a failure and disaster. This may be something as simple as an ant removing the single grain of sand that holds the slope in place.

Shocks - A sudden shock, such as an earthquake may trigger slope instability. Minor shocks like heavy trucks rambling down the road, trees blowing in the wind, or human made explosions can also trigger mass movement events.

Slope failure occurs whenever the driving forces overcome the resisting forces

The most common driving force is the "***downslope component"*** of the weight of the slope material such as vegetation, fill material, or buildings. The most common resisting force is the ***shear strength*** of the slope material acting along potential slip planes.

The shear strength can vary widely between the various geologic materials. It is controlled by such properties as ***cohesion forces*** due to electrical forces between clay particles or to the binding action of tree roots and the frictional forces resulting from ***surface friction*** and the ***interlocking*** between grains of soil or blocks of rock. The frictional forces increase with the size of the surface acting at a right angle to the potential failure plane (usually called normal stress N= w cos β

In general principle, it is important to distinguish those factors that contribute to increasing shear (disturbing forces) from those that contribute to low shear strength within the materials as illustrated in the following table:

Table1: Classification of forces contributing to increasing shear stress and decreasing

Shear strength

Controls of downslope force

- ❖ Hillslope gradient
- ❖ Steepening of the slope by tectonic tilting
- ❖ Undercutting of the slope by geomorphic processes or human interference
- ❖ Loading of the upper end of the slope
- ❖ Short-term downslope stresses generated by earthquake

Controls of shear strength

- ❖ Nature of geologic materials: rock type and structure (joints, faults, angle of dip), nature of weathering products
- ❖ Water-pressure changes due to fluctuations of rainfall; snow-melt; diversion of storm water; submergence; fluctuation of reservoir levels; leakage from canals, irrigated fields,

septic tanks, sewerage lines and water pipes; reduction of evapotranspiration following change of vegetation.

- ❖ Concentration of ground water flow by geologic structures such as joints, faults, or by the sequence of geologic materials
- ❖ Earthquake vibrations which can reduce the strength of weakly cemented sands or silts.
- ❖ Tree roots which can increase the cohesion of soils, which cohesion is lost when the roots decay after logging or burning

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Safety Factor Analysis

Movement occurs when the driving forces exceed resisting forces. This relationship is represented as the safety for a slope. The safety factor (FS) is expressed as a ratio between shear strength and shear stress.

The calculation of FS depends upon the on-site measurements of the geotechnical properties of the slope materials of the analysis of rock or soil samples in the laboratory.

Slope stability is evaluated by computing a ***safety factor Fs.*** The Fs is computed from the following equation

Fs= $\sum$ ***Forces resisting slope failure /*** $\sum$ ***Disturbing forces***

Or the ratio of the resisting forces to the driving forces

Or shear strength divide by shear stress

In soils or rocks containing water, the shear strength is strongly affected by the water pressure in the ***voids*** between the grains or blocks. This pressure supports a portion of the soil's weight and therefore, reduces the normal stress that is effective in producing friction.

The relationship of shear strength to its control is given by the following equation:

S=C + (N-p) tanϕ

Where C= cohesion; N= component of the weight of the saturated soil acting normal to the failure plane , p= pressure of water in the voids of the soil or rock; ϕ= angle of internal friction, which reflects the degree of interlocking and surface friction within the material and whose measurement is described in standard soil mechanics texts.

The problem in slope stability analysis is, however, that the forces involved (driving forces) are difficult to measure. Calculations of Fs depend upon the on-site measurements of the critical engineering parameter of the materials. Slopes can exist in three possible states i.e equilibrium slopes, stable/strong slopes, and unstable/ weak slopes

Therefore, slope stability is assessed as follows:

(i) If the safety factor (Fs) is greater than one, the resisting forces must exceed the driving forces and the slope is considered stable;
(ii) If the safety factor (Fs) is less than one, then the driving forces exceed the resisting forces and a slope failure can be expected.
(iii) If the safety factor (Fs) is equal to one, it means that the resisting forces are balancing with the destructive forces.

Slope stability is generally analyzed using force balances that characterize the relationship between factors driving and resisting slope failure. The **factor of safety** (*FS*) is the ratio of resisting shear strength to the driving shear stress, and it equals 1 at slope failure. Stable slopes have $FS > 1$, and unstable or failed slopes have (or had) $FS \leq 1$.

Rainfall reduces the effective normal force on a slope by increasing pore pressures in rock and soil. An examination of the ratio of driving to resisting forces reveals the relationships among the factors that resist, promote, and trigger slope instability.

Driving and Resisting Forces

The shear stress generated by the weight of the soil and rock overlying a potential failure plane is the driving force for slope instability. Shear stress is defined as the down-slope component of the weight of the slope-forming material.

The shear strength of slope-forming materials is the resisting force that works to counter the shear stress acting to move material downhill. Factors that decrease shear strength include weathering processes that weaken material strength and increases in pore pressure, which increases the buoyancy force that acts to reduce the effective normal stress

Environmental and Time-Dependent Effects

Slope failure is a good example of a geomorphic threshold. When the material on a formerly stable slope slides downhill, it means that something changed that upset a previous equilibrium between driving and resisting forces. The environmental factors that influence slope stability change over short and long time scales in response to rainfall or seismically-driven forcing, vegetation succession following disturbance, and the evolution of soil thickness and slope morphology.

Landslides on unstable slopes ($FS \leq 1$) are generally triggered by earthquake shaking or by intense rainfall events that saturate hillslope soils.

During storms, pore pressures increase as the water table in a hillside rises, thereby reducing the effective normal force and decreasing the shear strength.

More intense or longer-duration rainfall translates into a higher water table, and therefore greater pore pressures. Studies of the rainfall conditions associated with slope failures have shown that shallow failures in hillside soils tend to occur once rainfall exceeds a quantifiable intensity-duration threshold that varies by region.

In other words, debris flows tend to initiate once it rains hard enough for long enough to sufficiently saturate hillslopes. However, deep-seated landslides may be triggered long after rainfall, or in response to seasonal changes in the water table because of the time required for water to infiltrate to and raise the water table.

While landslides tend to be triggered by destabilizing events, the potential for slope failure also changes gradually over time as the hydrology and strength properties of a slope change.

Soil depth increases over time as colluvium fills in topographic hollows, resulting in decreased *FS*. When processes like tectonic uplift and stream incision cause a slope to steepen, its *FS* decreases. Thus, as slopes become steeper and soils thicker, slope failure becomes more likely.

It follows, therefore, that anything that reduces the resisting forces or increases the driving forces will lower the Fs, and thus increase the chances of landslide or other type of downslope movement.

Predicting the likelihood of landslides and related phenomena taking place is usually based on the analysis of landforms, geology and geomorphological processes to be found in the area, and this includes past processes e.g. a landslide is likely to repeat itself.

The forces of slope instability are not static; rather they tend to change with time. Therefore, depending on the changes in local conditions, the Fs may increase or decrease. Take for example, road construction that crosses the critical ***toe of the slope***, it will reduce the driving forces because some of the slope material is removed. In the same way it will reduce the resisting forces because the length of the slip plane is reduced, and it is this plane along which the resisting force (shear strength) acts.

The overall effect of the road construction is to lower the Fs, because the reduction of the driving forces is small compared to the reduction of the resisting forces. That is, only a small portion of the potential slide mass is removed but a relatively large portion of the total length along which resisting forces is removed.

APPLICATIONS OF SLOPE STABILITY ANALYSIS

- An understanding of slope processes and dynamics is important for engineering, hazard assessment, and land management applications.
- Recognition of landslide hazard zones and ancient landslides is essential for upland development and provides vitally important context for geotechnical engineering analyses.
- Building a house on an ancient slow-moving earthflow, or in the path of future debris flows can invite disaster if it is not recognized and accounted for in project design.
- Ancient landslides sometimes have residual strength lower than their original strength and thus can be reactivated by changes in slope hydrology that accompany development.
- Reading terrain to identify an upslope head scarp or downslope landslide toe is useful for identifying ancient landslides and assessing hazards to communities or new developments.
- Landslide hazard mapping of potentially unstable slopes — those that are prone to failure but that have not yet failed — can be based on slope stability models, extrapolation based on statistical characterization of observed failure locations, or the propensity for debris flows to initiate in steep, convergent topography.
- Human actions influence slope processes by changing the properties of hillslope materials, altering slope configuration, changing the hydrology, or adding and removing vegetation. Excavating the toe of a slope to make a road cut, construct a building pad, or mine gravel can remove basal support and trigger slope failure.
- Routing street or gutter runoff onto steep, slide-prone slopes can increase soil moisture levels and cause slopes to fail. The risks associated with clear-cutting steep, forested hillsides are significant and can be assessed using slope stability analysis to delineate areas that are especially susceptible to post-harvest slope failures.

- Changes to the erosion resistance of low-gradient slopes associated with agricultural practices like ploughing or overgrazing cause gully development, soil loss and other types of damage to agricultural lands, as well as sedimentation problems for locations downslope and downstream. Effective erosion control practices begin with an understanding of the nature of the slope processes and then increasing slope stability by either reducing the driving force, for example, by building terraces, or increasing the resisting force, for example, by building retaining walls or replanting denuded slopes.

Generally it is far less expensive and more effective to address sediment problems in streams by reducing erosion at its source on upland hillslopes than it is to deal with an overload of sediment and its environmental consequences downstream.

Landslide Hazards

Landslides become a hazard when it affects man and his livelihood.

Every year, several landslides occur globally leading to massive losses in life and property. There are several dramatic events which are always reported in the media, though quite a number of small less newsworthy events also occur.

The falling debris may have the following effects:

- Destruction of crops and fields along the slope.
- Sedimentation and siltation of rivers and streams and thus affecting the flow of rivers as well as the quality of water for human consumption
- Loss of lives and destruction of property. Many people have always been buried alive especially those settlements on steep slopes with properties worth millions of shillings also destroyed.
- Destruction of communication lines as well as transport links in form of roads which are cut off by the falling debris and thus disconnecting the areas from the main centers.
- There is increased government expenditure in trying to help those affected by landslides as well as opening up the destroyed communication routes.

GEO 3204: ADVANCED GEOMORPHOLOGY COURSE

Lecturer: Dr. Nseka Denis Galende

<u>Topic six: Deep chemical weathering of the tropical regions and laterization</u>

Learning outcomes for this topic

By the end of this topic, you should be able to;

1. Discuss the processes and the role of deep chemical weathering in the formation of laterites
2. Evaluate the economic and geomorphological implications of laterites to our region.

Laterites originated from deep chemical weathering processes which are typical of the humid tropical world.

Laterites as a result of mobilization of concentrates of iron called iron sequiseoxides. Most rocks have got iron. Iron and magnesium are some of the most abundant minerals in the earth's surface

The mobilization requires weathering or rotting of the rocks that contain iron and release of iron as concentrates.

The iron concentrates are mobilized and deposited in the subsurface where the rock has been weathered.

Conditions for laterization

Suitable gradient

For the rock to be weathered and the iron oxides to be deposited in the subsurface, there must be a suitable gradient.

The suitable gradient has to be generally a gentle landscape.

A gentle landscape facilitates the forces of movement of material vertically down into the subsurface.

It is when the landscape is gentle in sloping that the bulk of the materials can move into the subsurface.

Climatic conditions

It is mobilized during a time of high rainfall and certainly high temperatures.

This is the period of puriviation, when the conditions are wet and the weathered materials are mobilized by water into the subsurface.

After a period of puriviation (20 to 50 years), a period of desiccation follows.

Desiccation period is important to dry or make dry the concentrated iron products called sequiseoxides. And because of the viscous nature of the moving materials, they become dry hard.

The hard material is called laterite.

Laterites are products of weathering consisting of a wide iron concentration.

Types of laterites

There are two types of laterites; murrum or concretionary laterite and duricrust which is like a cemented material.

The economic significance of laterites

- Laterites are very important material for road construction
- Murrum has been used negatively in swamp reclamation because it can form a very solid foundation for the encroacher's house to exist.
- Murrum is not good in agricultural land. Soil scientists and tropical soil surveyors have often labeled laterites as the leprosy of the tropical region. Soil that is rich in laterites cannot provide rich minerals to enrich soils for plant growth. A soil that is therefore dominated by laterites is a soil that is deprived of usefulness for agriculture,
- Laterites tend to create a dense layer immediately blow the soil surface. This reduces chances of deep percolation of water from the incoming rain. It therefore creates parched water tables below the surface which can lead to crabbing if the storm becomes pro-longed. This can result into extensive flooding especially in a flat landscape.

MAKERERE UNIVERSITY
DEPARTMENT OF GEOGRAPHY GEO-INFORMATICS AND CLIMATIC SCIENCES
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GEO 3204: ADVANCED GEOMORPHOLOGY COURSE

Lecturer: Dr. Nseka Denis Galende

Topic 6: Hydro-Morphology of Drainage Basins

Learning outcomes for this topic

By the end of this topic, you should be able to;

1. Demonstrate the physical make-up of a drainage basins
2. Discuss the applications of Drainage Basins in water resource management

Basic Definitions

Drainage basin- can be defined as the unit of land surface which collect, concentrate and promote the movement of water and sediment. All land surfaces are composed of drainage basins.

Watershed- is defined as a body of land bounded above by a ridge or water divide and below by the level at which water drains from it. This term is often synonymously used with the term ***water catchment.***

Water enters a watershed as precipitation and leaves it as stream flow, flow below ground, evaporation and transpiration. The two terms are often used interchangeably as they, more or less, mean the same. It is important to note that river networks occur within the drainage basins or catchments, which frequently have finite boundaries called divides or watersheds.

The significance of drainage basins

The drainage basin provides the almost ideal natural unit over which hydrological processes are integrated, and for which water balance may be constructed to show the disposal of precipitation into a number of subsequent forms such as interception, soil moisture and ground water storages, evapotranspiration and runoff.

It is an area over which fluvial geomorphic processes operate and for which an energy balance can be constructed- whereby precipitation input is equated with an erosional output of water and gravity moved load.

Today, biologists, ecologists, hydro-geomorphologists and bio-geographers have turned to the drainage basins as ideal units in which to develop the ecosystem approach. It is in the drainage basin that ultimate ties between physical, economic and human resources needs must not only be clearly shown but also, positively utilized.

The unity of the drainage basin is most clearly seen in the delicate balance of processes, geomorphological and climatological, biogeographical and hydrological, which are at work in it.

The Historical Perspective

Historically, the concept of the drainage basin as an important and appropriate areal unit for the organization and human activity is undoubted.

Indeed, the earliest forms of human settlement and organized political systems/units developed in drainage basins. Drainage basins and stream channels were favored because of their water supply, fish and game, as well as rivers for transport.

Direct use of water as a source of power tied societies to valley locations. All this demonstrate the valuable role drainage basins have always played in human settlement and development.

Modern Perspective

Today, the importance of drainage basin management has been realized through some of the consequences of unplanned utilization of it. For example, one should expect some consequences from construction of settlements in flood plains, and construction of dams in mountains for water and power supply.

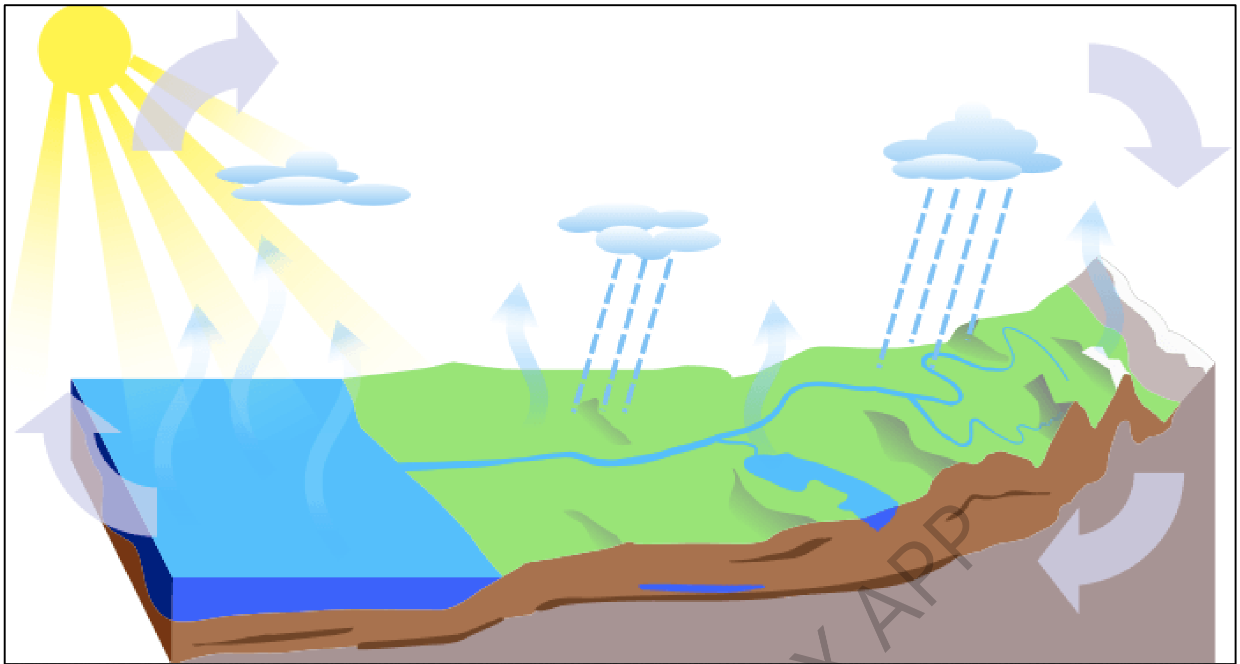
The technological advancement by man in many areas has made him "break free" from some of the earlier physical factor controls of the environment and drainage basins have not continued to exert a restrictive influence. Nevertheless, drainage basins remain natural units which require careful physical, economic, industrial and social planning if crises are to be avoided.

Many may believe that man's response to the proposed integrated approach of drainage basins hinges upon the existence of a powerful incentive such as a natural crisis, and yet environmental planning should not wait for crises to arise.

The Hydrological Cycle

The hydrological cycle is the cyclic movement of water from the sinks (water bodies, for example, the oceans, seas and lakes) to the atmosphere (the source) and then by precipitation in various forms (e.g. Rain, hail, snow etc.) to the earth where it collects in streams and river channels and runs back to the sinks.

See below, a diagrammatic illustration of the hydrological cycle



In the drainage basin or catchment studies, the main concerns are:

(a) The ways in which fluid or water is stored and transferred over and under the surface;
(b) Transport by water of sediment or dissolved materials;
(c) Its alteration of the earth's surface by erosion and deposition

Water is subject to natural fluctuations and human modification. Therefore, it is useful to have a conceptual framework within which to analyze environmental problems which have arisen from or to anticipate the consequences of development. Such framework is provided by the hydrological cycle.

The hydrological cycle describes the ways in which water moves around the earth as follows;

(1) During its endless circulation from the ocean to atmosphere to earth and back to ocean, the water is stored temporarily in streams, lakes, the soil, or ground water and becomes available for use.

(2) In the cycle, solar energy evaporates water from the ocean. This water is carried by winds over the continents, and when atmospheric conditions are favorable, a portion of the water is precipitated, generally as rain or snow. If cool conditions prevail at the ground surface, snow will be stored there until enough energy is available for melting. The melt water will, therefore, follow the same pathways as rain water.

If it rains in winter where temperatures are in negatives, it freezes into snow and thus ice. This makes water not available in drainage flows; it is not until when temperatures increase that the water melts. That is why during springs and summers there more water is flowing through the channels and sometimes causing floods.

3 (a) Before reaching the surface of the earth, most rain water is caught by vegetation

(b) Some of the water is stored upon leaf surfaces during wetting and the reminder falls to the ground from leaves and branches, or runs down trunks and stems.

(c) A small amount of water never reaches the ground, but is evaporated back to the atmosphere from vegetation during and after the rainstorm. The process by which water is short-circuited back to the atmosphere in this way is known as interception.

4 (a) Upon reaching the ground surface, a portion of the rain is absorbed by the soil. The portion that is not absorbed remains on the surface of the ground, fills small depressions, and eventually spills over and runs quickly downslope into streams as *overland flow*, which generates floods.

(b) The absorbed rain water seeps into the soil by the process of infiltration, and is held there as soil moisture by capillary forces. If the soil moisture content is raised sufficiently, infiltrating water will displace older water, which may percolate laterally through the top soil into streams as subsurface storm runoff or vertically to the ground water zone, when the pores of the soil or rocks are completely filled with water.

(c) From this zone water moves slowly into streams, swamps or lakes, providing surface runoff during dry weather.

(d) Not all infiltrated water reaches a stream. Some of it remains in the top soil after and is returned to the atmosphere by evaporation from the surface of soil or by transpiration from the leaves or plants. Another portion of waters evaporates from the streams, lakes and swamps.

5. The concept of the hydrological cycle can be extended to include the movement of sediment, chemicals, heat and biota contained in water. Therefore, the hydrological cycle includes the aqueous phase of the cycles of sediment, gases and minerals, heat and living matter. The unifying element in such a discussion is the storage and transport of water and its constituents. This extended definition of the hydrological cycle enhances the value of the cycle as a framework for analysis of many problems in planning and ecology.

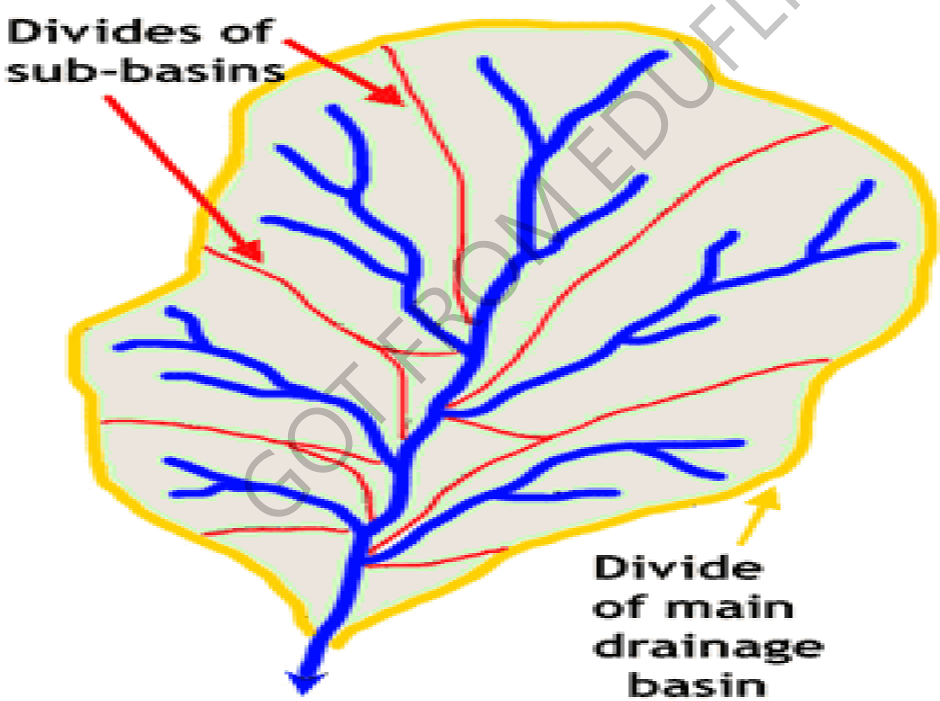
6. Rocks exposed at the surface of the earth combine with water, various gases (especially oxygen and carbon dioxide), and organic acids by a set of geologic processes known as weathering. The products of these reactions are soil and chemical solutions. The latter, flow through the soil and the ground water zone to steams, determining the chemical properties of each water resource, its suitability for irrigation, washing, drinking and other uses.

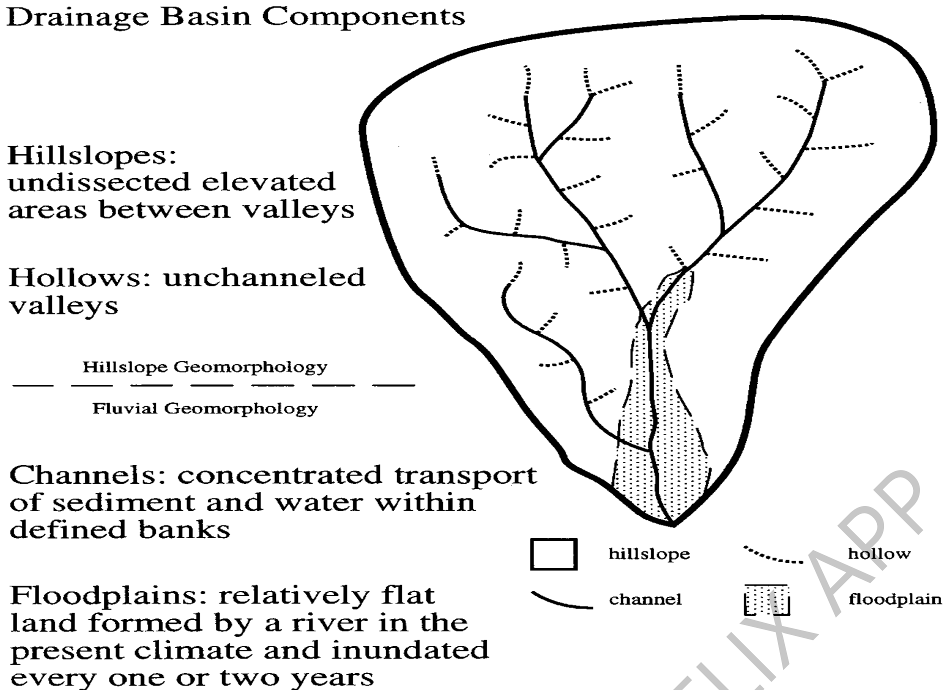
7. The residual soil is eventually eroded by processes such as *rain splash, sheet wash, gullying and landsliding*, which carry loosened particles into rivers through which they are transported to the sea

8. The transporting agents may be intermittent, and the eroded material may be deposited temporarily on hillslopes, in channels or flood plains of rivers or in lakes. It is by these processes that assemblages of landforms are produced. Hence, soils and landscape, then, are products of weathering and movement of sediment through the hydrological cycle. Sediment and solutes are eventually returned to the sea and incorporated into new rocks to complete the cycle of geologic materials.

Generally, this hydrological cycle is an approximate framework for analyzing human modifications of land and water resources

The structure of a drainage basin





There is need to understand the physical make-up of a drainage basin before one can appreciate its role as a planning unit in environmental management.

The fundamental elements of a drainage basin are:

(a) The valley and channel networks;
(b) The watershed or divide that surrounds it, demarcating it from adjacent basins.
(c) The organization of the network in the drainage basin is important because it reflects the efficiency of the main lines of energy and material flow in the system.

The structure of a drainage basin means the energy components or the nature and flow of energy of energy components e.g. are they dense, here you measure the ***drainage density*** which is measured in **km per km²** i.e. the total length of all the streams and channels divided by the area of the unit. The higher the density, the higher the efficiency of the drainage system. The main channel always occupies the lowest point in the drainage basin. Water in the drainage basin begins when it rains into the drainage basin.

The unity of a drainage basin has been elaborated on. Geomorphologically and to a large extent hydrologically, the river and its drainage basin are synonymous. It would be a mistake to regard the water flowing in the river channel as distinct from the remaining water within the drainage basin.

The work of water within the drainage basin commences from the moment of impact of a raindrop on the soil surface to its final exit from the basin via the main channel. Runoff is a basin-wide process. It actually occurs everywhere within the drainage basin-

(a) On surface (normally over only limited areas of the basin).
(b) Beneath the surface as interflow (subsurface flow) or base flow/ ground flow.

The latter type of flow is the main flow route. It should be noted that water movement in the drainage basin is the prime agent in crating landforms in fluvially eroded areas and is influenced by a wide variety of factors which include: climate, vegetation cover, and human activity.

Furthermore, parameters of drainage basin such as the surface shape, the nature and disposition of its channel network may act as indices of both the landforms which may have been developed and the hydrological processes operating to modify those landforms.

Hence, the basin and channel network characteristics are strongly associated, although not systematically (casually). In other words, the basin plan does not directly (but indirectly) determine channel network arrangement. For example, both characteristics are largely determined by such factors as geological structure and vegetation cover.

Many drainage basin networks have often shown random patterns so much so that it becomes difficult to associate them with any particular origin or development. In a few cases, however, a distinctive organized pattern may be clear, implying a strong environmental control such as bedrock structure.

Important Applications of Drainage Basins

The real importance to applied geomorphology, of a study of the structure of the drainage basin and its characteristics lies in the integrated nature of that structure. The following are key applications;

Many of the morphometric characteristics such as basin size, length of streams ***(drainage density)*** can be directly related to fluvial characteristics such as discharge. Such easily measured basin properties tend to have definable predictive qualities which can be used to infer the likely effects of any interference with the system by man. Using the same properties, estimates can be made of the dynamic characteristics of a river in a river basin. They can also, be used for an unmonitored part of an already developed area. All this is a vital requirement in a natural resource survey.

After studying one drainage basin e.g. A you can use the information to carry out developments in another drainage basin which has not been studied by comparing their flow channels, slope angles, soils. Thus you will be saving money which you would use to study drainage basin B. you thus save time and resources. You can predict drainage basin B by using results of drainage basin A.

It can show how efficient a drainage basin system is in an area; a drainage basin with many channels is more efficient than the one with few channels. Heavy sediment transportation is carried out by drainage basins with low/few channels.

It can help in predicting runoff by studying vegetation cover, soil depth, slope angle etc. steep slope lead to rapid runoff due to downslope component and conversely so for gentle slopes. Water has more effect on sandy soils than on clay soils. Runoff on vegetation has lower effect than on bare soil.

You can use variables from one measured area to predict what may happen on the same variables on another drainage basin.

You can group drainage basins with similar characteristics in terms of landforms, soils etc; you can go and carry out analysis in each of those groups. You can pick only one drainage basin in one group which results you can apply to the rest of the drainage basins in the same group.

Some limitations are, however, inherent in applying regression equations developed in one area to another area.

Also, the correlations between morphometric and dynamic properties may at times be unpredictable. In addition to this, study of a drainage basin requires assessment of particular applications in terms of history and geomorphological variability of the basin concerned.

Normally, predictive equations may be directly applied to some parts of the system but not to the whole system.

Hence careful geomorphological analysis must always be applied to assess the relevance of a predictive equation to each situation.

The concept of a steady state must be considered in the drainage basin; i.e., those portions of the basin (hillsides or river channels), where material exported balances with material imported.

The achievement of a steady state (in which landforms and rate of supply and removal of water and sediment are mutually adjusted) may be influenced by scale. There are three important scales:

(a) The meso-scale features e.g, slope and stream reaches
(b) Micro-scale features, e.g., sites in fluvial landforms
(c) The macro-scale. E.g., whole river basin. This scale is time dependent as a basin may still carry signs of past periods of geomorphological activity.

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Lecturer: Dr. Nseka Denis Galende

Topic 7a: Drainage basins processes

Learning outcomes for this topic

By the end of this topic, you should be able;

1. Discuss the mechanics of the drainage basin processes of runoff and infiltration
2. Evaluate the implications of drainage basin processes in the occurrence of natural disasters and environmental management

In drainage basin analysis, geomorphologists have the opportunity of using an "open system approach" which is very applicable to drainage basin dynamics and processes. Application of the approach, however, depends upon knowledge of the mechanics of the drainage and for over half a century the basin has been perceived in several different ways. An important conceptual view of the drainage basin was provided by Robert E. Horton in 1945 and this later came to be regarded as the ***overland flow model*** considered in the topic on overland flow.

An interpretation of the drainage basin processes is greatly assisted by the hydrological cycle framework. In general, the basin system can be visualized in terms of the water balance equation, which may be stated as follows:

Runoff (output of water) = Precipitation (input)- losses (evaporation) $\pm$ changes in storage

The main drainage basin processes include infiltration, runoff, erosion and deposition. These are the processes responsible for transfer of energy and material (water, sediment and solutes) from one part of the basin to the other and flow from the basin, which all contribute to slope process and change

Infiltration Process

1. Infiltration is an important process in the study of soil erosion and general drainage basin processes. This is mainly because the process determines how much water from a given rainfall event is available as runoff to cause erosion on the land surface.

2. Infiltration may be simply defined as the process of water entering the soil. This should not be confused with the hydraulic conductivity of the soil, which is only one of the several factors affecting the rate of infiltration. There is need to define two more terms used in infiltration process, namely infiltration rate and infiltration capacity.

(i) ***Infiltration rate*** also known as ***hydraulic conductivity*** is the volume flux of water across the surface, and is, in general, less than the maximum possible value. It is the rate of entry of water into the soil e.g. in one minute how much water will penetrate the soil e.g. 10 liters per minute.

(ii) **Infiltration capacity** is the maximum flux of water across the soil surface. It is the maximum amount of water soil is ready to shallow at a given time e.g. 1000 liters is 6 hours.

3. The typical infiltration curve shows a rapid initial infiltration rate, which drops fairly quickly to some constant value. As the water entering into the soil declines, runoff increases.

The water drain into the soil by two main forces:

(a) Gravity. One of the processes by which water enters the soil is by gravitation flow. This is the weight of the water which forces it through the soil pores.
(b) Capillary force- water is attracted to and held as a thin layer/film (molecular) around the soil particles. It is the force which pulls water to the soil particles.

During a rainstorm, the spaces between the soil particles become filled up with water and the capillary forces decrease so that the infiltration rates start high at the beginning of the storm and decline to a level which represents the maximum sustained rate, at which water can enter/pass through the soil- ***infiltration capacity***

Field capacity moisture is when all the water has gone away and it is now only held by the capillary forces of the particle and this occurs 24 hours after a rainstorm.

The process takes the following form:

- Soil moisture builds up leading to saturation, which causes a reduction in the hydraulic gradient (distance between the surface of the soil and the parent rock through which water can penetrate) near the surface. The process is speeded up by the existence of soil horizons of low permeability beneath more permeable surface horizons and by through flow from upslope.
- Changes in the soil surface, such as the reduction in pore size by clay mineral swelling and the fine particles inhibit infiltration
- If rainfall is less than infiltration capacity, the infiltration rate will be equal to rainfall rate.
- If rainfall intensity exceeds the ability of the soil to absorb moisture, infiltration occurs at the capacity rate.

5. The excess of rainfall over infiltration collects on the soil surface and runs over the ground to streams.

6. Infiltration is expressed in units of depth per unit time (normally, mm/hr), the same way as rainfall intensity. The two refer to the depth of a sheet of water that would soak into the soil in a chosen time interval.

7. The soil surface is a filter that determines the path by which rainwater reaches a stream channel:

(a) Water that does not infiltrate runs quickly over the ground surface, whereas water entering the soil moves much slowly underground. Therefore, the soil plays a major part in determining the volume of storm runoff, its timing, and its peak rate of flow. These are all, of importance to the hydrologist and geomorphologists, e.g., those who are interested in the planning of culverts, bridges and other small structures.
(b) On running over the ground surface, water is capable of eroding top soil and important organic residues on the surface.
(c) The soil conservationist is concerned with either inducing this overland flow to infiltrate or conducting it safely away from the fields or farm structures.
(d) Geomorphologists are also concerned with the magnitude, frequency, and spatial characteristics of infiltration relative to rainfall intensity, because overland flow is an important agent of landscape development.

The operations of the infiltration process

(1) Examination of a lump of soil or the sides of a pit dug through a soil profile reveals that soils consist of millions of particles of sand, silt and clay, separated by channels of different sizes.
(2) These channels include shrinkage cracks, wormholes, root holes, spaces between lumps or crumbs of soil, and very fine spaces between the individual particles themselves.
(3) It is these soil pores that help to encourage infiltration rate, the water being drawn into the soil by forces of gravity and capillary action and as a result:
(a) The rate of entry of water by free-gravity flow is limited by the diameters of the pores. As water moves along such pores, it is subjected to flow resistance, which increases as the diameter of the soil pore decreases.
(b) Under the influence of gravity, water moves vertically downward through the soil profile. On the other hand, capillary forces may move water vertically downward or with a horizontal component. They act to draw water into the narrower pores just as capillary forces drawing water up a narrow glass tube are greater than those in a wide tube.
(c) Although such forces are strongest in soils with very fine pores, the pores may be so small that there is considerable resistance to flow through them.
(d) In large pores such as wormholes or root holes, capillary forces are negligible and water flow through them.
(e) Infiltration therefore, involves three interdependent processes:

(i) Entry through the soil surface;

(ii) Storage within the soil;
(iii) Transmission through the soil.

Limitations on any of these processes can reduce infiltration rates. Also it is important to realize the close interrelationship between infiltration, and the subsurface storage and movement of soil moisture.

The Infiltration Curve/Equations

(1) The rate of infiltration declines rapidly during the early part of a storm and reaches an approximately constant value after 1 or 2 hours of rain when the soil has fully been saturated. Several processes combine to reduce the infiltration capacity during the storm:
- The filling of fine pores with water reduces capillary forces drawing water into the pores and fills the storage potential of the soil;
- Clay particles swell as they become wetter and reduce the size of pores; the impact of raindrops break up soil aggregates, splashing fine particles over the surface and washing them into pores where they impede the entry of water; the resistance by air trapped in the soil can also reduce infiltration capacity as it blocks water from entering the soil.
- In large rainstorms, it is the final, low rate of infiltration that largely determines the amount of surface runoff that is generated.

(2) Infiltration capacity corresponds theoretically to saturated hydraulic conductivity of the soil: (***saturated hydraulic conductivity is the ease with which pores of saturated soil transmit water. Or it is the amount of water that would move vertically through a unit area of saturated soil in a unit time***)
   a. Currently it is believed that it is the hydraulic conductivity of the wetting front that controls infiltration capacity.
   b. Explanation to this is that: air entrapped in the pores as the wetting front passes downwards through the soil limits the soil from attaining infiltration.

(3) A mathematical formula was developed by Philip (1957) to describe the change in infiltration rate over time;

$$\mathbf{i = A + B.\ t^{-1/2}}$$

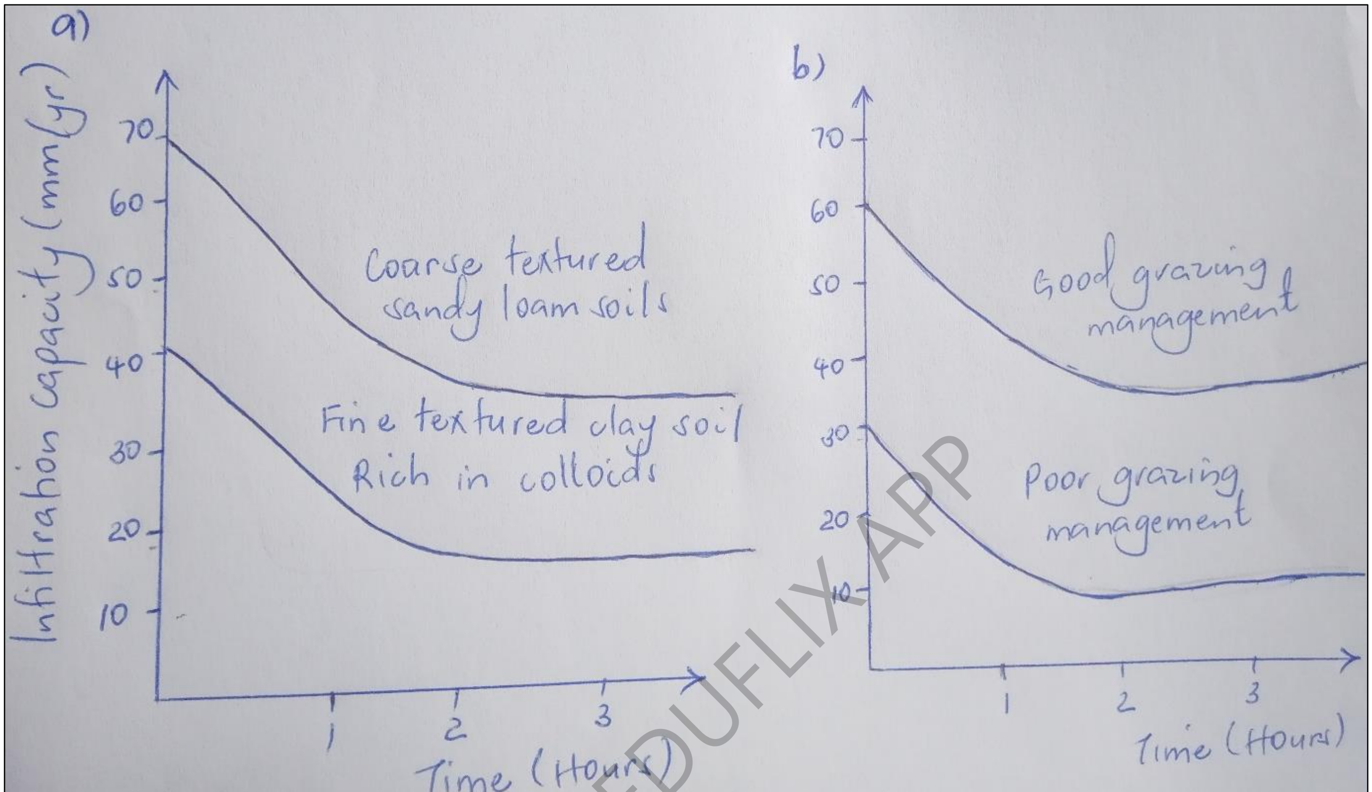
Where i= is the instantaneous rate of infiltration; A=transmission constant or saturated hydraulic conductivity of soil; B= sorptivity, defined as the slope of the line when I, is plotted against $t^{1/2}$; t= the time elapsed since the onset of rain ***(Sorptivity is the ability of the soil to absorb and transmit water by capillarity).***

(4) The equation has been found to be well applicable to soils in Southern Spain, but gives poorer results in semi-arid rangelands. It is particularly good for short time record of infiltration. A better empirical model has been developed by Robert E. Horton (1933)

Controls of infiltration

Many factors influence the shape of the infiltration curve, but the most important variables are: *Rainfall characteristics, soil properties, vegetation cover; land use etc*.

The following diagrams illustrate the influence of these factors



Rainfall control:

Long, heavy rainfall packs down loose soil surface, disperses fine soil particles and causes them to plug soil pores. Rainstorms of long duration fill up the storage potential of the soil and cause clays to swell or may saturate the soil completely.

Soil properties control

Coarse-textured soils such as sands have large pores down which water can easily drain, while the exceedingly fine pores in clays retard infiltration.

- If the soil particles are held together in aggregates by organic matter or small amount of clay, the soil will have a loose, friable structure that will allow rapid infiltration and drainage.
- The depth of the soil profile and its initial moisture content are important determinants of how much water can be stored in the soil before saturation is reached.

Therefore, deep, well drained, coarse-textured soils with a large content of organic matter will tend to have high infiltration rates. On the other hand, shallow soil profiles developed in clays will accept low rates and volumes of infiltration.

Vegetation cover control

Vegetation cover and, therefore, land use, are very important controls of infiltration.

- Vegetation and litter protect soil from packing by raindrops, and provide organic matter for binding soil particles together in open aggregates.
- Soil fauna that live on organic matter assist this process by churning together the mineral particles and the organic material

The manipulation of vegetation during land use causes large differences in infiltration capacity under the same rainfall regime and soil type. The problem is further aggravated by land management practices such as ploughing, which break up soil aggregates, or if the surface is compacted by vehicles or trampling by livestock. Each of these reductions of infiltration capacity increases the amount of surface runoff, and can produce soil erosion, flooding and other social and economic costs such as:

(i) The cost of soil conservation
(ii) The cost of channel modification
(iii) The cost of other attempts to minimize damages caused by excessive runoff.

Measurements of infiltration

The way infiltration is measured depends upon the problem at hand:

If detailed information is required for small areas in the design of some valuable installation or land management plan. Direct field measurement may be made and used in the calculation of runoff rates.

In such a case, a few measurements of infiltration are made in the major soil types of the region and used only as indices.

Most planning problems do not justify detailed field measurements. Instead, infiltration capacity must be estimated from soil types/properties and vegetation cover.

Errors from the second procedure are large and provide little more than an index of the runoff potential of a catchment.

In the evaluation of infiltration rates, use is made of natural and artificial rainfall events of water ponded on the surface of the soil.

Ring-Infiltrometers

Both single-ring and double-ring infiltrometers are used.

- A single-ring infiltrometers is a single cylinder or a simple wide tube, with a diameter of about 10 to 30 cm, that is driven into the soil 5 to 50 cm. water is then ponded 1 to 2cm deep inside the tube and is maintained at a constant level by supplying water from a graduated reservoir

- The rate of supply required to maintain a constant depth is measured in the graduated reservoir and indicates the rate at which water is entering the soil.
- Measurements with ring-infiltrometers only provide indices of the variations between sites, generally yielding values that are 2 to 10 times as great as infiltration capacities measured during natural rainfall under the same conditions.

The values are, however, useful in simulating to a degree;

(i) Infiltration conditions in some irrigated fields;
(ii) Seepage from ditches, septic systems, broken sewers, and broken water pipes

The main advantage of cylinder infiltrometers is that they are cheap, simple to install and use.

Sprinkling infiltrometers

Several types of equipment have been designed for simulating rainfall on small plots. They are generally called sprinkling infiltrometers. The plots vary from <1 to >100 sq. meters. Spray nozzles are designed to simulate closely the size and rainfall velocity of natural raindrops.

In the simulation, rainfall intensity, and the rate of runoff from the plot is measured. The difference between these two rates is the infiltration capacity.

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Topic 7b: Runoff Processes

When rain falls on a land surface, part of it may infiltrate, depending on the rate of rainfall and the permeability of the substrate. The amount of rainfall that exceeds the infiltration capacity collects in pools and eventually flows over the land surface. This process of overland flow is quite inefficient because a large surface area greatly resists water movement. Depending on the substrate resistance and power of the flow, the tendency is to incise to form a channel. This transition from overland flow to channel flow is the first step toward a response to rainfall input. Eventually the dissection by channels leads to the differentiation of hills from valleys.

Not all the rainfall is transformed to overland flow and infiltration to groundwater. A portion is lost to evaporation and to transpiration by plants. What eventually flows off the landscape from surface and subsurface sources is the runoff *R* given by

$$R = P - ET \pm S, \qquad (8)$$

Where *P* is the precipitation and *ET* is the combination of evaporation and transpiration; *S* is a storage term for water held in plants, soils, and subsurface rocks. The overland flow component of runoff appears very quickly after storms, while the subsurface flow components appear much more slowly. In channels, all forms of runoff generate increased stream power because of increased discharge. This allows streams to incise, thereby deepening valleys, which may widen through hillslope processes.

Several processes produce storm runoff. They include:

(a) Horton overland flow;
(b) Subsurface flow;
(c) Return flow;
(d) Direct precipitation onto saturated area;

The last two are also known as saturated overland flow. Each of these runoff processes has a difference response to rainfall or snow melt in the response of runoff produced its peak rate, and the timing of contributions to the channel. The relative importance of each processes in a region (or more particularly, on each slope) is affected by climate, geology, topography, soil characteristics, vegetation and land use.

The dominant processes vary between large and small storms, and this should be considered in overall planning and in individual design problems. Generally, there is need to divide the situation into environmental conditions:

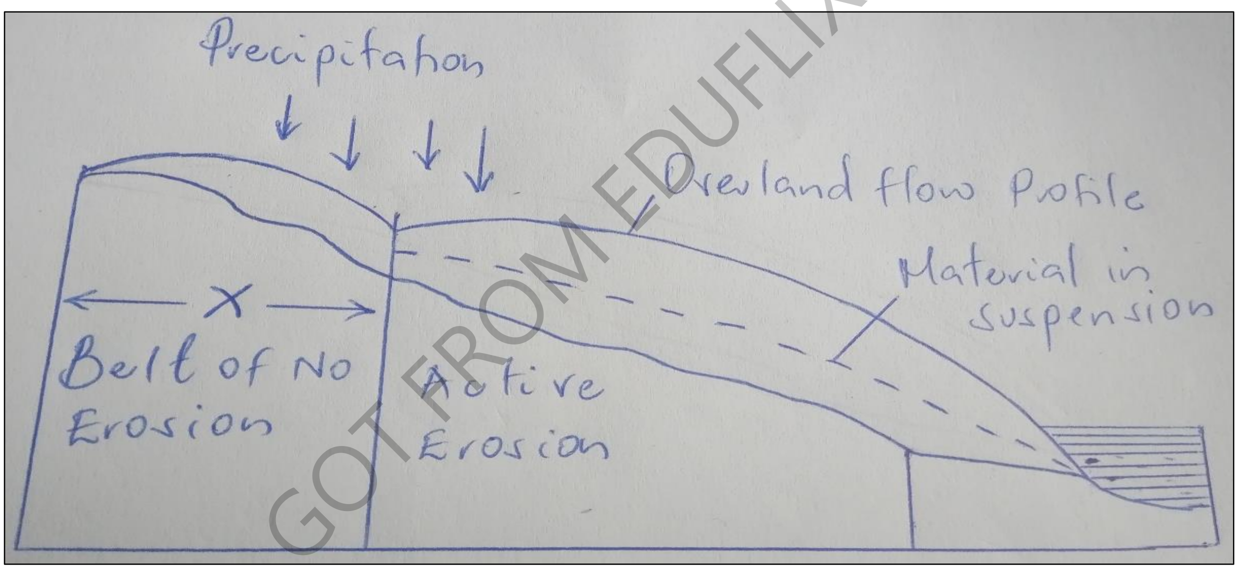
- The condition or region where rainfall intensity exceeds the infiltration capacity of the soil.
- The region or condition where the infiltration capacity is not a limiting factor.

The latter is typical of vegetation covered humid regions, while the former is typical of semi-arid and urban area.

Horton Overland flow

There is a maximum limiting rate at which a soil in a given condition can absorb rainfall. Robert E. Horton in 1933 keenly observed and analyzed the infiltration process. His conclusions became the foundation on modern quantitative hydrology.

He called this limiting rate, the infiltration capacity of the soil, and indicated that it declines with time after the onset of rainfall, reaching a fairly constant rate ½ to 2 hours into the storm. The sequence of Horton's model is depicted in the following diagram.



The form of hillslope overland flow according to the model of Horton"

Description of the processes in the model

(a) The model predicts that prolonged rain falling on the slopes of a drainage basin possessing relatively uniform infiltration capacity will, if the rain intensity is greater than the infiltration capacity, produce overland flow over all the basin approximately simultaneously.

(b) Water will accumulate on the soil surface and fill small depressions. The water stored in these depressions is called *depression storage*. Its maximum volume may vary from 0.1 cm on steep, smooth hillslopes to 5 cm on agricultural lands of low gradient that have been furrowed or terraced to catch this water.

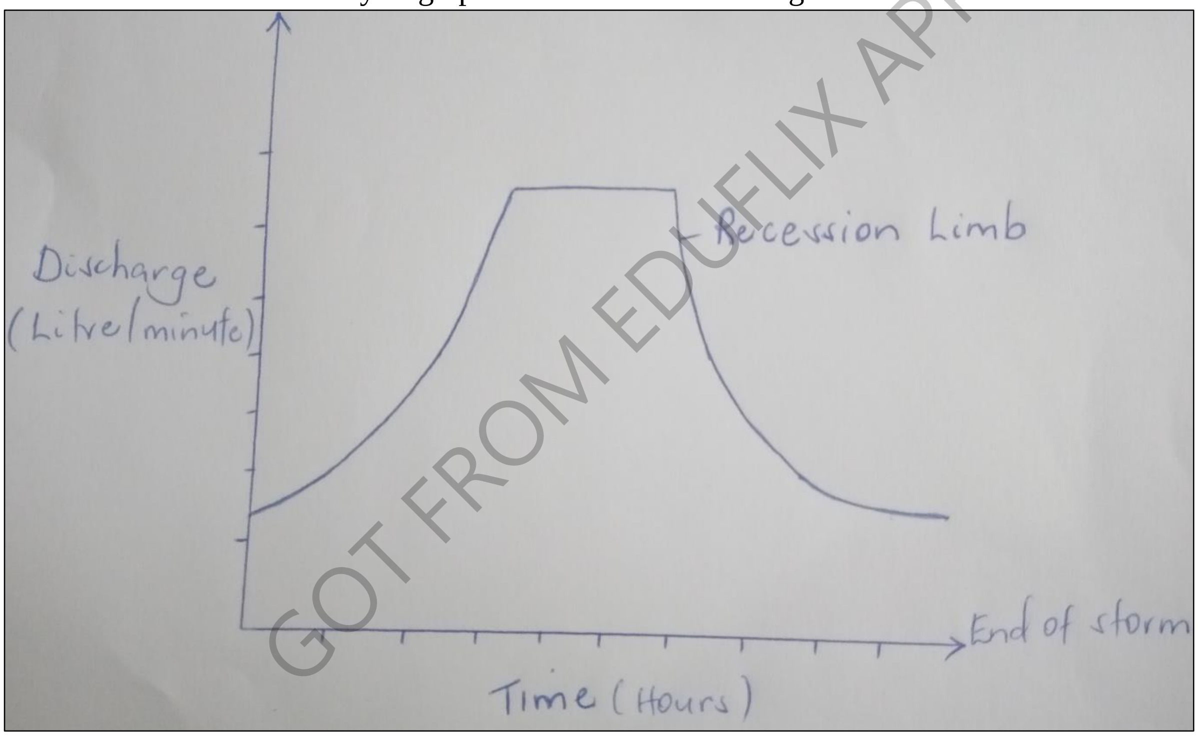
(c) Depression storage does not contribute to storm runoff. It either evaporates or infiltrates later.

(d) As the storm proceeds, the depression storage capacity is eventually exhausted, and water spills over to run down slope as ***an irregular sheet of overland flow.*** The sheet increases in depth and velocity, as more and more excess precipitation is added to it while it flows down slope. Velocities range from 10 to 500 m/hr as a depth of flowing water ranges up to one centimeter.

(e) Generally, overland flow enters micro-channels, which coalesce to form rivulets which discharge into small gullies. This continues until discharge into major channels occurs. A long each micro-channel, lateral flow from land surfaces takes place.

(f) There is normally water stored on the hillside in the process of flowing downslope. It is called surface detention. Once rainfall intensity exceeds the infiltration capacity, runoff rises rapidly to a sharp peak at the end of rainfall, followed by a rapid decline as soon as rainfall intensity decreases.

(g) Water stored as surface detention during the storm drains away to provide the steep limb of the hydrograph as illustrated in the diagram below.



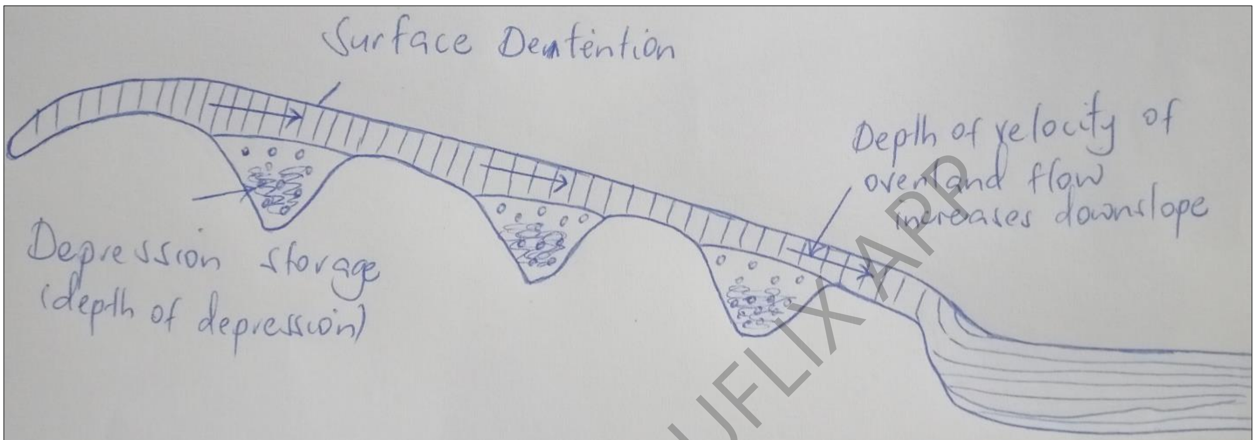
During the succeeding burst of rainfall, the process is repeated.

In areas where Horton overland flow is the dominant producer of storm runoff, it can be seen as a thin film or sheet or as a series of tiny rivulets over large areas of hillslopes. It does not necessarily occur over the whole drainage basin during a storm, however, since the infiltration capacity of soils may vary in even a small catchment.

Betson in 1967 observed that the area contributing Horton overland flow may be only a small portion of the catchment. This idea has become known as the ***partial-area concept*** of storm runoff and is a modification of the original Horton model.

Horton overland flow occurs most frequently on areas devoid of vegetation or possessing only a thin cover e.g., semi-arid rangelands and cultivated fields in regions of high rainfall intensity are places where this process can be observed. Also, it is normally experienced where soil has been compacted or the top soil removed on lawns, tracks and roads.

The flow is particularly obvious on paved urban areas. Also, barren soil heaps and construction sites experience Horton overland flow. The following diagram illustrates surface detention and depression storage conditions on hillslopes.



Overland flow moves downslope as an irregular sheet

On catchments of less than 1 km^2, intense storms sometimes yield over 5o% of rainfall as Horton overland flow, and in largest storms, the yield approaches 100% from the hillslopes underlain by fine-textured, bare soils.

Beyond 1 km ^{2}, the yield frequently declines with increasing drainage area, reflecting the lower average rainfall intensities and volumes over large areas and seepage losses in sandy flood plains and channel alluvium in arid regions.

While peak rates of runoff by this processes can be high (ranging up to 20 mm/hr for individual hillslopes and even 1 km^2 basins can generate rates up to 10cm/hr), for large catchments, peak runoff rate declines approximately with the square root of drainage area.

Runoff in Regions of High Infiltration

1. In most humid regions, infiltration capacities are high because of the following reason:

   (a) Vegetation protects the soil from rain packing and dispersal;

   (b) The supply of humus and the activity of micro-fauna create an open soil structure;

2. Under such conditions rainfall intensities generally do not exceed infiltration capacity, and Horton overland flow does not occur on large areas of the landscape.

3. Soil moisture is very important in determining the amount of runoff on a landscape resulting from a given rainstorm. At any depth below the soil surface, the moisture content of the soil profile will increase with distance from the hilltop.

4. Near the base of slope, soil moisture content is high, and when rainfall infiltrates the surface, water soon will be displaced downward into the saturated zone. This and the smaller depth of the water table near the stream combine to ensure that the vertical percolation will cause the water table to rise early in the storm.

5. Further upslope, the surface soil is drier, and some rainfall is stored in the profile before the displacement of soil moisture occurs. Since distance to water table is also greater, the transmission of water into the saturated zone occurs more slowly than at the bottom of the slope.

6. If the water table is deep enough, all the infiltrating water may go into storage in the unsaturated zone and not reach the water table for many days after the storm.

7. A slightly more complicated, but common situation is that in which the top soil is underlain by a horizon of lower permeability;

(a) Percolation is impeded by this horizon and water accumulates above it and flows downhill through the soil.
(b) Moving along a relatively short route, through a permeable soil, this subsurface storm flow reaches the stream channel quickly enough to determine the storm hydrograph in some regions.
(c) In other regions, however, it moves slowly and contributes only small amounts of runoff to the **receding limb** of the hydrograph.

8. Where the subsurface flow is the dominant contributor of the runoff:

(a) The volumes of runoff are much lower than those of Horton overland flow, being generally less than 20% of the rainfall. Values of 50% are, however, reached for very large storms on optimum conditions for subsurface storm flow.
(b) Otherwise most of the rain is stored in the soil and in the ground water zone and is released slowly to supply the copious base flow of these humid regions. By comparison with velocities of Horton overland flow, subsurface storm flow is very slow

9. The highest rates so far measured in the field are approximately 11 m/day, in highly permeable sandy loam on a steep hillside. It reaches channels only slowly and does not attain the same peak discharge rates as those generated by the Horton overland flow.

10. If the storm is large enough, or the water table or impending horizon shallow enough infiltration and percolation will cause the water table to rise to the ground surface.

When this happens, subsurface water can escape from the soil and flow to the channel over the land surface. This kind of runoff process is termed ***return flow***

That part of the hillside where return flow emerges from the subsurface is impervious to the rain falling on it. The rain must flow off the area as ***direct precipitation onto saturated area***. This runoff, together with return flow is called ***saturated overland flow***. It often moves at velocities as fast as those of subsurface storm flow, and can supply runoff to the channel more quickly than water following the subsurface route.

11. Hydrographs of this flow have higher peaks and much shorter lag-times than those of subsurface storm flow. Velocities of saturation overland flow cover the lower range of values of Hortonian runoff, because it usually flows on gentle foot-slopes which are thickly vegetated and rough.

As the storm progresses, the saturated area expands upslope, causing more of the catchment to contribute saturation overland flow. The saturated area also expands and contracts seasonally. The saturated areas may not be easy to see, especially in dense forest. Therefore, it requires careful examination while in the field.

12. The original conceptual model of generation of storm runoff in humid areas was developed by hydrologists of the US Forest Service in 1961 and the Tennessee Valley Authority in 1964. The model was termed the ***variable source concept of runoff***, a model that was elaborated upon by J.D. Hewlett and A.R. Hibbert in 1967. Hence it is sometimes called after their names.

MAKERERE UNIVERSITY
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Lecturer: Dr. Nseka Denis Galende

Topic Ten: Soil Erosion and Conservation

Learning outcomes for this topic

By the end of this topic, you should be able to;

1. Discuss the mechanics and controls of soil erosion processes
2. Evaluate soil conservation and management techniques

Definition of Soil Erosion: Soil erosion is the process of detaching and transporting soil material by the agents of erosion, particularly water and wind. Soil erosion by water is the most common form of erosion and land degradation. The traditionally prevention or reducing of soil erosion is viewed as being equal to soil conservation. However, the modern view of soil conservation is that it includes more than just control of soil erosion although soil erosion is the major cause of soil degradation. It also covers other land husbandry practices such as soil fertility management.

Prevention of soil erosion or soil conservation is equated to reducing the Rate to approximately that which is occurring under natural conditions. There are two types of erosion:

(a) Natural (geological or normal erosion): erosion process that naturally takes place on slopes. This includes soil-forming as well as soil eroding processes that maintain the soil in favorable balance, suitable for growth of most plants.
(b) Accelerated erosion: man-induced erosion which involves the breakdown of soil aggregates and accelerates removal of organic matter and mineral particles resulting from improper tillage and removal of natural vegetation.

Therefore, the following should be noted:

Geological erosion corresponds to gradual removal of soil by natural processes acting over a very long time without depleting productivity. It has contributed to the formation of our soils and their distribution on the surface of the earth. This long-time eroding process caused most of our topographic features such as canyon, stream channels and valleys.

Accelerated erosion, on the other hand, is caused by the activities of man and is responsible for depleting soil productivity, destroying land and filling reservoirs with sediment and polluting rivers. For this reason, accelerated erosion is one of the most important agricultural and environmental problems in the world. Erosion also adds to the removal of valuable plant nutrients lost with runoff.

Accelerated erosion is caused primarily by water and wind. The forces involved are:

- Attacking forces which remove and transport the soil particles;
- Resisting forces which retard erosion

Water erosion is the removal of soil from the land by running water, including runoff from melted snow and ice. The major types of erosion include raindrop, sheet, rill, gully and stream or channel erosion.

An overview of the erosion problem and processes

It is estimated that under natural conditions (geological) the average erosion rates are $4.5 g/m^2/year$ for moderate relief and $45 g/m^2/year$ for steep relief. In contrast, under man-induced (accelerated erosion) conditions represented by agricultural land, the rates increase to $4500 g/m^2/year$ on moderate slopes and $45{,}000 g/m^2/year$ on steep relief. This is an increase of 1000 folds, which is great indeed.

It should be noted, however, that these rates vary in different environments. The effects of erosion are many and far reaching. They occur both on-site and off-site.

On-site, land suffers decline in productivity, severe damage by gullies, dilapidation of moisture retaining capacity, lowering of the water table.

Off-site effects include sedimentation of streams and reservoirs, eutrophication and loss of quality of water and decline in potential fishing and others.

It is important to note that sedimentation is a major form of pollution, lowering water quality.

Processes and Mechanics of Erosion

Energy of Rainfall

PE and KE= are the most important eroding components on slopes. The energy can be expressed in the following relationships; **PE= m.g.h; KE= ½ MV²**

Where, PE= potential energy, KE= Kinetic energy, m=mass; g=gravity; h= height.

Velocity is calculated in Kg $(MS^{-1})^2$, or joules

That is to say, PE converts into motion or kinetic energy and this is related to the erosivity of rain. Most energy is expended in friction only:

(i)3-4% of the energy of running water and;

(ii) 0.2% of the energy of falling raindrops; are expended in erosion.

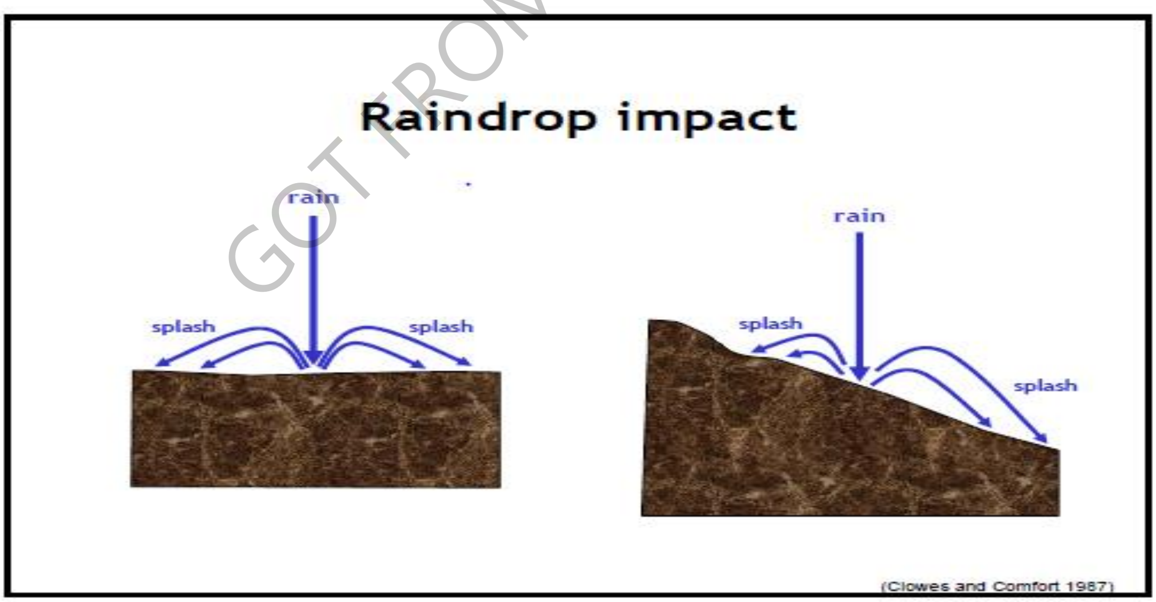
Water erosion on slopes reflects a combination of two dominant processes namely; rain splash and overland flow. The direct impact of rain splash serves to dislodge particles, by throwing them into the air, imparting stresses to particles adjacent to the point of impact, and undermining the larger particles.

Flowing water, as sheet or rill wash may entrain the particles dislodged by rain splash impact and, may be more efficient while rain is actually falling, due to the turbulence created in the flow. The process of rain splash and wash are discontinuous in both space and time, and although it is convenient to describe them as separate processes, they should nevertheless, be regarded as a single interacting phenomena.

Slope erosion is selective, since the larger particles although capable of being dislodged by falling rain, are frequently not transported by overland flow.

Rain splash Erosion

Raindrops strike bare ground with substantial force during intense rainfall events and the resulting impacts can move a significant amount of sediment by **rain splash**. On sloping ground, rain splash produces net downslope transport because even though some material may be splashed uphill, most goes downhill. As surface water flow deepens, less sediment is entrained because the water shields the soil surface from subsequent raindrop impacts. Consequently, the contribution of rain splash to hillslope sediment transport is limited to areas relatively close to drainage divides, where overland flow is minimal.



Rain splash, otherwise known as raindrop erosion results from the impact of raindrops directly on soil particles or on thin water surface. Indeed, water erosion starts when rain drops strike bare soil and detach the finer particles, which are carried off with the flowing water.

Although the impact on water in shallow streams may not splash soil, it does cause turbulence, providing a greater sediment carrying capacity.

Tremendous quantities of soil are splashed into the air, most of it more than once. Detachment of soil particles by rain drop impact is generally highest in the fine sand fractions (*0.25-0.05mm*). Clay particles *(≤0.002mm*), tend to resist splash detachment due to cohesive forces, but are easily transported once separated from the soil mass. Silt soils *(0.05-0.002mm)* commonly break down when wetted and the particles are easily detached and transported because they lack cohesion and are small in size.

Therefore, soils that are low in clay and organic matter content and high in silt and very fine sand tend to form aggregates which are relatively unstable and hence erodible. Tremendous quantities of soil are splashed into the air and the amount of soil splashed into the air has been estimated to be 50 to 90 times greater than that lost from wash off.

On the bare soil, estimates of 224mg/ha (100 tons/acre) have been made.

The relationship between erosion and rainfall momentum and energy is determined by raindrop mass, size, size distribution, shape, velocity and direction. Splash particles move more than 0.6m high and more than 1.5m laterally on level surfaces. Factors affecting the direction and distance of soil splash are slope, wind, surface conditions, and such impediments to splash such as vegetation cover and mulches.

On sloping land, the splash moves farther downhill than uphill not only because the soil particles travel farther but also because the angle of impact causes the splash reaction to be in a downhill direction.

Components of wind velocity up or downhill have an important effect on soil movement by splash. The following factors also influence rain splash.

- Surface roughness and impediments to counteract the effect of slope and wind;
- Contour furrows and ridges break up slope and cause more of the soil to be splashed uphill;
- If raindrops on crop residue or growing plants, the energy is absorbed and thus soil splash is reduced;
- Raindrop impact on bare soil not only causes splash but also decreases aggregation and causes deterioration of soil structure;
- Wash-out of fine materials result in the so called erosion pavement, which is the result of an accumulation of coarse particles or rock fragments at the surface. This effect may take place with either of the principal erosive agents, water or wind.

Besides splashing (dispersion) of soil particles, raindrops are agents of consolidation. The consolidation effect is best seen in the formation of a surface crust, usually on a few millimeters thick which results from **clogging** of the pores by soil compactions.

Observations indicate that this is associated with the dispersal of fine particles from soil aggregates of clods, which are translocated to infill the pores.

Measurements on splash and surface crust affected soils indicate that crusts have a dense surface skin or seal, about 0.1mm thick, with well oriented clay particles. Beneath this is a layer, 1 to 3mm thick, where the larger pore spaces are filled by finer washed-in material.

The most important effect of surface crust is to reduce infiltration capacity and thereby promote greater runoff. Measurements on a sandy semi-desert soil in Israel indicate that crusting reduces infiltration capacity from 100 mm hr^{-1} to 8 mm hr^{-1} and on a loess from 45 mm hr^{-1} to 5mm hr^{-1}.

Raindrop does not always fall onto a dry surface. During the storm, it may fall on surface water in the form of puddles or overland flow. Some studies indicate that as the thickness of the surface water layer increases, so does splash erosion. This is believed to be due to the turbulence which impacting raindrops impart on the water. However, there is a critical water depth beyond which erosion decreases again because all the energy is dissipated in the water and does not affect the soil surface.

Studies indicate different critical depth values as follows;

Approximately equal to the diameter of the raindrop;

One third of the diameter of the raindrop;

And one fifth of the diameter of the rain drop.

These studies were made with a variety of soils covering clays, silt loams and sandy loams. No increase in splash erosion with water depth has been observed.

Wind speed imparts a horizontal force to the falling raindrops so that they strike the surface at an angle from the vertical. This affects the relative proportion of upslope versus downslope splash, as well as increasing the impact velocity of the falling raindrop.

Sheet Erosion

Overland flow that is not concentrated into discrete channels and spreads across the ground surface is called **sheet wash**. Overland flow is rare on soil-mantled slopes because infiltration capacity generally exceeds rainfall rates and the rainwater sinks into the ground.

Consequently, sheet wash does not transport much sediment in humid or temperate environments. Unchannelized sheet wash does, however, transport significant amounts of material down undissected slopes in arid and semi-arid environments.

Rain splash and sheet wash are both diffusion-like processes that fill in topographic depressions and smooth over relief. Where enough overland flow concentrates to incise the ground surface it behaves as an advective process and acts to incise and enhance relief.

The idealized concept of sheet erosion has been that it was uniform removal of soil in thin layers from sloping land, resulting from sheet or overland flow occurring in thin layers. Presently, however, studies indicate that this idealized form of erosion rarely occurs. Rather, minute riling takes place almost simultaneously with the first detachment and movement of soil particles.

The constant meander and change of position of these microscopic rills obscure their presence from normal observation, hence establishing the false concept of sheet erosion.

The beating action of raindrops combined with surface flow causes these initial microscopic rills. From an energy point, raindrop erosion is far more important because rain drops have velocities of about 6 to 9 m/s, whereas overland flow velocities are about 0.3 to 0.6 m/s.

As noted earlier on, raindrops cause soil particles to be detached and increased sediment reduces the infiltration rate by sealing the soil pores. The eroding and transporting capacity/power of sheet flow are functions of depth and velocity of runoff for a given size, shape, and density of soil or aggregate.

Rill Erosion

Rill erosion is the removal of soil by water from small, but well-defined channels or streamlets when there is a concentration of overland flow.

Conventionally, rill erosion occurs when these channels have become sufficiently large and stable to be readily seen. It is difficult to get a universal definition of rills in terms of depth, but it is usually defined as being small enough to be easily removed by normal tillage, as well as small enough not to inhibit normal farm implements (tractors) operation.

Although rill erosion is often overlooked, it is the form of erosion in which most erosion occurs. Detachability in rill erosion is more serious because of the higher runoff velocities that are involved.

Rill erosion is most serious where intense storms occur on soils having high runoff-producing characteristics and loose shallow top soil.

It widely accepted that rills develop at ***a critical distance*** downslope where overland flow becomes channeled. Others have observed rills to start at the foot of slope during sudden storm bursts, and then rapidly extending upslope by head ward erosion. Thus, rills develop either upslope by head ward erosion or downslope by shear stress of runoff.

Rill flow can transport large grains so that where it is important, the wholesale removal of particles minimizes selection erosion. As expected from the greater erosive power than overland flow, rill erosion may account for the bulk of sediment removal from a hillside. Part of this is of course, derived from the interrill areas and is moved into rills by overland flow and rain splash. Estimates are that 80-90% of the material transported by rills may be derived in this way.

Gully Erosion

Gully erosion produces channels larger than rills. These channels carry water during and immediately after rains, and as distinguished from rills, gullies cannot be obliterated by tillage.

Gullies are, therefore, relatively permanent channels. They are normally steep sided, but in contrast to Stable River channels which have a relatively smooth, concave upwards long profile, gullies are characterized by a head-cut and various steps or knick-points along their course. Gully erosion is normally viewed as an advanced stage of sheet erosion. This type of erosion is, therefore, normally associated with landscape instability.

At one time it was thought that gullies develop as enlarged rills, but studies in the gullies (***arroyos)*** of South-Western U.S.A. revealed that their initiation is a much more complex process. The rate of gully erosion depends primarily on the runoff-producing characteristics of the watershed; the drainage area; soil characteristics; the alignment, size and shape of the gully; and the slope in the channel.

A gully develops by processes that may take place either simultaneously or during the different periods of its growth. These processes are:

- Waterfall erosion at the gully head;
- Channel erosion caused by water flowing through the gully or by raindrop splash on unprotected soil
- Alternate freezing and thawing of the exposed soil banks;
- Slides or mass movement of soil in the gully.

Five stages have been identified in the surface development of gullies on a hillside namely:

(a) A break in vegetation cover and removal of soil by overland flow;
(b) Small depressions or knick-points form on a hillside as a result of localized weakening of the vegetation by grazing, fire or other form of surface cover disturbance;
(c) Water concentrates in these depressions and enlarges them until several depressions coalesce and insipient channel formed;
(d) Erosion is concentrated on the head-cuts of the depressions where near-vertical scarps develop over which super critical flow occurs;
(e) Some soil particles are detached from the scarp itself but most erosion is associated with scouring at the base of the scarp which results in deepening of the channel and undermining of the head-wall, and lead to collapse and retreat of the scarp upslope (Ologe 1972).

(f) Sediment is produced further down the gully by stream bank erosion, partly due to the scouring action of running water and the sediment it contains, partly by slumping of the banks following saturation during flow.

Gully Development by subsurface flow

Not all gullies develop by surface erosion. Studies indicate that in certain cases e.g. after clearance of forests in humid regions, most water may be removed from the hillside by subsurface flow in pipes, and when heavy rain provides sufficient flow to flush out the soil in these pipes, the ground surface exposing the pipe network as gullies.

Numerous studies have indeed recorded evidence to the formation of gullies by ***pipe or tunnel*** collapse. Tunnel erosion is reported in many parts of the world such as Australia, New Zealand and Canada. It is not uncommon in areas with hilly and rolling topography, and with soils characterized by a sharp increase in clay content between A and B soil horizons. In such cases, one may find the upper layer varying from loamy sand to clay loam, while the lower layer ranges from alight to heavy clay. The subsurface horizon is thus with low permeability.

It has been observed that overgrazing and removal of vegetation cover in such areas causes soil surface crusting at the surface, leading to greater runoff. This passes into cracks and macro-pores, but on reaching the top of B horizon, moves along it as subsurface flow.

Yet another way in which gullies are formed is where linear landslides leave deep, steep-sided scars which may be occupied by running water in subsequent storms which has been observed in different areas.

Generally, the main cause of gully erosion is too much water, a condition that may be brought about by either climate change or alterations in land use. Climate change and land use changes are classified as external factors influencing gully formation, and this is through increased runoff and associated shear stresses which exceed threshold values (intrinsic factors). Thus the thresholds values are related to the internal causal factors

Consequently, the interplay of intrinsic and extrinsic thresholds makes gully erosion an extremely complex process and hence poor understanding of the whole subject up to the present. When designing strategies to control gully erosion, it not possible to treat gullies in the same way. For example, the dangers of doing so may arise from the failure to take into account of whether surface or subsurface erosion is the major cause.

Few studies have been undertaken on the role of gully erosion in sediment transport. Although gullies can remove vast quantities of soil, gully densities are not usually greater than 10 km/km-2 and the surface area covered by gullies is rarely more than 15% of the total area. Where it occurs, however, gullies can completely destroy the landscape or lead to slope disintegration.

Read about soil conservation and management.