PREDICTION OF SOIL LOSS DUE TO EPHEMERAL GULLIES IN ARABLE FIELDS

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PREDICTION OF SOIL LOSS DUE TO EPHEMERAL GULLIES IN ARABLE FIELDS

1. INTRODUCTION

The loss of soil from arable fields is a serious problem both to farmers and to action agencies concerned with erosion, productivity and water quality. The total erosion for a field is made up of several components due to different erosion processes. Often rill and inter-rill erosion is supplemented by gully erosion and wind erosion. Some gullies, here called ephemeral gullies because they are removed annually by tillage, are not accounted for in current erosion estimating procedures. However, indications are that they may be responsible for significant erosion over and above that being predicted. It is therefore important to develop methods to predict the contribution of ephemeral gullying to total erosion in arable fields.

2. DEFINITION OF EPHEMERAL GULLIES

Ephemeral gullies can be distinguished from other rills and gullies on the basis of three main criteria. These are:

(i) Ephemeral gullies are found only in arable fields (an alternative name for them, "arable cropland gullies" is based on this limitation).

(ii) Ephemeral gullies are formed by the concentration of surface runoff. This concentrated flow may result from local topography, from the convergence of rills or furrows, or by a combination of both causes. Consequently, ephemeral gullies may tend to cut across the rill or ridge and furrow pattern in a field.

(iii) Ephemeral gullies are obliterated each year by normal tillage operations and do not develop sufficiently to impede ordinary farm machinery. In this they differ from regular gullies, which cannot be crossed by ordinary machinery and which require that specialized machinery be used to remove them. If not erased, ephemeral gullies quickly grow to become regular gullies, disecting the field and preventing efficient farming.

The full definition of ephemeral gullies is subject to debate. The criteria presented here are not the last word and are only intended as a working definition to help to determine the nature of the phenomenon being studied and the limits to the study. Clearly the definition is not a morphological one, because it depends on farming practices as well as gully characteristics.

3. OBJECTIVES OF THE STUDY

The primary objective of this study is to produce an equation to predict the average annual soil loss in an arable field caused by the development and presence of ephemeral gullies. Secondary objectives are to investigate the physical processes of ephemeral gully formation, to ascertain the role of ephemeral gullies in the overall sediment erosion/transport/deposition system in fields, and to identify how the individual parameters of climate, topography and soils control ephemeral gully form and process. Clearly, these secondary objectives will form the basis for fulfillment of the primary objective, unless a purely empirical equation, with no process basis, is used.

Ideally, the equation produced should be amenable to use at a local level, without the need for a powerful mainframe computer. If the necessary calculations could be carried out on a hand held calculator, or a desktop computer, then the utility of the equation to field workers would be assured.

Also, if possible, this soil loss prediction equation should be an adjunct to the Universal Soil Loss Equation (USLE), using as many as the parameters of that equation as possible. It is not desired to produce a modified USLE for fields with ephemeral gullies, however. Instead it would be preferable to use USLE to predict rill and inter-rill erosion in the field in question and then add on the ephemeral gully contribution to total erosion, predicted from the new equation. That is, the new equation should be adjunct or additive to the USLE, rather than replacing it.

4. NEED FOR RESEARCH

At present the soil loss due to ephemeral gullies is not accounted for in soil loss calculations made by the Soil Conservation Service. Evidence gained in studies in the states of Alabama, Georgia and Mississippi suggests that under adverse conditions this loss can be very serious, with the result that calculations based only on rill and inter-rill erosion may underestimate the total soil loss by 50 to 100% (Miller, 1982; A. Thomas, Personal Communication, 1983; P. Forsythe, Personal Communication, 1983; W. Mildner, Personal Communication, 1983).

Also, experience in Mississippi suggests that some conservation practices which effectively control rill and inter-rill erosion (such as minimum tillage farming), may not be effective in reducing ephemeral gully erosion (P. Forsythe, Personal Communication, 1983).

Clearly, research is needed to investigate the causes and controls of ephemeral gully soil erosion, to develop methods of accounting for the growth and soil loss attributable to ephemeral gullying, and to identify conservation practices which do minimize soil loss due to ephemeral gully formation.

In the remainder of this report the research required to satisfy these needs is outlined and the progress made to date is reported. Firstly, the causes and controls of ephemeral gully formation are discussed. Secondly, possible strategies for the development of a prediction equation are considered. Thirdly, a research procedure for the next two years, leading to the attainment of the stated objectives, is proposed.

5. PROCESS OF EPHEMERAL GULLY FORMATION, DEVELOPMENT AND DESTRUCTION

The formation, development and destruction of an ephemeral gully are the result of a complex interaction of precipitation, soils, topography, agricultural practices and plant development. To illustrate the main features of this interaction the processes and controls of ephemeral gullying are outlined from gully initiation to obliteration.

5.1. Ephemeral Gully Formation

The formation of an ephemeral gully at a particular location and time is a stochastic process -- the result of a series of events that cannot be predicted deterministically. However, the general requirements for ephemeral gully formation can be identified and the conditions necessary for gully-genesis can be defined. In summary these are: concentrated surface runoff of sufficient magnitude and duration to initiate and maintain erosion, leading to channelization of the surface flow. These three requirements (concentrated surface runoff, erosion initiation and channelization) are examined sequentially.

5.1.1. Concentrated Surface Runoff

The first requirement for gully formation is the generation of concentrated surface runoff. Runoff may be either subsurface (through flow and groundwater flow) or surface (overland flow). Subsurface runoff is generated by any precipitation event that is not wholly evaporated, but surface runoff only occurs if the soil's infiltration capacity is exceeded. This capacity is not simply a function of the soil type, but varies through time. Consequently a storm of given severity may or may not produce surface runoff, depending on the time of year. The important temporal factors are crop canopy condition, antecedent weather and soil conditions (particularly soil moisture level at the start of the storm) and the state of the soil surface due to surface crusting or tillage (for example, whether the soil surface is plowed, disced or fallow). Clearly, it is not just the magnitude and duration of a storm that determines whether it produces surface runoff, but also the sequence of storms preceding it and its timing in relation to the agricultural year.

Runoff may be produced all over the field if the infiltration capacity is everywhere exceeded. Under these circumstances the field surface topography, together with any ridge and furrow system, controls the pattern of runoff and determines the areas of concentrated surface flow.

Without a ridge and furrow pattern, topographic control produces concentrated flow in low points (swales) in the field. Conversely, high points (spurs), exhibit diverging flowlines and do not have concentrated flow (Figure 1).

Often the ridge and furrow pattern tends to follow the contours in a field. As a result, furrow flow is approximately at right angles to

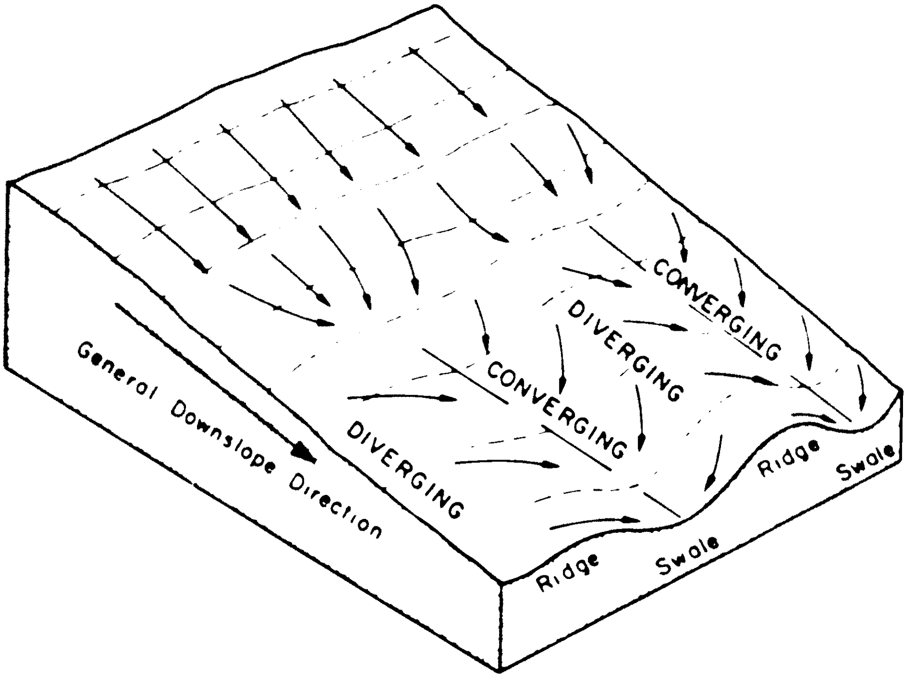


Figure 1. Topographic control of surface runoff producing concentrated flow in swales.

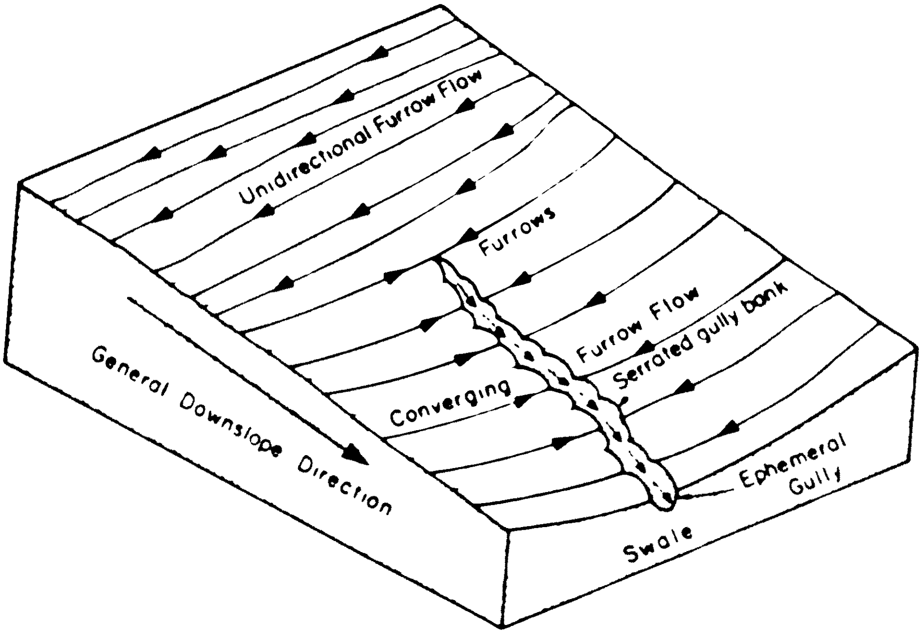
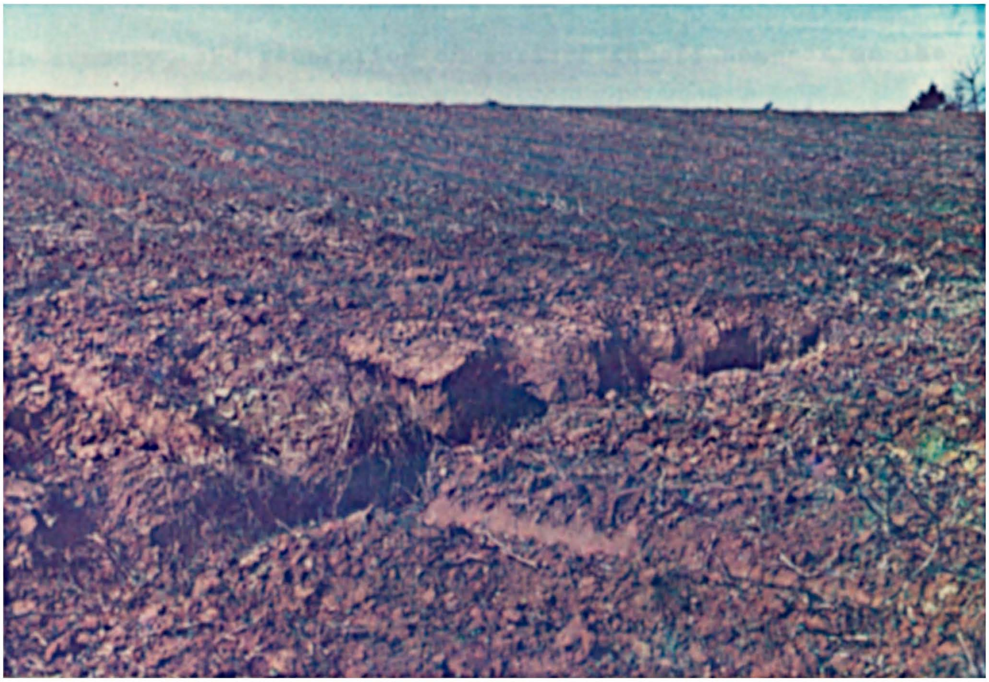


Figure 2. Converging furrow flow in plowed field producing concentrated flow and an ephemeral gully.

the downslope direction. However, secondary slopes, associated with swales and spurs, can result in the flow in a furrow converging from opposite directions (Figure 2). Continuity then demands that the accumulating water overflows into the next furrow downslope. Likewise, this furrow must also overflow because of the convergence of long furrow and overflowing water. In this way a cascade of furrow overflows occurs down the swale, and surface runoff is concentrated in the swale (photograph 1).

With or without a ridge and furrow pattern, surface runoff generated over the field will be concentrated in the swales. However, the process will be intensified by ridges and furrows that follow contours. In fact, farmers sometimes plow up and down the hill to try to prevent large concentrtions of flow and ephemeral gully formation (P. Forsythe, personal communication). Ridges and furrows plowed up and down the slope will inhibit concentrated flow in swales, at least initially, but do promote severe rilling.

Research in hydrology suggests that in many regions of the world general surface runoff occurs only rarely. Instead, surface runoff is generated by relatively small areas of a field. This results from convergence of subsurface runoff, leading to local saturation and surface runoff. These restricted source areas, which cover only part of a field, are called, "partial source areas." Partial source areas are not constant in extent but fluctuate according to soil moisture conditions. They expand with increasing soil moisture and contract with decreasing soil moisture. Partial areas are especially likely to occur where infiltration is impeded by a layer of low permeability. In arable fields such a layer is often present in the form of a "plow-pan" at



Photograph 1. Ephemeral gully produced by converging furrow flow due to Swale and Ridge Field Topography. (Goodwin Creek Watershed near Oxford, Miss.)

the depth of normal tillage, or an impermeable fragipan at some greater depth.

In areas of uniform subsurface drainage partial source areas are usually centered on swales or hollows in the field. Consequently, these areas experience surface runoff even when the majority of the field does not and this produces a higher frequency of surface runoff events in the swales.

In summary, the generation of surface runoff depends on the intensity, duration and timing of precipitation events, soil moisture conditions and soil infiltration capacity, the presence or absence of a plow-pan or other layer impeding water movement, the crop type and development, and soil surface conditions as modified by agricultural tillage practices. Runoff may be generated throughout the field but, more frequently, it may be produced by partial source areas. In either case flow is concentrated in the swales, especially when contour furrows are present. By contrast, spurs are areas of flow divergence. It follows that the first requirement for gully initiation, concentrated surface runoff, will be met in the swales in arable fields but not on the spurs.

5.1.2. Initiation of Erosion by Concentrated Flow

When concentrated surface runoff has been produced in a swale, the next stage in ephemeral gully formation is the initiation of surface erosion by the concentrating sheet flow.

The initiation of erosion by running water is a difficult topic which has been the subject of extensive research. For the case of non-cohesive particles of approximately spherical shape and without tight packing or imbrication, a theoretical approach based on simple mechanics produces a reasonably accurate stability equation. However, for arable soils with significant cohesion, complex particle geometries, and important soil structure and fabric, no simple mechanistic analysis has been successful. Most stability equations are highly empirical and their applicability is limited to conditions and soils close to those for the data base from which they were developed. In the case of ephemeral gully erosion, the soil being eroded comes from the plow layer and is highly disturbed by tillage. Its cohesive structure is disrupted and it may well behave as an almost noncohesive material made up of discrete aggregates of soil of the order of 1-10 mm in diameter.

The probability of aggragated soil being eroded can generally be expressed using a parameter or factor based on the excess of the applied shear stress due to the flow over the shear stress required to entrain the soil. It should be borne in mind that the actual failure of the soil particles being entrained is often not in a shear type mode. Despite this, the soil erodibility parameter and currently available erosion equations can be used to predict the initiation of erosion under concentrated flow.

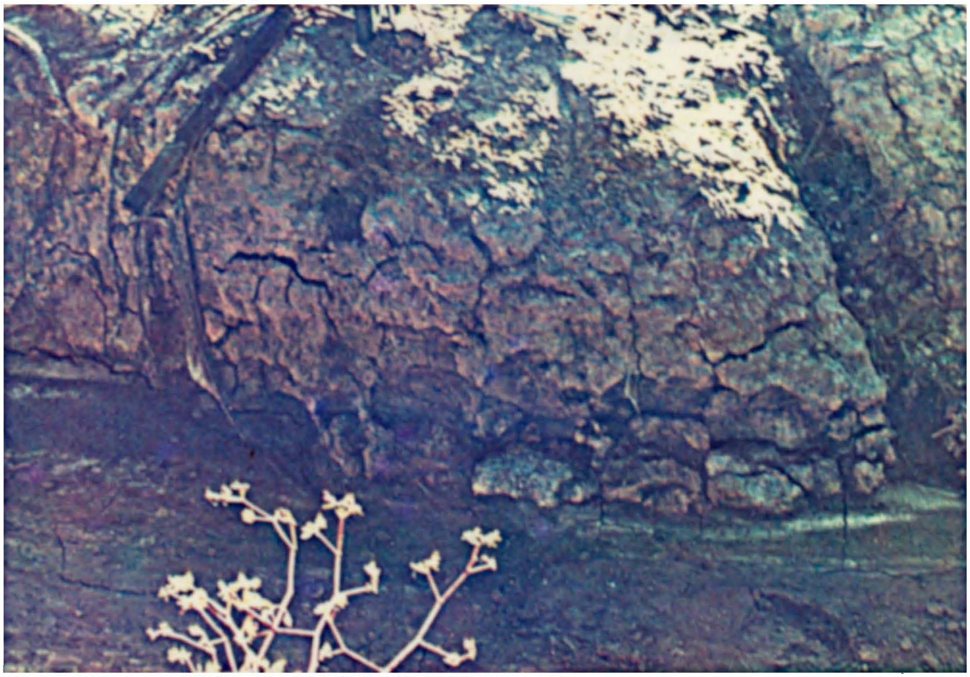
Once erosion is initiated the flow becomes channelized and there is positive feedback, because the more concentrated flow has increased erosive power. In this way the flow enlarges its channel, the eroded area capturing a greater and greater proportion of the sheet flow as it grows. Eventually, negative feedback between the flow and erosion occurs and the channel tends to stabilize. This happens because as the channel enlarges the near boundary velocity gradient is reduced, decreasing boundary shear stress and increasing boundary stability.

If the soil properties, particularly erodibility, do not change significantly with depth, a channel of approximately parabolic cross section results, with the boundary shear stress a little less than the critical value all around the perimeter. The channel dimensions are a function of the formative discharge, sediment supply, the slope of the swale and the boundary soil strength. If a plow-pan or other resistant layer is present a few inches below the soil surface, this can limit the channel depth and produce a wider, shallower cross section. In this case width becomes the limiting dimension and stability is achieved when the flow at the bank base (toe) is no longer able to scour the bank, and further widen the channel. Observations in Mississippi show that at least on the Memphis soils series the ephemeral gullies usually break through the plow-pan. In such cases the gully depth is limited by a resistant layer at greater depth or, by the stability of the gully banks with respect to mass failure (photograph 2).

Having achieved relatively stability, the gully channel will then transmit lesser discharges with only minor changes of morphology, unless there is a change in one or more of the controlling variables. These changes, and the gully response, are the subject of the next section.

In summary, the initiation of an ephemeral gully depends on the balance of erosive and resistive forces acting on the soil surface in a swale under concentrated surface runoff. Important variables (in addition to those already identified as controlling the generation of concentrated surface runoff) are shear stress due to the flow (a function of slope and depth) and soil erodibility factor. The cross sectional shape of the gully formed by the flow depends on the soil stratigraphy, and the channel dimensions depend on the controlling variables of formative water discharge and associated sediment discharge input to the

Photograph 2. Mechanical failures of ephemeral gully banks, limiting gully depth. (WES Field Study Site #1, near Vicksburg, Miss.)



Photograph 3. Headcut in an ephemeral gully. Overfall height about 6 inches. Resistant layer-plow pan. (WES Field Study Site #1, near Vicksburg, Miss.)

channel, swale slope and soil strength.

5.2. Ephemeral Gully Development

After it has formed, the ephemeral gully is developed and modified by subsequent storms that produce concentrated surface runoff. The nature of the gully development depends on the interaction of precipitation, soil conditions, arable practices, and crop type and growth. Like gully initiation, gully development is a stochastic process that cannot be predicted deterministically in a particular case. Despite this types and trends of gully development have been identified and these can be discussed under the general headings of degradation, aggradation, and stability.

5.2.1. Degradation

Degradation occurs when the sediment output from a reach is greater than the sediment input from upstream, the gully bed and banks being scoured to supply the imbalance. Degradation is usually initiated at the downstream end of a gully and works upstream either as a lowering of bed elevation and general steepening of gradient (evident as an upwards convexity in the thalweg profile), or as one or more distinct "head cuts" with overfalls. Which one occurs depends mostly on the soil properties, stratigraphy, and general relief. In uniform materials, upwards convexities are observed, but the breaching of a surface crust, plow-pan, or resistant layer often produces headcutting (photograph 3).

Degradation may be caused by a change in any of the parameters controlling gully channel form and size. An increase in discharge through the gully, a decrease in sediment input, an increase in slope, a decrease in boundary soil strength, or combination of these changes produces degradation.

An increased discharge may be the result of a particularly severe storm, or of a series of storms close together. Also, it can result from a change in runoff characteristics of the field in response to tillage of the surface soil, crop development, or surface sealing. The gully channel dimensions are directly proportional to discharge and so an increased discharge causes gully enlargement by degradation.

Agricultural practices and crop development can also produce reduced sediment input to the gully, leading to degradation. Any practices that tend to decrease rill and inter-rill erosion, which supply sediment to the gully, will promote gully degradation unless steps are taken to prevent this.

The slope of the gully can increase along the channel because of topographic control, that is a steepening of the swale gradient, or by base level lowering at the gully outlet. Often basal lowering generates a distinct wave of degradation (in the form of headcuts) that works up the gully system.

Decreased soil strength, leading to degradation, can come about because of weakening by saturation or by severe desiccation, or can follow the breaching of a resistant layer, again usually producing headcutting.

Degradation produces an enlarged gully channel, with oversteepened, nearly vertical banks that fail under gravity to produce widening and further erosion (photograph 2). It is common, therefore, for degradation to produce first bed lowering and deepening, and second bank failure and widening throughout the gully channel system. The effects of degradation progress all the way through the drainage network, even extending to furrows and rills that are tributaries to the gully, and

Photograph 4. Degradation of furrow resulting from ephemeral gully degradation. Headcut in furrow to left of center has overfall of about 6 inches. (WES Site #1, near Vicksburg, Miss.)

Photograph 5. Headward extension of ephemeral gully system by headcutting due to channel degradation. Overfall is at lower center of photograph.

often resulting in headward extension of the drainage network towards the topographic divide (photographs 4 and 5).

Degradation increases the sediment yield from an ephemeral gully. The increased yield results from the soil excavated to lower the bed, bank failures due to oversteepening, furrow and rill scouring and headward extension of the drainage network by the initiation of new ephemeral gullies. The degradational sediment yield is additional to any increase in yield produced by the increased delivery of rill and interrill erosion products which are transported through the gully system. This pattern of sediment production is shown schematically in Figure 3.

5.2.2. Aggradation

Aggradation occurs when the sediment output from a reach is smaller than the sediment input from upstream, the bed being filled to accommodate the imbalance. Aggradation may be initiated anywhere in a gully system and is evident as an upwards concavity in the long profile or sometimes as a distinct "slug" of sediment moving downstream through the drainage network.

Aggradation, like degradation, is caused by a change in one or more of the parameters controlling gully channel form and shape: discharge, sediment input, slope, and boundary soil strength. However, aggradation differs from degradation because for aggradation to occur there must be sediment supplied to the channel from some source upstream. Degradation can, and often is, associated with zero or negligible sediment input to the channel.

A decrease in discharge promotes aggradation because it reduces the sediment transport capacity of the flow. The excess load (provided the input is sufficient) is deposited on the bed, raising its elevation.

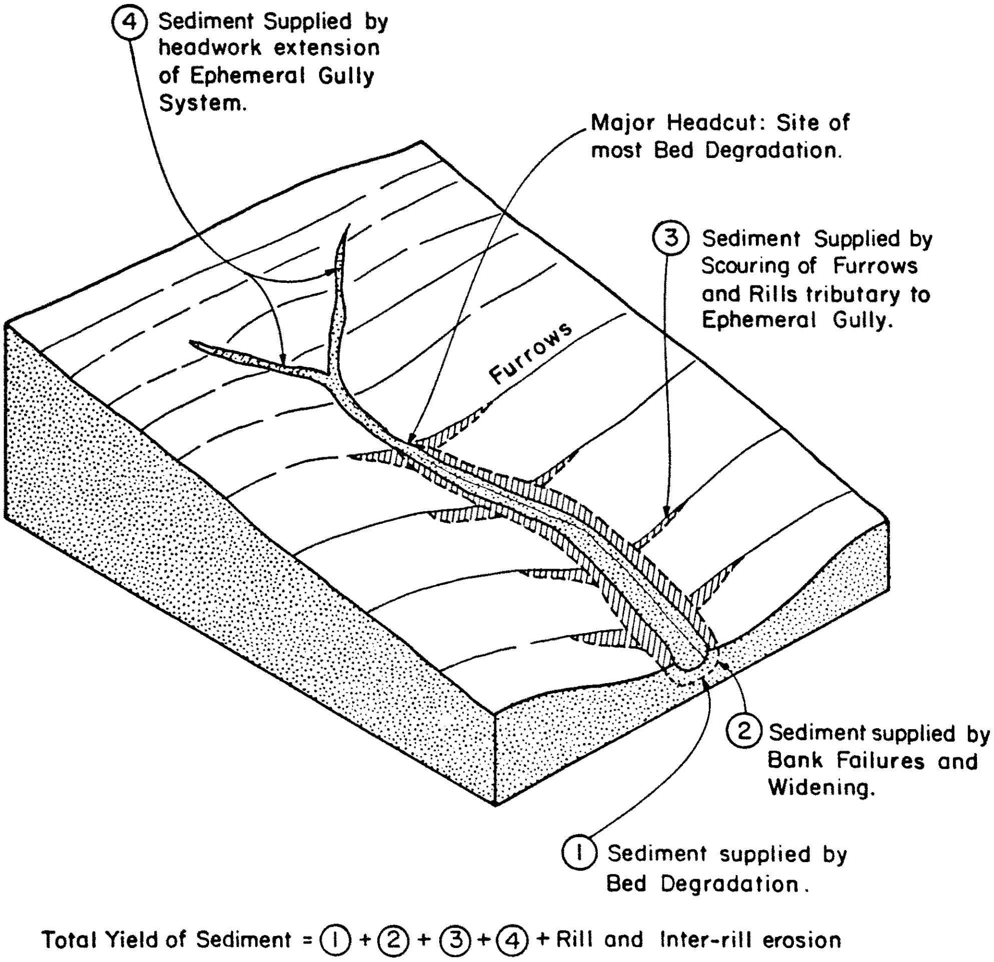


Figure 3. **Schematic representation of gully degradation.**

Decreased discharge may result from reduced precipitation, or reduced runoff, but as sediment input to the channel from rill and inter-rill erosion is also reduced, this is unlikely to cause significant aggradation. Reduced discharge also results from seepage of water out of the gully into the ground. This does lead to aggradation, and produces discontinuous gullies. Aggradation due to reduced discharge occurs most commonly when the flow decreass to zero after a rainfall event. Depositionary features are therefore widespread in ephemeral gullies (photograph 6).

Increased sediment production by rill and inter-rill erosion may produce gully aggradation if the sediment transport capacity is exceeded. This is observed where a severely scoured furrow or rill enters the gully, producing a bar which partially obstructs the gully channel. Very often though sediment transport in the gully is limited not by the flow hydraulics but by the supply of sediment, so that even a considerable increase in input can be accommodated and no aggradation results.

A decrease in energy slope along the channel is the most common cause of aggradation. As with discharge, the sediment transport capacity of a flow is a power function of energy slope and consequently quite a subtle reduction of energy slope can be responsible for considerable aggradation provided that there is sufficient sediment input to feed the deposition.

The energy slope is made up of the water surface slope plus the downstream change in velocity head:

$$S_E = \frac{dh}{ds} + \frac{d}{ds}\left(\frac{V^2}{2g}\right) \qquad [5.1]$$

Photograph 6. Deposition in an ephemeral gully left by receding flow at the end of a runoff event. Lobe will be re-eroded on next rising flow stage. (WES Study Site #2)

Photograph 7. Deposition in an aggrading ephemeral gully. Note braided channel pattern and plugging of tributary furrows (previously degraded) by sediment. (WES Study Site #1).

where S_E = energy slope

h = water surface elevation

s = longstream distance

v = mean velocity

g = gravitational accel.

Topography controls the channel bed slope and a flattening of the down swale gradient due to complex hillslope profiles, or towards the bottom of the field often produces deposition and aggradation. Likewise, the backwater effects of a culvert or flow constriction at the field drainage outlet are often responsible for a decrease in velocity, reduction in energy gradient and extensive aggradation in the form of a delta.

An increase in boundary material strength along the channel can result in a smaller cross section and loss of channel capacity. The flow then spreads out, tending towards a return to sheet flow. Loss of transport capacity as the flow disperses, can produce aggradation and channel avulsions on an alluvial fan.

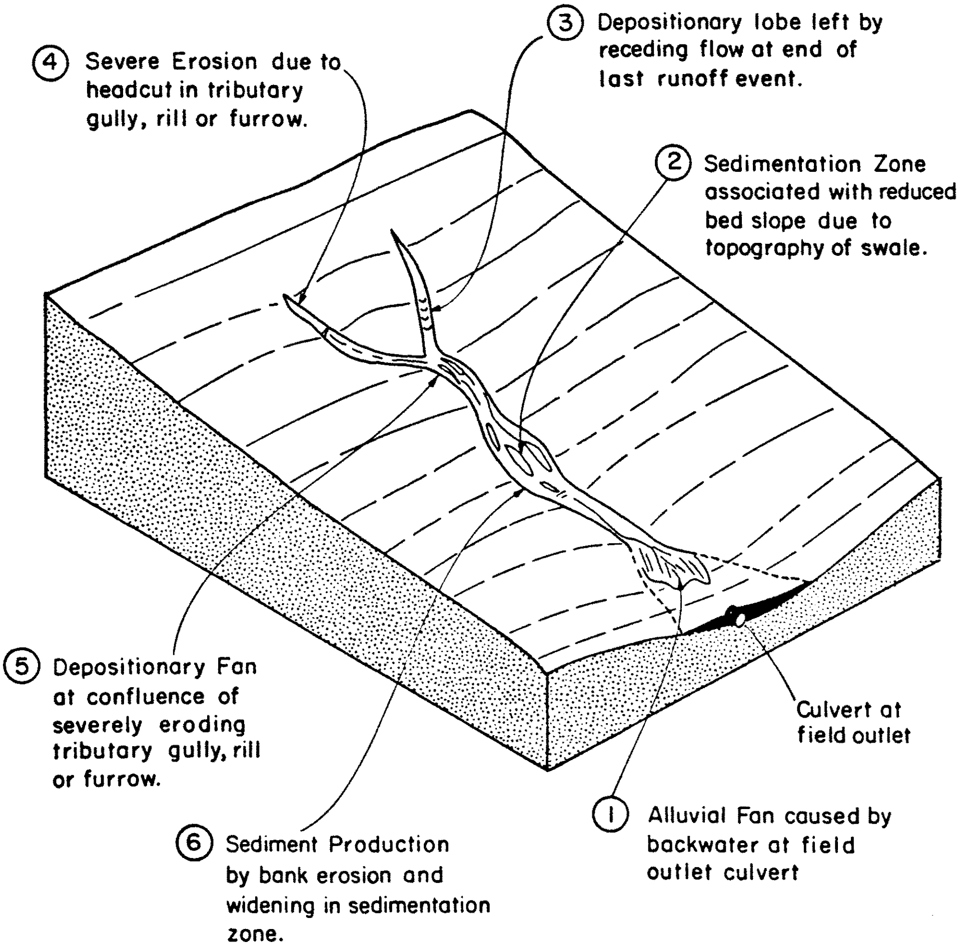
Aggradation reduces channel depth and increases shear stress on the banks. This usually leads to widening because the banks cannot sustain the greater shear. Commonly, aggradation produces a wide, shallow channel with pronounced depositional features on the bed, and a decreased channel capacity. Aggrading channels are commonly unstable and the channel pattern may be braided or wandering. Avulsions of unstable channels produce characteristic aggradational features such as alluvial fans or deltas (photograph 7).

The effects of aggradation progress both upstream and downstream in the gully system. The sediment itself always moves downstream, often in the form of a wave of deposition or a "slug" of sediment. The speed of this wave or slug is much less than that of the flow producing it, leading to complex interactions of flow, sediment and channel form. The reductions of channel gradient and energy slope associated with aggradation feed back upstream to promote further deposition, so that a wave of deposition may progress back up through the drainage network whilst the slug of sediment moves down through it.

Aggradation decreases the sediment yield from an ephemeral gully. The yield from an aggrading ephemeral gully consists of the rill and inter-rill erosion products minus the net sediment storage in the gully channel. This storage is the difference of bed, bar and alluvial fan deposition and any sediment production from widening. This pattern of sediment yield is shown schematically in Figure 4. It should be remembered that the storage of sediment in an ephemeral gully system can be substantial. For example, photograph 8 shows about 4 inches of accumulated sediment in a small gully.

5.2.3. Stability

A stable gully is one which is just able to transport the sediment supplied to it by rill and inter-rill erosion. The form, dimensions and extent of the gully do not change significantly with time and the sediment yield at the outlet of the field is equal to the erosion rate produced by rill and inter-rill processes. However, it should be noted that in this case the soil loss from the field may still be greater than that predicted purely from considerations of raindrop, sheet flow and rill erosion. This is the case because the presence of the gully increases the efficiency with which sediment is removed from the field, especially if the soil is aggregated. This is described by the "sedi-



$$\text{Total Sediment Yield} = \text{Rill} + \text{Interrill Erosion} + \textcircled{4} + \textcircled{5} - \underbrace{(\textcircled{1} + \textcircled{2} + \textcircled{3} + \textcircled{5})}_{\text{Channel Storage of Sediment}}$$

Figure 4. Schematic representation of gully aggradation.

ment delivery ratio" for the field, which is the ratio of soil loss predicted by the Univeral Soil Loss Equation to that physically leaving the field. A ratio of unity indicates a fully efficient, stable gully system. Ratios of greater and less than one indicate gully degradation and aggradation in the systems, respectively. In an ungullied field the sediment delivery ratio should always be well below unity.

In a stable gully the form and dimensions of the channel are in equilibrium with the controlling parameters of discharge, sediment input, energy slope and boundary soil strength. Given the highly variable nature of each of these variables, it is obvious that gullies with equilibrium channels are rare. Usually such equilibrium as does exist is of a dynamic nature, erosion and deposition processes being fairly well matched to produce a channel that maintains reasonably conservative form and size.

5.2.4. Complex Response of Ephemeral Gullies

The nature of gully response to a change in external control has been greatly simplified in the preceding sections, to illustrate the types of response that occur, how they relate to the controlling variables and how they effect sediment yield. In fact it is the rule rather than the exception that degradation, aggradation and stability coexist at different reaches in a gully at any particular moment. The system by which either discontinuities in gully development, or a single, simple change in external control produces a complex response has been described by Schumm (1978). Hey (1979) has produced a conceptual model that simulates many of the main features of complex response based on the processes of sediment entrainment, transport and deposition. A full account of complex response is beyond the scope of this report, but in

Photograph 8. Sediment storage in an aggrading ephemeral gully. Depth of bed aggradation is about 4 inches in this sedimentation zone midway along the gully system. (WES Study Site #1).

summary the theory shows how the sediment production from a fluvial system follows a damped oscillation after an external pertubation (such as base level lowering) disturbs its equilibrium.

Ephemeral gullies present an obvious application for the principles of complex response. In form and size they are strikingly similar to the drainage channels in Professor Schumm's experimental rainfall/erosion facility from which some of the theory was developed. The problem of predicting sediment yield from an ephemeral gully from basic principles is complicated because the yield depends not only on external pertubations and gully form and size, but also on the particular stages of complex response dominating the system at the beginning and end of the period of interest.

In summary, the erosion of an ephemeral gully results from the sequence of rainfall/runoff events that it experiences, the supply of sediment by rill and inter-rill erosion, the topography of the swale in which it is located, the strength of boundary materials forming the channel and the nature of base level control at the downstream end of the gully. Gully erosion is rarely a simple, progressive process of degradation or aggradation leading to stability, but usually involves phases of degradation and aggradation in complex response to intrinsic discontinuities in the development process and to changes in the external variables listed above.

Sediment yield from an ephemeral gully is the net product of the degradational and aggradational phases involved in complex response, together with the sediment supplied by rill and inter-rill erosion and transported through the gully to its outlet. This usually results in a damped oscillation in sediment yield through time following disturbance of the gully by a large runoff event, by a change in sediment supply, by soil properties or by base level control.

5.3. Ephemeral Gully Destruction

The ephemeral gully is destroyed and the cycle of events closed when normal surface tillage operations obliterate the channel. Provided that no special machinery (bulldozer, drag line, etc.) is used to fill in the gully then by current definition the gully was ephemeral. The timing of gully destruction in the hydrologic year depends on the geographic location, weather conditions and crop type. Consequently, at any one time, the cycle of gully initiation/development/destruction will be at different stages both within and between regions. Ephemeral gullying is not a closed cycle because there is always a net loss of soil and a lowering of the ground surface, particularly in the swale around the gully itself. The soil that fills the gully after tillage is usually loosely packed and highly aggregated so that its erodibility is much greater than the surrounding in situ soil. As a result, the ephemeral gully tends to re-excavate the old channel and the feature recurs at about the same location year after year. Consequently, the swale becomes more and more pronounced with each cycle, tending to intensify the ephemeral gullying by increasing the tendency for concentrated flow in the swale. Eventually, unless preventative measures are taken, the swale becomes so pronounced and the gully development between tilling so severe that the channel can no longer be destroyed by normal tillage. The ephemeral gully has then become a regular gully, a permanent feature of the landscape.

6. DEVELOPMENT OF AN EQUATION TO PREDICT EPHEMERAL GULLY EROSION

6.1. Definition of Erosion Processes

It is generally recognized that soil erosion due to rainfall and runoff on arable fields can be divided into three categories: sheet erosion, rill erosion, and gully erosion. Sheet erosion is the removal of a thin layer of soil from the soil surface by a combination of raindrop impact and sheet flow of surface runoff. Rill erosion is soil removal by small concentrations of surface runoff in small channels. Gully erosion is the removal of soil by large concentrations of surface runoff in channels that form a drainage network. Clearly ephemeral gully erosion is not a sheet erosion phenomenon, but the semantic question arises of whether ephemeral gullies are large rills or small gullies.

Meyer (1976) differentiates between rills and gullies on the basis of their formative processes. He notes that rills are formed by soil detachment by concentrated runoff while gullies are developed through massive soil removal by concentrated runoff with significant lateral inflow and with slumping of gully sidewalls from gravitational forces and excess moisture. The difference is that rills are entirely fluvial in origin and form, while gullies are significantly affected by gravitational forces and soil pore water pressure in addition to fluvial processes. The importance of gravitational forces and soil pore water pressure to gully sidewall stability has been documented in a series of papers by Bradford, Piest and Spomer, based on experiments in Iowa (see for example Piest, Bradford and Spomer, 1975; Bradford and Piest, 1980). Thorne, Little and Murphey (1981) used the principles of soil mechanics to develop dimensionless stability charts that successfully predicted critical gully wall heights and angles for stability.

In the case of ephemeral gullies, the forces of gravity and soil pore water pressure are of secondary importance to those of fluid shear, drag and lift. However, the nearly vertical walls of some ephemeral gullies, the presence of tension cracks parallel to the bank line and observations of small slab type failures of sidewalls during widening all indicate that gravitational forces and soil water pressure are still significant in determining gully form, especially in weakly cohesive soils and where a resistant plow-pan or resistive layer limits channel depth, and promotes widening. For example, photograh 2 clearly shows tension cracks and slumping failures of the side walls of an ephemeral gully.

Having differentiated between rills and gullies, Meyer (1976) suggests that such differentiation may be simply one of time and stage of development by stating that, "Gullies may be considered as large rills that cannot be crossed or obliterated by subsequent tillage." That a rill may develop into a gully given sufficient time is clearly indicated by other classification schemes for surface drainage channels. For example, Bogolyabova and Karaushev (1979) used a qualitative classification first suggested by Sobolev (1948). This is based on four stages of gully development: rilling, headcutting, equilibrium and waning. After the waning stage the gully becomes a ravine. That is it becomes a valley type feature rather than an active channel. By this system, ephemeral gullies would alternate between the rilling and headcutting stages tending towards equilibrium but in most years being erased by tillage prior to the equilibrium form.

Miller and Keith (1981) used a somewhat similar classification system but attempted to introduce quantitative criteria based on gully size and form. Their four classes are: Class I, critical or severely eroded areas, usually of less than an acre, which experience concentrated runoff and which will develop into classic gullies if left untreated. Class I gullies do not exhibit the characteristic features of gullies such as vertical sidewalls or headcuts. Classes II to IV are classic gullies with vertical sidewalls and headcuts, their classification depending on their size. Miller and Keith's criteria are summarized in Table 1. If a gully meets any single criterion of a higher class, even though all other criteria are in lower classes, the gully belongs in the higher class. In Table 1 the slope length factor (SF) is given by:

$$SF = (FS - 3)\ GL$$

where FS is the gully floor slope, in percent, and GL is the gully length in feet. By Miller and Keith's criteria, ephemeral gullies are Class I type, although they are small even for this category.

Table 1. Quantitative Classification of Gullies after Miller and Keith (1981).

Gully Class	Soil Erodibility	Drainage Aread (acres)	Maximum Gully Depth (feet)	Slope Length Factor
I	Slight to Moderate	< 40	< 5	< 1000
II	Severe	< 60	< 30	< 1000
III	Severe	< 100	< 40	< 2000
IV	Severe	> 100	> 40	> 2000

In summary, it seems that ephemeral gullies are large rills which have not become regular gullies although they do exhibit several of the attributes of gullies, such as large concentrations of flow, vertical sidewalls with gravitational failures, and a drainage network, albeit at a small scale.

These considerations show that ephemeral gullies fit into the classification scheme somewhere between rills and gullies and suggest that possibly methods for predicting erosion due to either rills or gullies might be applicable to ephemeral gullies. However, because ephemeral gullies do not fit comfortably into either class of channel, some modification of the methods must be expected. In the remainder of this section, currently available methods for soil loss prediction under rilled and gullied conditions are reviewed to identify potential candidates for modification into a procedure to calculate soil loss under ephemeral gullying conditions.

Methods to predict the erosion of soil caused by raindrop impact, sheet flow and concentrated flow in channels fall into two groups. Firstly, there are process based approaches that attempt to account for and characterize the various processes of soil detachment, entrainment, transport and deposition involved in soil erosion. In order to use this approach to determine the annual soil loss from a field, it is necessary to apply the equations on an event by event basis, modelling surface runoff, soil erosion, ground surface response and rill development through the year and arriving finally at a cumulative soil loss for the year. If an average annual soil loss is required then it is necessary to determine what sequence of rainfall/runoff events (in terms of magnitude, duration, timing and sequence) constitutes an average year. Clearly many problems arise in this regard, in addition to all those involved in simulating the complex processes involved. Usually a stochastic approach is adopted in applying this type of analysis. These difficulties led to much research effort being expended on the statistical approach to soil loss prediction. In this approach large amounts of data are collected and multiple-regression techniques are used to relate dependent variables (soil loss, ground surface lowering, sediment yield from a watershed) to controlling or independent variables (rainfall erosivity, soil erodibility, topography, surface treatment, crop development and conservation practice). The accuracy of this type of approach depends entirely on the completeness and extent of data and its applicability to the region in question. Good results are obtained when the equations are applied within the region for which they were developed, but serious errors occur when it is attempted to apply the equations outside their data bases.

Clearly both approaches have problems and advantages. Firstly, process based methods are reviewed and secondly statistical methods.

6.2 Process Based Approach to Erosion Prediction

6.2.1 Background

The key to predicting erosion on the basis of the physical processes involved is in developing mathematic models that describe those processes quantitatively. Specifically, the models must deal with the generation of surface runoff, and the detachment, entrainment, transport, and deposition of sediment.

Many researchers have attempted all or part of this modelling requirement and a review of all of their work would produce an extremely long and rather repetitive report. Instead, two of the more typical recent approaches that illustrate the main points relevant to this study are reviewed briefly, and then most space is devoted to the preferred model: the CREAMS2 model developed by the US Department of Agriculture, Agricultural Research Service.

David and Beer (1975) divided soil erosion into factors representing rain splash erosion, erosion of impervious areas, sheet erosion by overland flow, and channel erosion.

Their total erosion equation is simply the sum of these components:

$$E = T' + E_r + E_s + E_i + E_c \qquad (6.1)$$

where T' = overland flow transport capacity (if less than available detachment storage) or available detachment storage (if less than transport capacity)

E = total erosion for specific period

E_r = amount of scour by overland flow

E_s = amount of soil splashed directly into channels in specific time period.

E_i = amount of sediment picked up from impervious areas

E_c = channel bed and bank scouring

The Kentucky Watershed Model, a modification of the Stanford Watershed Model, was used to supply overland flow values for use in the erosion model. The process equations were based on previous theoretical and experimental studies.

The component relevant to this study is that of channel bed and bank scouring. Clearly, this is not independent of the sediment supplied to the channel by the other components and so some consideration of all of the processes is required. Initially, however it is desirable to concentrate on the channel erosion.

David and Beer (1975) present a functional equation for channel scour of the form:

$$E_c = fn\ (Y,V,ds,n,S,\gamma d) \tag{6.2}$$

where, Y = flow depth

V = velocity

ds = sediment diameter

n = roughness coefficient

S = gradient

γd = specific weight of sediment

They point out that sediment scour and transport equations for channels are subject to large errors. In open channel flow the depth, velocity and slope are well related to discharge. Consequently, channel scour can be expressed simply as a power function of discharge:

$$E_c = \beta Q^a \tag{6.3}$$

where, β = factor representing the sediment properties

a = a positive number

Q = mean daily discharge.

However the values of a and β are in practice very difficult to determine and the selection of mean daily discharge as the representative flow for scour prediction is questionable.

Komura (1976) also differentiated between raindrop splash, sheet, rill and gully erosion. However, he produced an equation for total slope erosion which lumps together all these components. Water flow was modelled using a method for gradually varied flow. Sediment transport computations are based on the Kalinske bedload formula, and considerations of water and sediment continuity are used to estimate erosion down the slope. Komura's equation for fully turbulent flow is:

$$E = \frac{0.00113\ C_A C_E}{D} (fI)^{15/8}\ L^{3/8}\ S_o^{3/2} \tag{6.4}$$

where E = erosion in kilograms per hour per square meter

D = mean sediment size in millimeters

f = runoff coefficient

I = rainfall intensity in millimeters per hour

L = slope length in meters

S_o = slope gradient

C_A = bare soil area ratio

C_E = erodibility coefficient

The erodibility coefficient varies according to the presence of rills and gullies, taking values of unity if sheet erosion predominates, five if rills are present, and ten if gullies are present. Komura defined gullies as channels not erasable by normal cultivation, and so a value of erodibility coefficient greater than 5 but less than 10 seems appropriate for fields with ephemeral gullies.

Studies like these, using hydrologic models for surface runoff and leading to equations for total erosion that are either the summation of component equations for different processes, or, are lumped equations for all processes, are precursors to the CREAMS2 model.

6.2.2 CREAMS and CREAMS2 Models

CREAMS [Chemicals, Runoff, and Erosion from Agricultural Management Systems] is a field scale model using the latest process equations to describe the hydrologic, sedimentary and chemical dynamics of flow from croplands. The model is made up of sub-units concerned with the simulation of surface water hydrology, estimation of sediment movement, and the movement of nutrients and pesticides. CREAMS2 is a recently developed successor to CREAMS. It has new and increased capabilities and is in most respects a more physically based model than its predecessor. Table 6-2 lists some of the major differences between the CREAMS

Table 2. Major Differences Between CREAMS and CREAMS2

FEATURE	CREAMS	CREAMS2
STRUCTURE	3 SEQUENTIAL MODELS - Hydrology - Erosion Sediment - Nutrients Pesticides English Units only	1 INTEGRATED MODEL - Interactive structure - Optional computations Metric or English Input and/or Output
SOIL WATER DYNAMICS	Tipping Bucket storage routing - conceptual - lumped root extraction	Solves Richards Eq. Multilayer Soil Distributed Root Extraction
SOIL WATER TRANSPORT	Some in surface zone	Complete through profile with adsorption
SOIL TEMPERATURE	None	Solves for Heat Diffusion and H_2O convection
PESTICIDE ACCOUNTING	Surface zone only K_d used	Throughout profile K_{oc} used
PLANT GROWTH	Fixed by Lal diagram Water stress limit	Mechanistic Model heat, water, and nutrient stress radiation and degree-day driven - standing residue conversion - double cropping - variable rotation - perenniels
MANAGEMENT PRACTICES	External, by parameter changes. No feedback to hydrology	Efficient specification for cultivation, fertilization, irrig., tile drainage, manure applic., grazing. Feedback to hydrology and other components.

and CREAMS2.

CREAMS is made up of 3 submodels dealing with hydrology, sediment and nutrients/pesticides. CREAMS2 is an integrated model rather than a 3 model set, allowing greater interaction between hydrologic, sedimentary and chemical processes. CREAMS2 has a series of user selectable options by which the individual can tailor the model to his needs. This is possible because the model is fundamentally based and deals with the physical processes operating in the field, rather than using regression techniques to relate independent and dependent variables.

The feasibility of using CREAMS2 to predict ephemeral gully erosion and sediment yield depends on the capability of the model to accurately characterize concentrated flow erosion in swales, on the length and complexity of the computations involved, and on the requirements for input data to run the model for this purpose. The equations must be able to stand alone and simulate those aspects of the hydrological and sedimentary system controlling ephemeral gullying, without involving all aspects. The computations must be amenable to analysis on at most a small computer, in order to satisfy the original requirement for a model usable at local level. The data required must be readily available or easily obtained from field observation, again to make the model usable.

In the remainder of this section, the hydrologic and sedimentary aspects of CREAMS2 are examined in detail with particular reference to these questions.

Hydrologic Simulation

The hydrologic simulation in CREAMS2 is required for an ephemeral gully erosion equation because it predicts surface runoff characteristics which are required to compute the sediment detachment and movement.

CREAMS2 has four options for handling the field hydrology simulation. Selection of a particular option depends on the type of rainfall data available and the hydrologic precision required in the estimation of runoff and sediment transport dynamics.

Option 1 is the simplist and fastest. It uses daily rainfall data and the SCS curve number technique to estimate daily runoff. In modelling terms it is a "spatially lumped parameter method."

Option 2 uses a spatially distributed estimation of runoff assuming steady flow. That is, it is time-lumped rather than spatially-lumped. Again, only daily rainfall data are required, and the curve number technique is employed.

Option 3 estimates both time and space distributions of runoff so that the hydraulics of surface runoff can be treated as unsteady and nonuniform. That is, it is neither time or space lumped. This is achieved using a statistical rain model to generate rainfall parameters from daily records rather than using actual data on rainfall distribution through a storm.

Option 4 is a fully distributed hydrologic simulation. It is more realistic than options 1 through 3, but requires a "breakpoint" or pluviograph record of changing rainfall intensity within each storm. Unsteady and nonuniform surface flow dynamics are calculated along the entire flow path through the field.

Sediment Movement Simulation

Sediment movement in CREAMS2 is handled in one of four ways, depending on the hydrologic model option selected and the level of detail of information required.

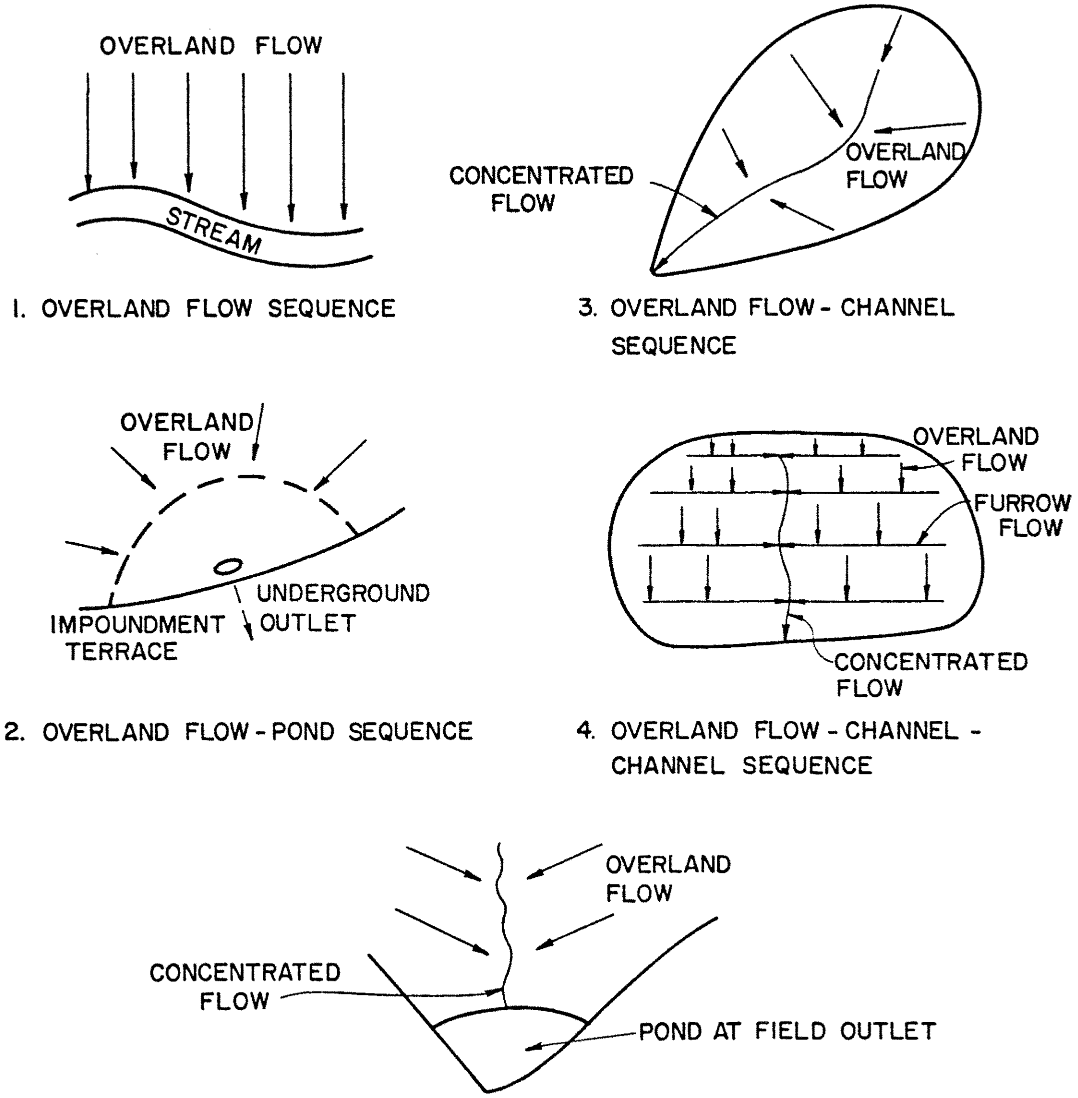
When daily rainfall data are used in hydrologic options 1 through

3, on-site erosion or off-site sediment yield may be calculated from any one of three alternatives. The simplist approach is to use an empirical sediment erosion equation based on a modified Universal Soil Loss Equation (Foster et al. 1983). If more detailed output is required, a modification of the CREAMS sediment erosion/yield submodel (based on runoff volume and peak, and storm erosivity) can be used. For the best results from daily rainfall data, a quasi-dynamic version of the CREAMS sediment submodel is used.

When using option 4 (the fully distributed simulation) to model field hydrology, the sediment is handled by fundamentally based equations for processes of soil detachment, entrainment, transport and deposition.

It is desirable that the ephemeral gully application of CREAMS2 be feasible with either daily or breakpoint rainfall data. For daily rainfall data, sediment option 3 would be appropriate in ephemeral gully erosion calculations. Options 1 and 2 are too simplisitc to provide the data required. For breakpoint data, sediment option 4 would be used.

The framework for both sediment options 3 and 4 is division of the surface runoff-sediment movement system in a field into a particular sequence of the elements: overland flow, channel flow and pond accumulation. Some typical sequences are shown in Fig. 5. For ephemeral gullies, sequences 3 and 4, for fields without and with contour furrows respectively, are applicable. Where a controlled field outlet causes ponding at the downstream end of the ephemeral gully, sequence 5 is appropriate. In the computations sediment is routed through the sequence from uppermost to lowermost element. This makes it possible to calculate total sediment yield or sediment erosion in a particular ele-



1. OVERLAND FLOW SEQUENCE

2. OVERLAND FLOW - POND SEQUENCE

3. OVERLAND FLOW - CHANNEL SEQUENCE

4. OVERLAND FLOW - CHANNEL - CHANNEL SEQUENCE

5. OVERLAND FLOW - CHANNEL - POND SEQUENCE

Figure 5. Schematic diagram of typical runoff-sediment movement systems in arable fields used in CREAMS Sediment Options 3 and 4.

ment. For example, the models could be applied in this study either to estimate ephemeral gully erosion in the element of the model dealing with concentrated channel flow, or they could be used to obtain the sediment yield at the outlet of an ephemeral gullied field. The models have versatility and can be tailored to the user's needs to produce the information required.

The major difference between sediment options 3 and 4 is that in option 3 rill and interrill erosion are lumped together when the soil loss ratio is calculated, while in option 4 they are considered separately. This allows option 4 to account separately for the different impacts of field management practices, such as no-till farming, on rill and interrill erosion rates. This cannot be achieved in option 3.

In the next two subsections rill and interrill erosion equations for options 3 and 4 are reviewed briefly.

Option 3: Quasi-dynamic Sediment Movement Model

The quasi-dynamic erosion/sediment yield option of CREAMS2 is physically based. This obviates the need for calibration to specific sites. Synthetic runoff hydrographs along the field slope and synthetic storm erosivity data generated from hydrologic option 3 are used to drive the sedimentary processes. The process equations are those determining rill erosion, interrill erosion sediment transport capacity and sediment deposition. These operate within the constraints of water and sediment continuity to produce erosion and deposition throughout the field. Interrill erosion (in metric units) is determined from:

$$D_i = 4.57(EI)(S + 0.014)K \phi P \tag{6.5}$$

where,

EI = product of storms energy E and its maximum 30 minute intensity I. (see Section 6.3.2 for a more complete explanation).

D_i = interrill erosion [kg/m^2] for the storm

S = sine of slope angle

P = contouring factor from USLE

K = soil erodibility factor from USLE

φ = soil loss ratio for effect of plant cover management.

Rill erosion comes from:

$$D_r = (6.86 \cdot 10^6)\ m\ v_u\ \sigma_p^{1/3}\ (x/22.1)^{(m-1)} S^2 K\ \varphi\ P \qquad (6.6)$$

where,

D_r = rill erosion (kg/m^2) for the storm

m = slope length exponent

x = distance downslope from origin of overland flow

σ_p = peak runoff rate for the storm (mm/hr)

v_u = depth of runoff for the storm (mm)

These equations are applied through the storm, so that D_i varies with instantaneous rainfall erosivity and D_r with runoff discharge. This better models actual rill and interrill erosion than does the second sediment option which is based on peak runoff alone.

The transport equation used in CREAMS2 is the Yalin (1963) equation. This was selected on the basis of an evaluation of several equations applied to shallow flow and erosion by rill and interrill flows (Alonso et al. 1981). The Yalin equation is:

$$P_s = W_s/(S_p\ g\rho\ d\ V_*) = 0.635\ \delta(1 - (1/\sigma)\ln\ (1+\sigma)) \qquad (6.7)$$

where

P_s = nondimensional transport rate

W_s = transport capacity per unit width (mass/(length . time).

S_p = specific gravity of particles

g = gravitational acceleration (length/time^2)

ρ = water density (mass/volume)

d = particle diameter

V_* = shear velocity (length/time)

and

$$\sigma = A\ \delta \tag{6.8}$$

where

$$A = 2.45(S_p)^{-0.4}\ (Y_{cr})^{0.5} \tag{6.9}$$

$$\delta = (Y/Y_{cr}) - 1,\ \left[\text{if } Y < Y_{cr},\ \delta = 0\right] \tag{6.10}$$

$$Y = (V_*)^2/(S_{p-1})gd \tag{6.11}$$

Y_{cr} = critical dimensionless shear force from Shield's curve.

The shear velocity is calculated from the overall flow parameters:

$$V_* = \sqrt{(gRS_f)} \tag{6.12}$$

where R = hydraulic radius, or depth for wide flows

S_f = energy gradient

This is related to the average boundary shear stress by:

$$V_* = \sqrt{\frac{\tau_o}{\rho}} \tag{6.13}$$

where τ_o = boundary shear stress.

Sediment is made up of a mixture of particles of different sizes. These are divided into size classes and the Yalin equation is applied individually to the size classes making up the size distribution. The transport rates for the classes are summed to obtain the total. Allowance is made for excesses and deficits of transport capacity in particular size classes so that transport capacity is shifted from classes having an excess over availability to ones with a transport capacity deficit.

The sediment data required to apply the model are the size and density distributions. It should be noted that usually these particles are aggregates of smaller primary particles (sand, silt and clay). The parameters for the aggregates vary with soil type and management practice for particular fields. If no data are available on the aggregate properties, the model can generate this information from the composition of the soil in terms of percentage sand, silt and clay (Foster et al., 1982).

Deposition of sediment from transport is described by:

$$D = (\beta V_s/q)(T_c - g_s) \qquad (6.14)$$

where,

D = Deposition Rate

β = Turbulence Factor = 0.5 for overland flow or 1.0 for concentrated flow

q_s = Discharge per unit width

T_c = Sediment transport capacity

g = Sediment load

V_s = Particle fall velocity

This equation is applied to each size class in turn, to determine the deposition rate for that size class. In this way selective deposition of coarser/heavier particles is accounted for.

Values for the soil loss ratio describing the effects of field management and plant canopy development (φ) in equations (6.5) and (6.6) are taken from the work of Wischmeier and Smith (1978) and Laflen et al.(1983). However, the values are updated daily in CREAMS2 rather than averaged for crop stage, to improve accuracy.

Values of soil loss ratio are calculated using Wischmeier's (1975) subfactor approach. The three subfactors are: I. Canopy, II. Ground Cover and surface roughness, and III. Within Soil Effects. The soil loss ratio value is the product of values for the three subfactors.

In this approach rill and interrill erosion are lumped as far as soil loss ratio is concerned. However, in actuality the subfactors have different effects on rill versus interrill erosion. For example ground cover is more effective in controlling rill erosion than interrill erosion. The values calculated therefore represent averages for the effects of the subfactors on rill and interrill erosion.

There is evidence that the accuracy of erosion estimates can be increased by separating rill and interill effects in calculating soil loss ratios and so this is incorporated into the dynamic option of CREAMS2, option 4.

Option 4: Dynamic Sediment Movement Model

In the dynamic sediment movement model, rill and interrill erosion are analyzed separately and the interactions of interrill erosion, and rill erosion and deposition, with sediment transport capacity throughout the storm event are considered. This is a significant improvement over option 3, because often deposition may control soil loss at the beginning and end of a storm, whilst detachment is controlling loss during the middle period, and this is accounted for in the dynamic option.

The runoff pattern follows the furrows to low points (swales) where breakover occurs to produce large concentrations of flow. This is precisely the flow pattern believed to initiate ephemeral gullies in swales. If no furrow pattern is present sheet flow is assumed to flow straight downslope.

Interrill areas are the side slopes of furrows in plowed fields and sheet flow areas of unplowed fields. For these areas interrill erosion is calculated from (Foster, 1982):

$$D_i = 0.0138\ K\ (2.96(\sin\theta)^{0.79}+0.56)\varphi_i \tag{6.15}$$

where,

D_i = interrill erosion rate (kg/m^2 h)

i_e = effective rainfall intensity (mm/h)

θ = slope angle of interrill area

φ_i = soil loss ratio for interrill erosion

The effective rainfall intensity represents the effects of canopy interception, diameter of reformed drops falling from the canopy, their velocity and the reduction in rainfall amount reaching the ground due to interception. The interrill soil loss ratio is determined from:

$$\varphi_i = \phi_u\ \xi\ \exp(-0.21(y_c/y_b-1)^{1.18}) \tag{6.16}$$

where,

φ_u = soil loss ratio for subfactor III (within soil effects)

ξ = fraction of soil surface exposed to raindrop impact and canopy droplet impact

y_c = flow depth with ground cover

y_b = flow depth with bare soil

Rill erosion, in furrows and small concentrations of flow, is calculated from (Foster and Meyer, 1972; Foster and Meyer, 1975):

$$D = (D_c/T_c)(T_c - g) \tag{6.17}$$

where,

D = rill erosion rate (kg/m^2 h)

D_c = rill erosion detachment capacity

T_c = sediment transport capacity (kg/m h)

g = sediment load

Approximate values for detachment and transport capacity are given by:

$$D_c = a_D \tau_s^{3/2} \tag{6.18}$$

$$T_c = a_T \tau_s^{3/2} \tag{6.19}$$

where,

a_D = detachment capacity coefficient

a_T = transport capacity coefficient

τ_s = shear stress on soil (N/m^2)

and,

$$a_D = 139\ K\ \phi_u\ \phi_r \tag{6.20}$$

where,

φ_u = soil loss ratio sub-type III, accounting a factor for the effect of buried mulch stones and roots reducing rill erosion

$$\varphi_r = \exp(-1.8\ M_b) \tag{6.21}$$

M_b = mulch rte (kg/m^2) in tilled zone

Also,

$$a_T = 188-468f_c+907f_c^2 \tag{6.22}$$

for $f_c \leq 0.22$ and,

$$a_T = 130 \tag{6.23}$$

for $f_c > 0.22$

where,

f_c = clay fraction in soil

Concentrated Flow

Concentrated flow produces new erosion processes that demand different equations to those for rill and interrill erosion. In CREAMS2 both Options 3 and 4 model channel erosion by concentrated flow using:

$$D_f = K_f(\tau_s-\tau_{cr}) \tag{6.24}$$

where,

D_f = detachment rate at a point on the wetted perimeter of the concentrated flow

K_f = soil erodibility factor for erosion by concentrated flow

τ_s = shear stress on soil at that point on wetted perimeter

τ_{cr} = critical shear stress for detachment

The equations for sediment characteristics, transport capacity and deposition are carried over to the concentrated flow areas.

Impoundments

If the channel (concentrated flow) leads to an impoundment (pond) before leaving the field, this will induce local deposition during and following each runoff event. The amount of sediment passing through the pond and out of the field depends on the trap-efficiency of the pond. This is accounted for in CREAMS2 by empirical equations for the fraction of material passed in each size class (Knisel, 1980).

6.2.3 Feasibility of Using CREAMS2 to Predict Ephemeral Gully Erosion

It appears that CREAMS2 has the capability to predict ephemeral gully erosion in theory. However, as it has not to date actually been used for this purpose under test conditions, this has yet to be demonstrated practically.

It should be a priority of the research progrm of the Soil Conservation Service to apply CREAMS2 for this purpose and prove that the model can produce accurate and reliable results. In fact this project, for CREAMS rather than CREAMS2, is being undertaken by researchers at Iowa State University (Laflen and Watson, personal communication, 1983).

It appears that the length and complexity of the calculations involved in such an application will be considerable. Possibly, CREAMS2 may be simplified for its ephemeral gully erosion use, but this rather defeats the object of CREAMS2 which was to unify the sub-model approach of CREAMS. Also, experience shows that rill, interrill and concentrated flow erosion are inter-related and attempts to work with the concentrated flow erosion alone may well be futile.

In their present forms both CREAMS and CREAMS2 require mainframe computers for their calculations. This would disqualify them from consideration unless simplifications can be introduced with the constraints just mentioned. Data requirements certainly go beyond that which is routinely available and this too limits the potential for easy application.

In summary, CREAMS and CREAMS2 represent the latest attempts at a process-based approach to runoff and sediment modelling for field sized catchments. As such, they reflect the complexity of the processes involved and illustrate why simple empirical models have such limited applicability. There is little point in trying to develop a new process-based approach for ephemeral gully erosion prediction. To do so would merely replicate the work already done on CREAMS. Application of CREAMS or CREAMS2 is the logical alternative. However, it should be borne in mind that it is possible that CREAMS or CREAMS2 cannot fit the requirements of the project because it is too big for a desk top computer, to complicated for easy application and requires data beyond that usually available. Therefore, whilst encouraging research into application of CREAMS or CREAMS2, work should also proceed on developing simpler empirical and semi-empirical models which although less elegant than CREAMS are sure to be easily usable.

6.3 Empirically Based Approach to Erosion Prediction

6.3.1 Background

The most widely used approach to erosion prediction is the Universal Soil Loss Equation (USLE):

$$A = (0.224)RKLSCP \qquad (6.25)$$

where,

A = soil loss in kg/m^2s

R = rainfall erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope gradient factor

C = cropping management factor

P = erosion control practice factor.

The USLE was developed as an aid to conservation practice planning, although with careful application and precise evaluation of its various factors, it can also be used as a research tool. The equation predicts the annual average soil loss from rill and inter-rill erosion. As such it does not predict soil loss due to ephemeral gullying. However, as the best developed empirical soil loss prediction equation, USLE does provide the obvious starting point for development of an empirically based ephemeral gully erosion equation. Consequently, before suggesting how this development might be accomplished, it is relevant to review briefly the factors in the USLE and how they affect the erosion phenomena.

6.3.2 USLE

The factors in the USLE were developed using standard erosion plots 22.13 m long by 1.83 m wide, on a uniform slope of 9%. The standard plot was tilled up and down the slope and was in continuous fallow for at least two years. However, not all the data used in the USLE in fact came from this standard surface, leading to the ranges of statistical deviation used in development.

Each factor represents some physically defined aspect of erosion and each is now outlined separately.

Rainfall Erosivity Factor, R

This index is based on the product of two rainstorm characteristics: kinetic energy, E, and maximum thirty minute intensity, I_{30}. This product is divided by 173.6 to obtain R. The E factor is found by summing kinetic energy throughout the storm in increments. Mathematically:

$$\Sigma E = \sum_{j=1}^{j=n} [(1.213+0.890\log_{10} I_j)(I_j T_j)] \tag{6.26}$$

where,

ΣE = kinetic energy for storm

n = number of increments

I_j = rainfall intensity (mm/hr) for jth increment

T_j = length of jth increment (hr).

The R factor is then:

$$R = \frac{\Sigma EI_{30}}{173.6} \qquad (6.27)$$

where, I_{30} = maximum 30-minute rainfall intensity (mm/hr).

In practice the R value is obtained from a map of R factor for the area of interest. More or less detailed maps are available for the contiguous United States (Fig. 6) and Hawaii, as well as some other parts of the world.

Soil Erodibility Factor, K

This factor is a quantitative description of the inherent erodibility of a particular soil. It reflects the fact that for equivalent conditions different soils erode at different rates. K values for most soils in the U.S.A. have been determined by the SCS.

Direct measurement of the K factor, if no SCS value is available, is difficult, costly and time consuming. Consequently, the usual approach is to estimate K on the basis of other soil parameters which control erodibility and are more easily measured.

Most commonly the nomograph of Wischmeier et al. (1971) is used (Fig. 7). This is based on the five parameters identified as being most important to soil erodibility: percent silt + very fine sand, percent sand, organic matter content, soil structure and permeability.

The Slope Length Factor L, and Slope Gradient Factor S

Slope length, L, is defined as the distance from the point of origin of overland flow, to the point where the slope decreases sufficiently for deposition to occur, or to the point where surface runoff enters a channel which is part of a drainage network. Slope gradient,

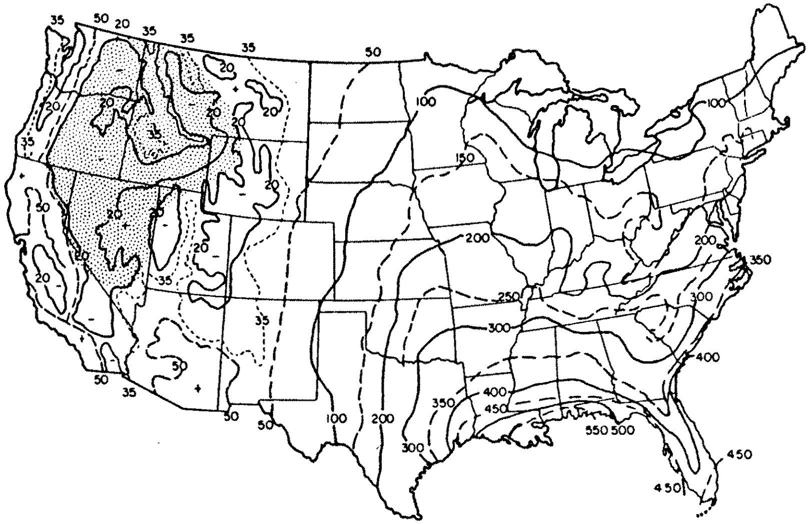
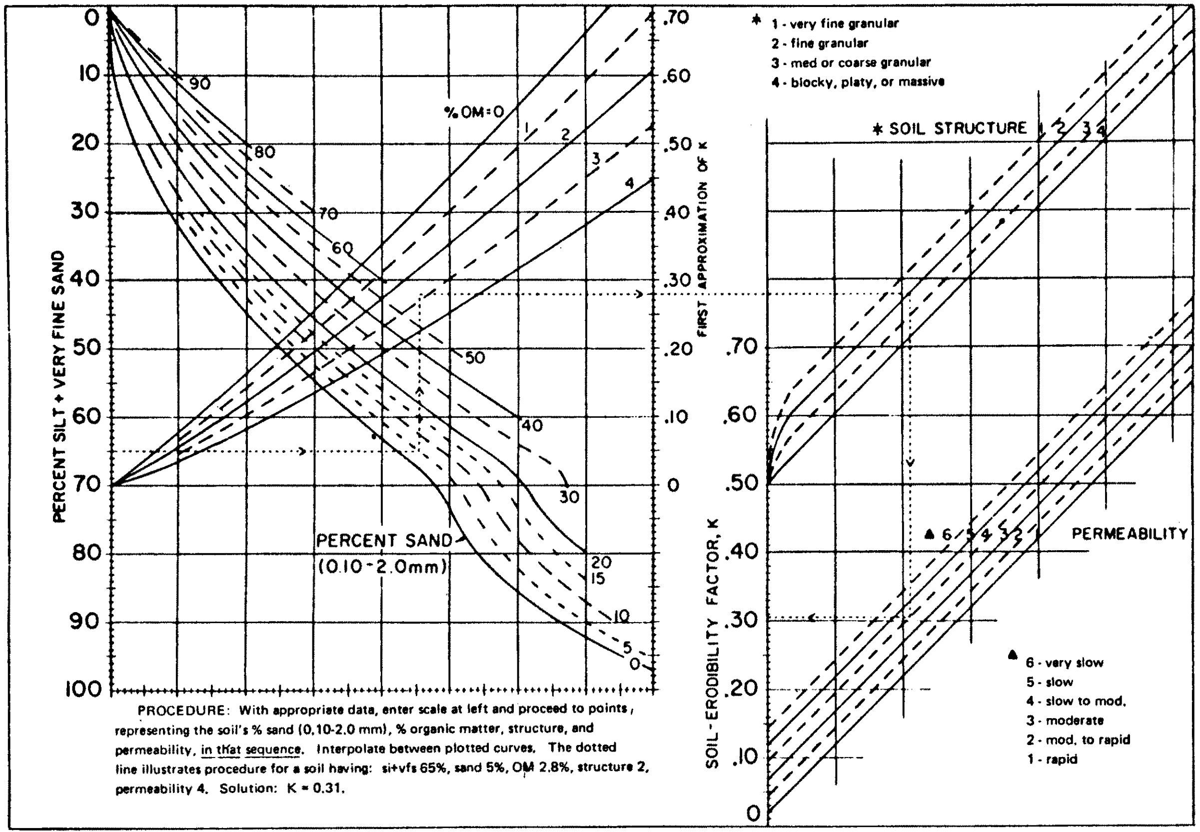


Figure 6. Average values of R for the U.S.A. (after Kirkby and Morgan, 1980).



PROCEDURE: With appropriate data, enter scale at left and proceed to points, representing the soil's % sand (0.10-2.0 mm), % organic matter, structure, and permeability, in that sequence. Interpolate between plotted curves. The dotted line illustrates procedure for a soil having: si+vfs 65%, sand 5%, OM 2.8%, structure 2, permeability 4. Solution: K = 0.31.

Figure 7. Nomograph used to determine K (ARS, 1975).

S, is the field or field segment slope, in percent. Often the two factors are combined into a single topographic factor LS. Values of LS can be conveniently obtained from a graph like Fig. 8.

However, in the field there are often practical difficulties in determining representative values for slope length and gradient. Particularly, the effects of complex slopes are not well represented by a single topographic factor. This led Foster and Wischmeier (1974) to develop a slope segment approach. In this approach the slope is split into a series of internally uniform segments and the soil loss for the whole slope is calculated from:

$$A = 0.224RKCP \; \frac{\sum_{j=1}^{j=n} (S_j x_j^{(m+1)} - S_j x_{(j-1)}^{(m+1)}}{x_e (22.13)^m} \qquad (6.28)$$

where,

x_j = distance from slope top to end of jth segment (m)

$x_{(j-1)}$ = distance from slope top to top of jth segment (m)

x_e = total slope length (m)

S_j = slope gradient for jth segment given by:

$S = (0.43+0.3s+0.043s^2)/6.613$

s = slope in percent.

The exponent m depends on slope gradient for the segment, being defined by:

$m = 0.5$ for slope $\geq 5\%$

$m = 0.4$ for $5\% > \text{slope} > 3\%$

$m = 0.3$ for $3\% \geq \text{slope} \geq 1\%$

$m = 0.2$ for $1\% > \text{slope}$.

Variations in K downslope can also be accounted for segment by segment.

Crop Management Factor, C

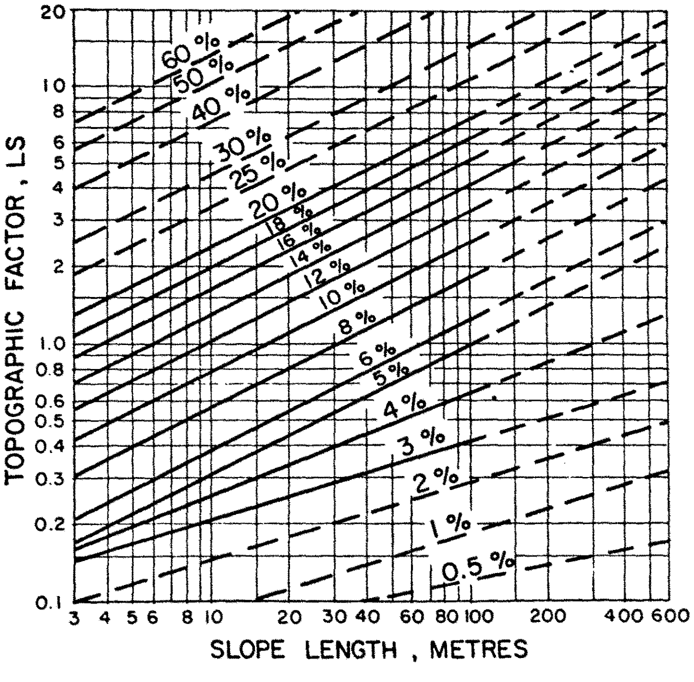


Fig. 8. Topographic factor LS based on slope length and gradient (Wischmeier and Smith, 1978).

This factor represents the ratio of soil loss from a specific crop to the loss from a tilled, continuous fallow condition for the same soil, topography and rainfall. It includes the interrelated effects of plant cover, crop sequence, productivity level, growing season length, cultural practices, residue management, and rainfall distribution. Extensive tables of soil loss ratios for different cropping and management effects have been developed and the most popular schemes are presented in Wischmeier and Smith (1978). An example of the tables is shown in Table 6.3.

Erosion Control Practice Factor, P

This factor represents the ratio of soil loss using a specific erosion control practice, to that occurring under up-and-down the hill tillage for the same soil, topography, crop and rainfall. The practices usually considered are: contouring, contour-strip cropping, and terracing. Other common conservation practices, such as, conservation tillage, crop rotations and retention of residues are included in the crop management factor, C. Values of P for vaarious practices have been tabulated by Wischmeier and Smith (1978) and an example is given in Table 6.4.

Application

Having calculated the soil loss from the USLE, it is necessary to decide if this loss is tolerable, or if it must be reduced by improved cropping or conservation practices. This is determined by comparing the actual average annual soil loss (from USLE) to the soil loss tolerance, T, which is the maximum rate of soil erosion that permits a high level of productivity to be maintained. The T value depends on factors such as, the depth of top soil, sub-soil characteristics, and rate of soil

Table 3. Example of the Cropping-Management (C) Factor Evaluation after Wischmeier and Smith (1978).

Crop Stage Period	Dates	Percent of Ann. Erosion Index	Crop Stage Soil Loss, C Percentage	C Factor
Meadow	1/1-4/15	10	0.4	0.0004
Rough ploughed sod	4/15-5/5	5	8	0.0040
Disked and corn seedbed	5/5-6/1	10	22	0.0220
10-50 percent canopy	6/1-6/20	13	19	0.0247
50-75 percent canopy	6/20-7/10	14	17	0.0238
75 percent canopy-harvest	7/10-10/15	40	10	0.0400
Residue	10/15-12/31	8	14	0.0112
	1/1-4/1	8	14	0.0112
Oat seedbed	4/1-4/15	2/12	0.0024	
10-50 percent canopy	4/15-5/1	4/12	0.0048	
50-75 percent canopy	5/1-6/1	11	11	0.0121
75 percent harvest	6/1-6/15	9	7	0.0063
New meadow in oat stubble	6/15-8/15	38	2	0.0076
Meadow (16.5 months)	8/15-1/1	128	0.4	0.0051
Total		300		0.1756
Average Annual C Factor			0.0585	

Table 4. Erosion Control Practice Factor, P, after Wischmeier and Smith (1978).

1-2	0.60	0.30	0.12
3-8	0.50	0.25	0.10
9-12	0.60	0.30	0.12
13-16	0.70	0.35	0.14
17-20	0.80	0.40	0.16
21-25	0.90	0.45	0.18

profile development. Values for soils in the U.S.A. are obtained from the Soil Conservation Service's handbooks.

6.3.3 An Empirical Equation for Ephemeral Gully Erosion

USLE cannot be used directly to predict ephemeral gully erosion. The main reason for this is that the processes of rill and inter-rill erosion represented in the USLE are different to those of channel erosion responsible for ephemeral gully development. This was recognized by Foster et al. in 1977. They developed modified factors in the USLE to separate out rill (channel) and inter-rill (raindrop, sheet flow) erosion:

$$A = x\ K_r(as^e)F_tC_rP_r/\lambda_u + K_i(bs+c)I_tC_iP_i \qquad (6.29)$$

Rill erosion = D_r · Interrill erosion = D_i

where,

F_t = runoff erosivity

C_i = cropping factor for inter-rill erosion

C_r = cropping factor for rill erosion

I_t = rainfall erosivity

K_i = soil erodibility for inter-rill erosion

K_r = soil erodibility for rill erosion

D_i = average inter-rill erosion over slope length x

D_r = average rill erosion over slope length x

P_i = conservation practice for inter-rill erosion

P_r = conservation practice for rill erosion

a,b,c and e = coefficients

s = sine of slope angle

λ_u = length of unit plot (22.1 m)

There has been considerable research into the factors for runoff erosivity, soil erodibility with respect to runoff and the impact of cropping and conservation practices on runoff erosion.

The runoff parameters suggested by Foster et al. (1977) would be much more applicable to ephemeral gully erosion, especially during the initial stages, than would the usual USLE parameters for rill and inter-rill erosion. Therefore, it is proposed here to replace the R, K, C and P factors in the USLE with F_t, K_r, C_r and P_r type factors, to produce an ephemeral gully erosion equation (EGEE). The primary difference between the equations would be that the EGEE would describe erosion in areas of major flow concentration, rather than in areas of overland sheet flow and rill flow (USLE).

As stated earlier, the locations of areas of concentrated flow are controlled by field surface topography and, possibly, subsurfce topography of an impermeable layer or plow-pan. Therefore, the topographic indices, L and S in the USLE must be replaced, because they do not address the problem of topographic control of surface runoff pattern.

The new topographic indices must identify the areas of a field that experience major concentrated flow, and which therefore are prone to ephemeral gullying. Once the extent of the gully prone areas is determined, the soil erosion within those areas (dominated by channel processes) can be completed on the basis of the amount and erosivity of concentrated runoff, erodibility of the soil for runoff, cropping factor for runoff, and conservation factor for runoff. The effects of these factors must be investigted as their impacts on ephemeral gullying are probably different to those on rilling.

Topographic Indices

Concentrated flow occurs where overland flow streamlies converge in swales or hollows in the landscape. These features may be readily identified qualitatively from contour maps, but a quantitative definition that would predict the intensity of concentration of flow, as well as the extent requires a numerical analysis of field topography.

Beven and Kirkby (1979) used an area/slope index to predict the contributing area for surface runoff in each lumped sub-catchment unit of their semi-distributed runoff model. O'Laughlin (1980) also used this index to predict the extent of surface saturation.

McCaig (1983) suggests that a log transform of the area/slope index is more appropriate and proposes:

$$T.I. = \ln(a/\tan B) \tag{6.30}$$

where T.I. = topographic index

a = upslope contributing area

B = slope angle in degrees.

Both these topographic indices are difficult to define for actual points in real fields. Detailed, precise field survey data are required and there is an element of subjectivity in determining the upslope contributing area, a.

To address this problem, Evans (1980), developed surface derivation indices to describe surface topography. These are based on grided altitude data, are easy to develop, and are not subjective. In applying the method, spot heights are determined for a matrix of evenly spaced points over the field in question. The spacing of the points depends on the detail required and the data available. For example, from a field survey of a 2 acre field, points might be spaced at 20 feet. The spot heights are considered in 3x3 submatrices. For each submatrix the topographic indices for the central point are calculated on the basis for the altitude of that point, and the surrounding eight other points. The indices are produced by fitting best-fit quadratic equations through the points, to yield four measures of topography for the central point. These are: slope (plane tangent to the ground surface) in terms of gradient and aspect; profile convexity (rate of change of slope); and planform convexity (rate of change of aspect, i.e., convexity of contours). In this way the gradient, aspect, profile convexity and planform convexity of every point in the matrix, except those at the boundary around the edge of the matrix, are calculated. All of this output is obtained from single computer run of the gridded altitude data.

Burt and Butcher (1983) used these topographic indices in a study of runoff in south-west England. They found that areas of saturation (and therefore, concentrated overland flow) were quite well predicted by areas of strong planform concavity (negative convexity). That is areas where surface and groundwater flow were concentrated by converging streamlines. Predictions were improved still further when a compound topographic index of area/slope index multiplied by planform concavity was applied. However, there was considerably more work involved in the compound index because of the requirement of measuring the upslope contribting area.

For this study, it is proposed to use the compound topographic index (CTI) defined by:

$$\mathrm{CTI} = [\ \frac{a}{s}\ \mathrm{Planc}] \tag{6.31}$$

where:

a = upslope contributing area

s = local slope gradient

Planc = planform convexity index

as the numerical variable to predict the areas of concentrated surface runoff in fields.

The CTI accounts firstly for the contributing area upslope of the point in question, which is a good measure of the volume of runoff. Secondly, it includes the local gradient, s, which represents the intensity of runoff. Thirdly, it includes the planform concavity of the local contours, which represents the degree of convergence of the surface runoff. These are the factors identified as being critical to ephemeral gullying, in Section 5.1.

Once the map of CTI values for the field has been produced, the field may be divided into areas prone to ephemeral gully erosion and areas dominated by rill and inter-rill erosion. An example is shown in Fig. 9. Then the EGEE may be applied to the former, and the USLE to the latter. The total erosion for the field is the sum of these components.

The delineation of the two areas is based on a critical CTI value for ephemeral gully formation. This will depend on the erosivity of runoff and the erodibility of the soil with respect to ephemeral gully (channel) formation. Hence:

$$CTI_{CRIT} = \text{function}\left(\frac{F_t}{K_r}\right) \tag{6.32}$$

where

CTI_{CRIT} = critical CTI value for ephemeral gully formation

K_r = soil erodibility for runoff erosion

F_t = runoff erosivity

The form of the EGEE applied to ephemeral gully prone areas will be:

$$E = \text{constant}[F_t K_r (CTI-CTI_{CRIT}) C_r P_r] \tag{6.33}$$

where

E = ephemeral gully erosion

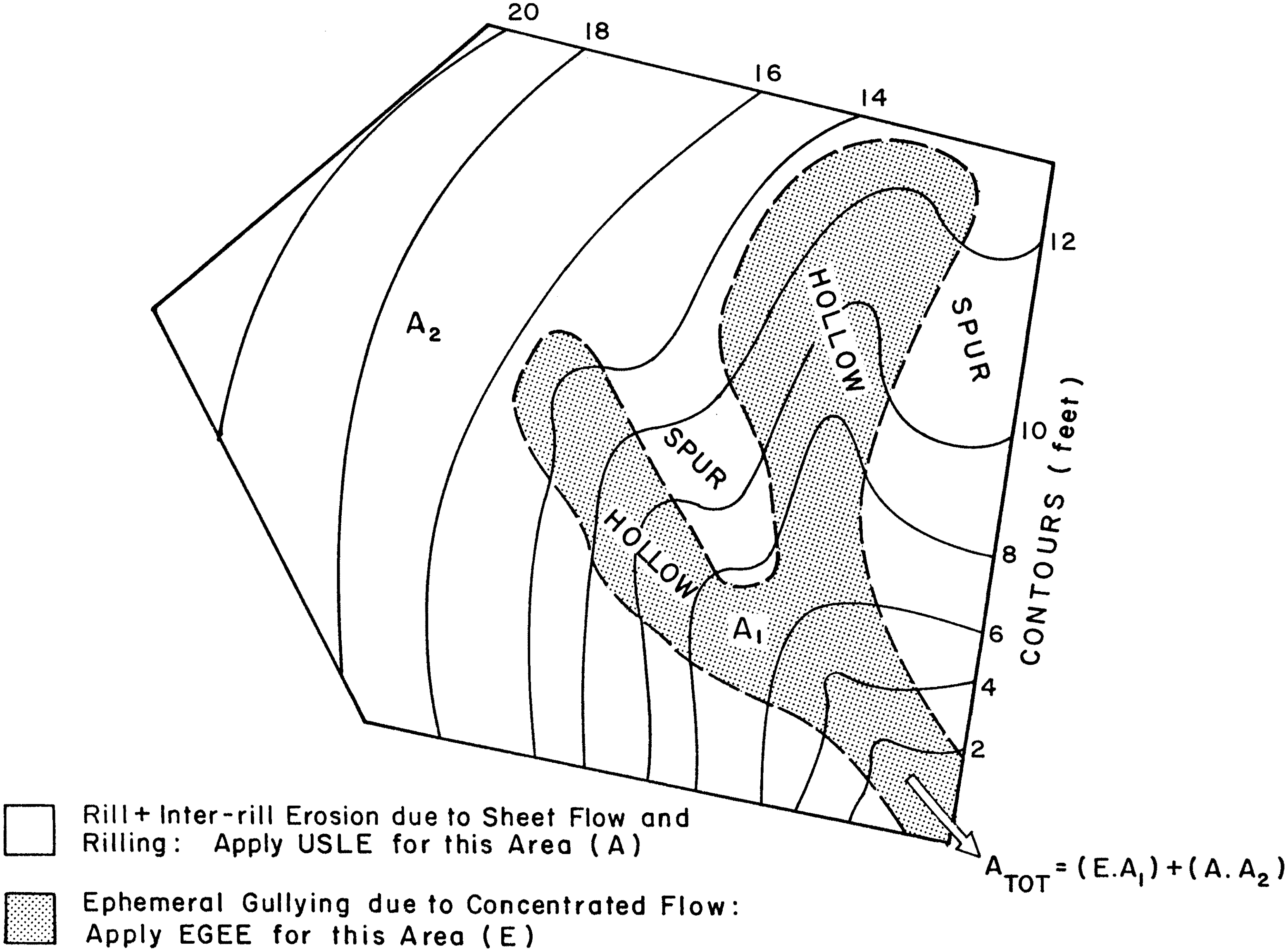


Figure 9. Division of field into areas dominated by Ephemeral Gully Erosion (A_1) and Rill and Interrill Erosion (A_2) on basis of CTI values.

The total erosion is then given by:

$$A_{TOT} = (E.Area_1) + (A.Area_2) \tag{6.34}$$

where,

A_{TOT} = total erosion rate for field (kg/s)

E = ephemeral gully erosion rate kg/m^2s

$Area_1$ = area prone to ephemeral gullying (m^2)

A = erosion rate from USLE (kg/m^2s)

$Area_2$ = area experiencing rill and inter-rill erosion (m^2)

This equation presents the total erosion as the sum of ephemeral gully plus rill and inter-rill erosion. The ephemeral gully contribution is based on the erosivity of runoff, erodibility of soil with respect to runoff, quantity, intensity and degree of concentration of runoff, and cropping management factors with respect to runoff erosion. It is applied to the area of the field prone to ephemeral gully formaton, which depends on the erosivity of the runoff and the erodibility of the soil with regard to runoff. The rill and inter-rill contribution is based on the USLE, applied outside the area of ephemeral gullying. Within that area, experience shows that the ephemeral gully erosion dominates over rill and inter-rill erosion.

Usually the ephemeral gully area will be a relatively small proportion of the field-probably about ten percent. Within that area ephemeral gully erosion may well be ten times that from rill + inter-rill erosion, however, so that the total erosion for the field is almost evenly divided between ephemeral gully and USLE contributions.

In a field with no ephemeral gully equation (6.34) reduces to the USLE as expected.

7. RESEARCH PROCEDURE

7.1. Data Requirements

Field data are required for three major purposes in this project. Firstly, they are needed to develop and verify the equations for erosion due to ephemeral gullying. Secondly, they are needed to test the usefulness of the equations when applied to actual field conditions to predict ephemeral gully erosion. Thirdly, they are required to investigate the effectiveness of various soil conservation practices in controlling ephemeral gully erosion. The nature of the field data required differs between these purposes. In the first case, detailed and comprehensive field data are essential. The object is to develop the empirical coefficients in those equations that involve them, and to verify the form of both the empirical and theoretical equations. This can only be achieved with a data set that includes measurements of all important variables and parameters. Estimation or calculation of variables or parameters should be avoided as much as possible. Clearly, this requires an intensive, scientific study over a restricted area. This is quite different from the type of data collection likely to be undertaken to routinely apply the equations. These types of data are needed for the second task, that is testing of the fully developed and verified equations to ensure a) that they can be applied using simple data, and b) that they give reasonably accurate estimates of ephemeral gully erosion on that basis. In the third case, long-term experiments under controlled conditions of cropping, management, and conservation practice are required to isolate the effectiveness of particular strategies of erosion control.

Data sets of the second type - field observations of climatic conditions, soil parameters, crop and management factors, and ephemeral gully voided volume are being collected in a field study by the Waterways Experiment Station, U.S. Army Corps of Engineers (Lawson Smith, personal communication, 1983) for the Mississippi Bluff Line region. Studies of a similar nature are being undertaken in several other regions (W. Mildner, personal communication, 1983).

Data sets of the first and third types are more difficult to obtain. Therefore, it is proposed to collect these date in a field study jointly organized and executed by the principal investigator in this project and the ARS Sedimentation Laboratory at Oxford Mississippi. This is appropriate because:

(i) The sedimentation laboratory is located in the Mississippi Bluff Line region which is an area of primary interest in this study.

(ii) The staff of the Sedimentation Laboratory have years of experience in running field studies of the type required.

(iii) The Sedimentation Laboratory has been designated as the lead location for studies of gully erosion and sedimentation, and a major contributing location for studies of rill and ephemeral gully erosion (D. A. Farrell, ARS Overview, Resource Modelling Conference, Pingree Park, October 1983).

(iv) The principal investigator and Sedimentation Laboratory staff have cooperated in field studies before and have a good working relationship (Thorne, Little and Murphey, 1981).

In the next section the field site selected and the measurement and monitoring techniques to be employed are described.

7.2. Field Site

In October 1983 the principal investigator and ARS scientists made a field reconnaissance trip to select a field site. An excellent site was found in the upper end of the Goodwin Creek watershed. This watershed is a major field study area and is already equipped with 13 meteorological, channel flow and sediment load measuring stations. Two fields were selected close to gauging stations 8 and 9 in this series (Fig. 10), so that additional meteorological measurements would not be necessary. The drainage basins to be used are on Peoria loess. Each has an area of about 4 acres and a very well defined watershed divide all around it (Figure 10). At present one watershed is in soybean and has a well developed ephemeral gully system (Photographs 9 and 10) which drains into a large gully at an overfall of about 5 feet. The second watershed is in pasture and does not have an ephemeral gully network in it although it does have an overenlarged furrow in a small corn path, which has the dimensions and appearance of an ephermeral gully. Field drainage is again into a large gully, incised below field level. Based on pro-rating the discharge at station 9 by watershed area, peak runoff for the ephemeral gully at the overfall will be of the order of 9 cfs. Peak runoff on the pasture site is expected to be similar to, or smaller than this.

The physical size of the watersheds, their proximity, clearly defined boundaries, and overfall outlets all make them good field sites, and excellent paired catchments. It is intended initially to use watershed #2 (pasture) as a control, maintaining it in good grass cover.

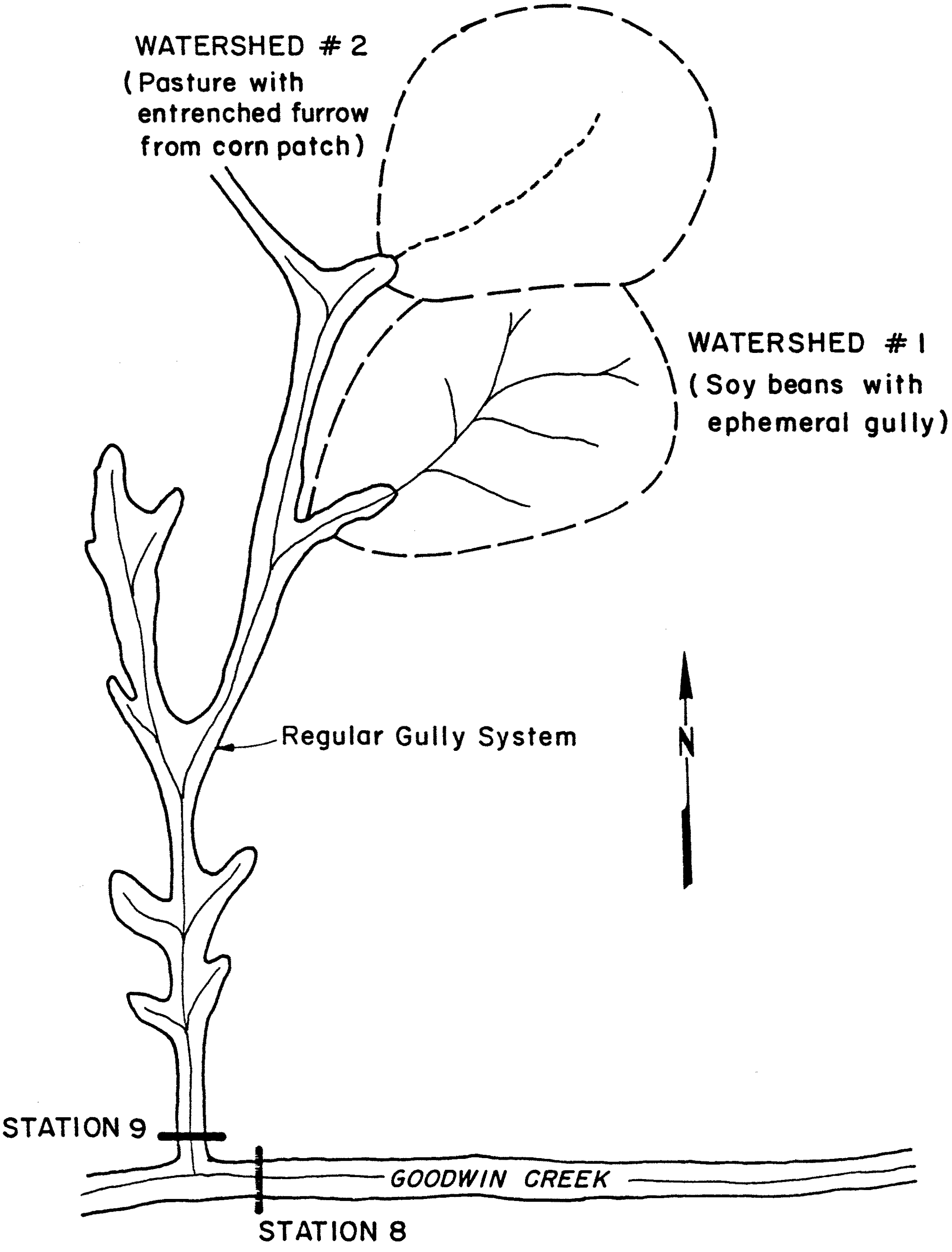


Fig. 10. Sketch map of field study area in Goodwin Creek Experimental Watershed, Mississippi.

Photograph 9. Ephemeral Gully at Field Site in Watershed #2.
Top width is about 2 feet.

Photograph 10. Field site in Goodwin Creek Watershed. View down ephemeral gully swale from drainage divide with Watershed #2. In Watershed #1, soybean field (November, 1983).

Watershed #1 (soybeans) will then yield comparative data for ephemeral gully erosion, together with sediment yield from an ephemerally gullied cropland.

The land owners are already cooperating with ARS in the Goodwin Creek study and are willing to cooperate further for this study. In recompense his lower field will be protected from further advance of the overfall at the ephemeral gully outlet, which otherwise threatens to destroy the field as far as crop production is concerned.

In future years it is proposed to switch the pasture field into soybeans using "no till" management, to determine whether this prevents ephemeral gully development.

7.3. Data Collection

In the field study the parameters to be measured on each watershed are:

(i) Total water discharge and sediment yield at the field drainage outlet.

(ii) Ephemeral gully development spatially and temporally.

(iii) Soil voided from ephemeral gully channel(s).

(iv) Soil properties (moisture content, primary and tertiary particle size distributions, temperature, horizons).

(v) Meteorological and climatological conditions.

(vi) Management and cropping factors.

The measurements will be made using the following methods and instruments.

(i) Water and sediment will be monitored at the field outlet using "H" flumes, Coshocton Wheels, and sediment traps. The hardware was already mostly available at the Sedimentation Laboratory. Continuous discharge records will be obtained from a stage recorder. Sediment yield will be computed on an event basis by emptying the sediment trap. The Sedimentation Laboratory staff have years of experience using these measurement methods - see for example, McDowell, Bolton and Ryan (1967) as a typical application to a gully system. The overfalls provide excellent locations for the hardware. The overfalls are being reveted with the "H" flumes in place and the Coshocton Wheels and sediment traps installed below in the ravine of the major gully.

(ii) Gully development will be monitored by low level aerial photographs from a light aircraft. The great utility of this technique has been demonstrated in studies in Georgia (Adrien Thomas, personal communication, 1983). This technique may also be adopted in the WES study next year, as ground surveying has proven too expensive for the repeat runs necessary to provide information on temporal development of ephemeral gullies. The aerial photo's will be rerun several times per year to provide these data.

Aerial photographs will be used in conjunction with ground truth supplied by an initial survey of the watershed by E.D.M. together with levelled targets at several locations in the watersheds. Using this approach resolution of ± 0.10 ft can be obtained which is more than adequate for this study.

The data will be used to plot maps of an ephemeral gully distribution with average widths and depths noted on a reach by reach basis.

(iii) Soil voided from the ephemeral gully system can be calculated from the results of (ii). As a check some cross-sections will be closely monitored using a rill-o-meter. This provides detailed x-sectional information which will be compared to that obtained from the low level aerial photographs. A limited number of rillometer x-sections will be established throughout the watersheds to provide back-up and check data.

(iv) Soil properties will be established using standard soil sampling and analysis techniques with which the sedimentation Lab has years of experience. Soil moisture probes an shallow wells will be installed at several locations throughout each the watershed, and monitored continuously using the same recording device as for water stage at the H-flume. Soil temperature will be measured similarly.

(v) Meteorological and climatological data are routinely collected in the Goodwin Creek Study. This means 1) no additional instruments or stations are required, and 2) a data base of several years already exists for the site chosen.

(vi) Management and cropping will be closely controlled by the research staff. The farmer has agreed to this in exchange for due compensation for loss of crop yield. It is planned to have the usual crop (soybeans) planted and to follow standard procedures in watershed #1 for the next several years. The timing of management practices (tillage) will be closely linked to the sequence of storm events and aerial photography/ground surveying schedule to optimize data collection. In watershed #2 the pasture will be maintained and enhanced before arable farming begins in about 2 years time. This is essential so that "no till" management is given an effective test. For "no till" to be effective there must be no vestiges of furrows from revious plowing and this can only be assured if the field has been untilled and in pasture for several years.

The field study is alreay underway. The approximate time table is:

December 1983 - March 1984	Install "H" flumes, Coshocton Wheels, and sediment traps, set up soil moisture and temperature probes. Establish data recording devices and begin collection of background data.
March - April 1984	Collect background data primarily for shake down and debugging of field installation.
April 1984	Conduct field survey and run first set of aerial photographs.

May 1984-April 1985	Monitor complete year of ephemeral gully development and sediment effects.

In this timetable data analysis will be on-going and the field experiment will be modified as necessary in the light of the data collected and analyzed. The field will be plowed in May 1984 to begin the first year of study and again in May 1985 to conclude it. It is planned that the study be maintained in 1985/86 possibly with different management and cropping practices.

7.4. Data Analysis

The data analysis in this study, like the data requirement, falls into three categories. Firstly, the detailed scientific data from the USDA Sedimentation Laboratory study will be used to calibrate and produce the predictive equations proposed in sections 6.2 and 6.3 of this report. Secondly, the data from the empirical studies of WES and other investigators will be used to test the accuracy of the equations for actual field use. This will ensure that the equations are tested against data other than that from which they were developed and that the testing data (being collected independently) are free of possible investigator bias. Thirdly, in future years the effectiveness of different soil conservation measures in controlling ephemeral gully erosion and in reducing sediment yield from gully prone fields will be investigated.

It should be noted that the field data will be made freely available to all interested parties as it checked, reduced and compiled.

8. ACKNOWLEDGEMENTS

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