A REVIEW OF GULLY EROSION AND ITS CONTROL

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Explanation of Some Terms Used

Alluvium is material deposited from water.

Colluvium is material that has moved by gravity.

Many of the deposits referred to as alluvial in the test are partly colluvial, particularly on very steep slopes. The one word is used for convenience.

Alluvial fans are bodies of material spread over a wide area around the bottom of slopes or the mouths of valleys. They may grade downslope into alluvial valley fills or spread over them. Many old fans have been dissected by shallow valleys which in turn have been partly filled with alluvium.

Swales are drainage lines in the form of gentle depressions that have been partly filled with alluvium. Larger depressions are called alluvial valleys. They often show a sequence of cut and refill events (Figure 4).

As an alluvial deposit ages, a soil develops in its upper part. A distinction is made in this report between the soils and the underlying alluvium, whereas the practice within SCA has been to call the whole unit "soil".

A REVIEW OF GULLY EROSION AND ITS CONTROL

There are two reasons why a review is necessary. The first is that present control measures are not entirely satisfactory - in particular, a more detailed understanding of the mechanisms of different kinds of gullies is needed so that treatments can be designed to suit. Secondly, information is now available on the rates of advance and distribution of gullies in a large part of Victoria. This allows some planning of priorities for the treatment of various areas and kinds of gullies. The erosion problem is so great that priorities are needed to make the best use of our limited funds, manpower, and equipment.

WHY GULLY EROSION OCCURS

Under natural conditions, most of the hills and valleys were covered by forest or woodland. The trees, and some of the grasses (particularly Kangaroo and Wallaby grasses) had extensive, deep root systems. The roots had two main effects - they bound the soil together, and used up most of the moisture in the ground. Because the soil was kept fairly dry, most of the rain was soaked up, and runoff occurred only during heavy storms. A small portion of the water soaking into the soil penetrated deeply enough to pass beyond the reach of roots, and entered permeable seams of bedrock or alluvium as groundwater.

The first form of land-use by Europeans was to graze stock on the native grasses under the trees. But in most areas, it was soon found that the trees used up too much soil moisture to allow a good grass cover, so the trees were destroyed. It is most unfortunate that the deep-rooting perennial native grasses disappeared quickly under grazing pressure. So it was not long before most of the pastures consisted largely of shallow-rooted native grasses and introduced weeds, many of which were only annuals. These alterations in vegetation had considerable effects on the moisture balance of the land.

On the hillslopes, there was an increase in surface runoff. This was caused by:

1. The diminished ground cover during summer (at least) allowed water to flow away rapidly, so that there was less time for it to soak in.

2. Many soils suffered a reduction of permeability (surface sealing) because they were compacted by stock and by raindrop impact.

Landholders' observations suggest that runoff from thunderstorms was approximately doubled by degeneration of the vegetation and soil. Data from the Parwan Experimental Catchments (for the reverse process) suggest that changes of this order of magnitude are possible.

In many instances, there was also an increase in sub-surface seepage on the hillsopes, because:

1. The higher runoff was locally concentrated down cracks, burrows and stumpholes.

2. There as no longer enough deep-rooted vegetation to use up the concentrated filtration.

This seepage is most noticeable where it is flushing salt out of the rocks and soil (Plate 1).

The increases in runoff and seepage from the slopes caused the alluvium and soils in the valley to become wetter than before, particularly since the valley flats no longer had deep-rooted vegetation either. The salt seepage from the hillslopes accelerated deterioration of the land by further reducing vegetation and causing soils to develop surface seals.

The overall effects of clearing and grazing, then, were to increase the amount and speed of both surface runoff and seepage, and to remove most of the binding effects of root systems.

HOW GULLY EROSION OPERATES

There are two fundamentally different kinds of gullies: those developing mainly by scour, and those developing mainly by headward erosion.

i. Scour Gullies

These occur where runoff is concentrated onto loose, unprotected soil or alluvium. The concentration may be caused by either the coalescence of a series of rills, or by collection of runoff in a depression such as a roadside drain. The soil particles are removed by sluicing - the washing effect of running water on loose grains - and the material that is most easily moved is that of the size fine to medium sand. Material of this size may be in the form of loose sand, or in the case of heavier soils, it could be derived by slaking - the disintegration of large aggregates during wetting.

The development of scour gullies will therefore be favoured by:

(a) Runoff of high intensity and duration

(b) Concentration of runoff

(c) Steep slopes

(d) Loose soil

For example, some of the most spectacular scour gullies developed on the flanks of the Colbinabbin Range, where the long, steep slopes, and the clay soil forms loose aggregates. Intense storms breaking when the ground was bare-fallowed caused gullies more than 200 yards long to develop in a few hours.

One of the characteristics of a scour gully is that it develops considerable length quickly, and later cuts downwards and sideways. A scour gully may lengthen both up-slope or downslope by further scouring. In many instances, the fan of debris at the lower end of a scour gully has a higher gradient than the general slope and is a favourable location for new scour gullies. Some scour gullies later develop into headward eroding types.

ii Headward-Eroding Gullies

These depend on scouring, tunnelling, or natural or artificial scarps to give them a start. But once started, there are many different mechanisms of headward erosion, falling into three main groups: those caused largely by surface runoff, by gravity collapse and by sub-surface seepage.

MECHANSIMS CAUSED BY SURFACE RUNOFF

The most obvious mechanisms of headward erosion caused by surface runoff are those associated with waterfalls. The direction action of a waterfall is similar in principle to that of heavy rain, though usually much more powerful - the energy of falling water hitting the soil breaks the soil particles loose and carries them away. This direction action is most effective when the waterfall hits a bench or slope (Figure 1). Once the gully head has been trimmed vertical this mechanism become ineffective, unless the waterfall is blown back against the headwall.

If the waterfall is clear of the headwall, its energy is spent in digging a plunge pool and in turbulence within the pool. The theory that a plunge pool undermines the headwall has received some emphasis in the past. But observations of more than a hundred gullies during flows up to 3 ft deep do not confirm this idea (Plate 3. In fact, the greater the flow the further the plunge pool tends to be centred from the headwall. It is only in small gullies, during floods near bankfull, that plunge pool turbulence is an important mechanism of erosion. Note that concrete chutes are somewhat similar to the latter case if they have a small drop at the toe with a large volume of water; a plunge pool forms in contact with the toe, and undermines it. The "ski-jump" chute was designed to move the plunge pool away from the concrete.

Undercutting of the headwall will occur if the plunging water is diverted back against it. This happens if large, tough blocks of soil drop into the plunge pool, and the water running around the blocks scours material off the headwall. But this mechanism is not usually persistent and is rarely solely responsible for headwall erosion.

Water running over a gully head and trickling back against the headwall causes some erosion by wetting the soil. The most obvious mechanism is spalling, by which faleks of material peel off the wall and drop. Spalling is most common in tough, slowly permeable soils, such as a compacted gravelly loam. Water soaks slowly into this material, and the wetted part breaks off from the drier material underneath. The other mechanism is slaking which was mentioned earlier in connection with scouring. It occurs most rapidly when dry aggregated clayey soils and alluvium are wetted.

Both slaking and spalling can occur in hollows in the headwall, because thin films of water running down the face of the wall are drawn back preferentially into the hollows by surface tension effects. The hollows are enlarged, and may become big enough to cause the headwall to collapse, (Plate 16c). These hollows can form at the bottom of a headwall, and care must be taken that they are not mistaken for other mechanisms of erosion.

MECHANISMS OF GRAVITY COLLAPSE.

The next group of mechanisms to be considered consists of those involving collapse of the headwall under gravity. When soil or alluvial material is wet, it is heavier and often weaker than when dry. If there are lines of weakness such as old cracks running through it then blocks may fall away along them. If the material becomes very weak when wet, the whole of the headwall may collapse in the form of a slump or earthflow (Figure 2).

An important feature of the collapse mechanisms is that they can operate only when other mechanism has steepened the gully head (e.g. waterfall action). If this did not happen, then the head would collapse in and become stable. Conversely, a waterfall without collapse mechanisms would also become stable.

Sometimes the side or headwall of a gully becomes saturated with water only where a flood has been in contact with it. The saturated part collapses up to the floodmark, undermining the wall (Plate 7). This is most likely to happen in dispersible clay soils that crack extensively during summer, and are then subjected to a flash flood.

MECHANISMS OF EROSION BY SEEPAGE

There is a variety of kinds of seepage erosion, depending on the arrangement and properties of various soils and layers of alluvium. They form several gradational series, so it is difficult ot name them satisfactorily. For convenience they can be placed in two sub-groups.

Sub-Group A

These kinds of seepage erosion occur where water flows through a layer of loose grains and washes them out. This basic mechanism of erosion can be called extrusion. This is seen when a hole is dug in a sandy beach - once the water table is struck, the sand keeps pouring into the hold. But it is not always necessary to have a clean sandy layer. Many clayey sands can be washed out because the clay disperses finely when wetted and can be winnowed out.

Headward advance by any kind of undermining is called sapping, so if a whole layer is washed out by extrusion, the mechanism is extrusion sapping. In some instances only a narrow part of a layer is washed out and a tunnel is formed - extrusion tunnelling.

There are several different kinds of extrusion sapping and extrusion tunnelling, depending on the location of the eroding layer in a gully head. The layer may be at the bottom of the head (Plate 8 and Figure 3A) in which case the mechanism is called basal extrusion sapping. Sometimes there are several erodible layers, and the mechanism is multiple extrusion sapping (Figure 3B). One of the most common sapping layers is the A2 horizon of solodic and podzolic soils. The impermeable B horizon in these soils causes seepage to concentrate in the sandy A horizons, which wash out under shallow rooted grasses (Plate 9 and Figure 3C). This is called A horizon extrusion sapping. Extrusion tunnels may also occur in the A horizon.

Most kinds of sapping are associated with other mechanisms of erosion. Basal and multiple sapping cause collapse mechanisms to operate, and A horizon sapping opens up the subsoil to attack by waterfall action and scouring.

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If no other mechanisms operate with A horizon sapping, then only the topsoil is stripped off. This is called A horizon sheet sapping because the end result resembles sheet erosion rather than gullying (Plate 10).

Sub-Group B

Seepage erosion occurring by extrusion is found in essentially permeable materials. In essentially impermeable materials (e.g. compacted clay loams), seepage is confined to cracks, burrows, and root-holes. The seepage erodes the walls of these passages until tunnels are formed (Plate 11). This basic mechanism can be called crevice tunnelling.

Crevice tunnelling involves sluicing of material from the walls of the crevice. It is aided by slaking and dispersion of clay aggregates.

Many gullies are formed by the collapse of tunnels deep in the alluvial deposits of valleys (Plate 12). It is often difficult to specify where the gully head is located in these situations.

Another common kind of sapping by crevice tunnelling is found in young soils on alluvium, particularly in the more arid Districts in the hill country. The upper pats of these soils crack into columns during summer, and runoff from thunderstorms scours out myriads of tunnels along the cracks. During winter, more erosion occurs, until the columns collapse, causing wide, ragged gullies to progress up-slop (Plate 13 and 14). This mechanism is called tunnel-sapping in columnar alluvial soils.

Yet another kind of tunnel-sapping occurs in marshy soils in the wetter parts of the hilly country (e.g. Alexandra). The top-soils are gleyed, being bluish grey in colour and having a high content of humus. They have a strong blocky structure and large numbers of tunnels develop along the cracks between the blocks. Ultimately the topsoil collapses over the tunnels, exposing the subsoil to attack by waterfalls and scouring. This mechanism is called tunnel-sapping in valley marsh soils (Plate 15).

We can conclude that the essential factors involved in extrusion sapping and in tunnelling are:

1. Permeable layers, or cracks and holes in impermeable material.
2. A lack of cohesion between grains in the layers (easy dispersion of clay-rich layers).
3. A supply of seepage water.

COMBINATIONS OF MECHANISMS

It has already been mentioned that some mechanisms act together in causing headward erosion, and that some actually need to be associated with others to cause a headward advance. In fact, most gully heads are a combination of different mechanisms, each acting under different conditions, perhaps at different times of the year, and at different rates. Here is an example:

The gully shown in Plate 16 is located near Beaufort, and is cut in a valley marsh soil and the underlying deep alluvial deposit. The alluvium is a tough gravelly silt loam. During late autumn and early winter, 1968, which were very wet, a lot of tunnel-sapping occurred in the topsoil. The soil was eroded back more than 20 ft. during a series of storms. This left a bench on the alluvium, which was attacked by the waterfall and scour. Spalling also attacked the headwall previously cut in the alluvium. Late in 1968, when there was only light runoff, the tunnel-sapping virtually stopped. But spalling in the alluvium continued, so that the bench was almost eliminated in time. This pattern of erosion was repeated during 1969 and 1970, but at a much slower rate because there was less runoff and seepage than in 1968. But late in 1970, the gully head, advancing up the valley, met a layer of permeable sand in the alluvium and some basal slipping started as well.

Although many mechanisms may be present, it often happens that one is most important, and can be called a key mechanism. In the above example, the tunnel-sapping is the key mechanism, because it opens up the alluvium to attach by other mechanisms. If the tunnel-sapping could somehow be stopped, the progress of the head would immediately slow down. The waterfall and scouring, together with spalling, would slowly erode the bench away, until the head was vertical. The waterfall would then cease to be effective, and only spalling would occur, so the head would move even more slowly.

There are some common combinations of soil type, topography and climate which result in common combinations of mechanisms.

A list of examples of these, together with descriptions, is available in roneo form from the SCA head office, so that they can inspected in the field.

DISCUSSION OF CONTROL MEASURES

(i) Pasture Improvement

The first aim of present erosion control measures is to reduce runoff and establish a ground cover to protect the soil. Compacted, impermeable soils are first of all ripped on the contour. This causes most of the rain to infiltrate the soil, and so runoff is greatly reduced. Many soils quickly develop new surface seals, so cultivation may have to be repeated every few years.

In grazing land, ripping is accompanied by pasture improvement, particularly the establishment of deep-rooted perennials such as *Phalaris tuberosa*. These two control measures stop sheet erosion, and then, by reducing runoff, help to stop gullying by scour and waterfalls.

However, care must be taken to avoid aggravating other mechanisms of erosion when applying these control measures. If only shallow-rooted grasses are sown after contour ripping or furrowing, then the vegetation may not be able to cope with the high infiltration. The result is an increase in sub-surface seepage, which develops into tunnelling and sapping. This is why emphasis is now placed on deep-rooted grasses such as phalaris. This can be seen as an attempt to imitate the original water balance under forest or woodland.

Although phalaris is the best species available for this purpose, there are still some problems, and some further research is needed. The alluvium under the soils in many valleys contains toxic or near toxic concentrations of salt, even where there is no indication at the soil surface. This situation has been observed in districts where the mean annual rainfall is as high as 28 inches. It has been recommended that a survey be carried out to determine the extent of this problem. Where it does occur, it is doubtful if the improved pasture grasses can develop the deep root systems of which they are capable. So in much of the hilly regions of central Victoria, seepage could persist in the valleys and still cause sapping and tunnelling. It is recommended that the soils in the valleys should be sampled and analysed at depth during conservation planning, to see whether phalaris will be capable of reducing deep seepage, or whether a more salt-tolerant perennial is needed. In the latter case, the advice of the Agronomy Section should be sought.

Some difficulty is also being experienced in establishing phalaris on shallow hill-slope soils below about 22 inch mean annual rainfall, although some cultivars may be satisfactory. The possibility of using Kangaroo Grass, with well-disciplined occasional grazing, is being investigated. The Pyrenees District demonstration area at Landsborough shows the possibilities of this species.

Another problem with improved pastures is that some deep-rooted perennials do not closely simulate the original tress in their effect on the soil. Lucerne, for example, dries out the soil to a considerable depth, but does not have a network of roots to hold the soil together, particularly in self-mulching clays. The result is that in some area large, deep cracks appear in long-established lucerne paddocks. These cracks could lead to tunnelling. Phalaris has a better web of roots than lucerne, but even so, it should be watched in heavy clay soils to see if cracking develops.

Where perennial pastures are not likely to be completely satisfactory, it may be necessary to introduce some trees as part of the catchment control scheme. There is very little information on the hydrological cycle in the 18 to 22 inch rainfall zone on any soil type. Nor is there any for slightly higher rainfall zones where the solodic soil patter of the Parwan is not applicable. It has been recommended that data be collected for these problem zones, so that the necessary amount of cover, and depth of root systems can be found.

After ripping and pasture improvement, the next stage in gully control is disposing of the remaining runoff. It can be diverted away from the gully head and either stored in dams, spread for absorption, or dropped into the gully at a safe place. Alternatively, the gully head can be stabilized by vegetation, by a grassed chute, or an artificial structure, and the water allowed to run into the gully. Now these control measures were developed to combat the effects of surface runoff, but they are often successful in stopping erosion by other mechanisms. It is interesting to see why this should be so, and how an understanding of the mechanisms can lead to improvements.

(ii) Division of Surface Runoff

It is easy to understand that diversion of runoff will stop headward erosion by waterfalls, scouring, collapses and spalling. In soils where only these mechanisms operate, diversion is the only treatment necessary, and in time, the heads will collapse in to a stable shape. Diversion is also often successful where A horizon sapping is the key mechanism. This shows that most of the seepage in the A horizon comes from surface runoff soaking into the soil over a few tens of feet up-slope from the head. So, if the diversion bank is placed too close to the head, then enough seepage may still reach the head to cause sapping and tunnelling. This problems is often aggravated by the practice of scooping soil for the bank from its up-slope side. It would be better to scoop soil from the down-slope side, i.e. to use all fill banks. Care must be taken to ensure that no water is ponded on either the up-slope or downslope side of the bank. Where possible, compaction of the A horizon at a moist condition before the bank is built on it would be one way of stopping any seepage.

Diversion is a much riskier treatment for gullies in valley marsh and columnar alluvial soils. This is because cracks and tunnels extend often for ten yards up-valley from a gully head. In these cases, some form of seepage cutoff is definitely needed underneath the diversion banks. One method would be to cut a narrow trench right across the valley, penetrating down into the impermeable sub-soil. The trench should then be packed with clay, observing the procedure for building earth dams. It may be necessary in valley marsh soils to impregnate the clay with a chemical to keep yabbies (land-crabs) from tunnelling through it. Research is in progress on the effectiveness and cost of driving steel or plastic sheets into the ground to act as cut-offs.

Where deep-seated tunnelling and sapping are important mechanisms of erosion, the seepage is probably collected over a considerable distance up-slop from the gully head, and diversion of runoff near the head will not be effective.

(iii) Stabilization with Trees

Where the topography or other considerations do not allow diversion of surface runoff, the gully head must be stabilized, and the water allowed to run over it. In the wetter districts it may be possible to stabilize a gully head solely by vegetation.

Some difficulties are encountered where the alluvium has tough layers that cannot be penetrated by the roots of poplars or willows. Some kind of sapping is then likely to occur between the roots and the top of the cemented bank (Plate 18).

Although grassed chutes are partly a vegetative control, their erosion control action is similar to that of artificial structures, so these two measures will be discussed together.

(iv) Structures and Grassed Chutes

When properly maintained, all structures and grassed chutes eliminate erosion by spalling, scour, and waterfall action. Most of them eliminate mechanisms of gravity collapse because the original gully head is battered back to a stable configuration. However, earthflows may occur in highly dispersible clays at even very low gradients unless deep networks of roots are established. Verandah structures do not provide any protection from gravity collapses.

Some structures fail because of the weakness of the joint between natural and artificial materials, even when "keys " are fitted. During the dry seasons, the earth pulls away from the structure, and tunnels can develop along the craks.

But the fundamental problem is that structures and grasses chutes are not intended to stop erosion caused by seepage. Where they are successful in sapping or tunnelling heads, it is only because the concrete slabs of a structure, or the turf of a grasses chute, block off the eroding layers. This is a very unstable situation, and expensive structures should not be built where these mechanisms are operating, unless the seepage can be cut off in some way.

(v) Research

It is clear, then that sapping and tunnelling heads are the most difficult to deal with, and that there is not treatment that can be regarded as being completely satisfactory for deep-seated sapping and tunnelling. There are three approaches to the control of these mechanisms.

One approach is to reduce runoff and seepage even more than is achieved by present methods. This might involve partial re-afforestation of a catchment, or at least the planting of trees near the gully. Hydrological data are needed to determine what is required.

Another approach is to stop the flow of water within the alluvium and soils by blocking the passages with cements. Portland cement, lime-soil mixtures, bitumenous emulsions, or plastic cements could be used. Field trials with Polyvinyl Acetate have shown that it is effective, cheap and easy to apply in extensively cracked soils, but it lasts only for about two years. It may be possible to develop means of waterproofing it. The main problem with grouting is to obtain adequate penetration of the eroding layers - clay can disperse so finely that it will be eroded by seepage moving at rates of less than 100 ft. per year. Another problem is that if water is dammed up in a layer, it may escape elsewhere and cause other tunnelling.

The third approach to the control of sapping and tunnelling is to alter the properties of the soil so that it is not affected by the seepage. This essentially means preventing the dispersion of clays. This could, perhaps, be done by replacing absrobed sodium by calcium, e.g. by adding solutions of lime. Aluminium hydroxide also stabilizes clays. Another method is to render the clay hydrophobic, and this is being field-tested at present.

THE RATE OF GULLY EROSION

A knowledge of the rate of erosion is interesting in itself, because it is one indication of the size of the problem we are facing. But it is more useful if the factors controlling the rates can be determined, because this shows what control measures should be empahsized. The relative rates of erosion of different kinds of gullies are also important because they show the order of priority for treatment.

How Rates of Erosion are Measured

There are several ways of measuring the rate of gully erosion. This can be in terms of gully length, which is easiest and most accurate, and therefore the basis most commonly used. For some gullies, it is possible to measure plan area and volume as well. The time basis of the study can be a single storm, a season, or a year. In these cases, a vigil network is established, in which a series of gullies are surveyed and pegged, then re-visited, photographed, and measured at the appropriate times. Alternatively, average rates can be measured over a long time by comparing the positions of gully heads with these shown on aerial photographs.

Factors Controlling Rates of Erosion

A series of analyses have been made on data from gullies in the vicinity of Alexandra, Colbinabbin, Inglewood, Ararat, Darraweit Guim, and Glenthompson. The first of these analyses was designed to test the effect of topography on the rate of erosion. The results show that neither the slope of the catchment, nor the slpe of the ground at gully head, influences the rate of erosion of mechanisms of headward advance. This result does not refer to scour gullies, which are assisted by steep slopes.

A second analysis showed that catchment area, in the sense that it is a measure of water supply is not as important a factor as is generally believed. It is often noticeable that gullies with large catchments move faster than those with small catchments. On the whole, this is supported by the analysis. But the relationship is usually that mechanisms very with catchment size, and that different mecahnisms have different rates of erosion. If only one mechanism (type of gully) is considered, catchment area has very little influence on the rate of erosion.

The analyses showed that the most important factors controlling the rates of gully head advance are "mechanism of erosion" and "hydrological conditions". The latter includes rainfall intensity and duration, antecedent moisture, land management and condition. These factors are too complex to be represented as figures in equations, but we can still gain some useful information about them.

Although there are figures for the average and extreme rates of erosion of the different mechanisms, they refer to specific events and times of the past. They would be misleading if used for forecasting purposes without extreme caution. Therefore, it is best to rank the mechanisms in the order of their rates. This gives us an order of priority for treatment. Using gully length as the basis for measurement, the order is:

1. Scouring is the fastest mechanism

2. Deep tunnelling; tunnel-sapping in both columnar alluvial soils and valley marsh soils

3. Earthflows

4. A horizon sapping

5. Collapse mechanisms other than earthflows; basal and multiple extrusion sapping

6. Spalling

Note that some mechanisms are omitted because they rarely control the rate of erosion.

If gully area is used as the basis for measurement, then scour gullies become much less important. The tendency for the two kinds of tunnel-sapping to create wide, ragged gullies raises them in rank, so the order is approximately:

1. Tunnel sapping in both columnar alluvial soils and valley marsh soils.

2. Deep tunnelling

3. Earthflows, A horizon sapping, collapse mechanisms, basal and multiple sapping, scouring.

4. Spalling

Although there are not enough data on volume rate of erosion to allow a list to be prepared, it seems that the order is similar to that for area, except that collapse mechanisms and spring sapping are more important, and that tunnel-sapping in the shallow alluvial soils is less important. Tunnel-sapping in valley marsh soils is probably the fastest mechanism in terms of volume of material eroded.

It may be noted that the mechanisms that are most difficult to control (sapping and tunnelling) are among the fastest operating in Victoria.

The other factor to be considered is "hydrological conditions". It is impossible to study the effects of a single storm on the rate of erosion at present, because too many things are involved. And often, the effects of a single storm are not revealed until some time later - particularly in the case of tunnelling. But we can see what conditions favour gully development.

Souring is mostly caused by torrential rain falling when the ground is bare. These conditions also cause some rapid headward erosion, but the greatest hazard for headward erosion is a prolonged wet period, during which the ground is almost continually saturated. This provides the seepage for sapping and tunnelling, and also weakens the ground, favouring collapses. During "normal" years, there is relatively little erosion. For example, the period April - August 1968 was continually wet, and in most gullies, there was then about 2 or 3 times as much erosion as in the whole of 1966, 1969, and 1970 put together.

There have been periods of greater gully development than 1968. Apart from local variations, it appears that 1870, 1894, 1916-18, 1928-31 and 1955-56 were exceptionally wet, and there are many records of rapid erosion at these times. This spasmodic character of gully erosion must always be kept in mind during planning and assessment of conservation works. To be specific, there has not been a major test of control measures since 1956, except perhaps in the North East.

It is interesting to note that in some areas during the drought of 1967 there was more gully head erosion than during either 1969 or 1970. This was because the ground cracked severely during the drought, and the few runoff events caused a lost of tunnelling and spalling. The cracking also helped many heads to collapse.

Comparison with other Places

Finally, it is worthwhile to compare the rates of erosion in Victorian gullies with those elsewhere. This cannot be done in detail because there is little published information on this subject.

It appears that scouring is not as important in Victoria as in many other places. A major reason is that torrential rains are not as common here as in (say) northern New South Wales and the east coast of the USA. The rate of headward erosion in Victoria are similar to some reported in Israel and India, except that the tunnelling mechanisms here are faster. Basal extrusion sapping does not create such rapid and vast gullies as have been reported in the USA and Nigeria.

THE DISTRIBUTION OF GULLIES

This is another aspect of the size of the problem of gully erosion, and complements the information on the rate of erosion.

How the Distribution can be Studied

The distribution of gullies in Victoria has been studied in terms of the density of gully channels, that is, the miles of channel per square mile of land. The technique used to map gullies on aerial photos, and transfer results to a grid system in which the squares represented 16 square miles. The density was then measured for each square. The use of a large grid was intended to eliminate the influence of individual farms on the densities.

The most detailed information available on gully density is a map of gullies in the "Northern Slopes" region. This includes the country north of the "Great Divide", from the Hume Highway to The Grampians. The remainder of Victoria has been partially covered by maps of selected localities.

A General analysis of the distribution

Gullying occurs over the full range of rainfall without any consistent variation, apart from a change in density and character at about 30-35 inch mean annual rainfall mark. At higher rainfalls, clay soils are usually stable, and rarely gully except by scour. Sandy and peaty soils, however, are susceptible to gullying. In districts where the rainfall is less than about 35 inches, gullying is more common, but its distribution seems to be governed by factors other than mean annual rainfall.

In the Northern Slopes region, the average density of gullies is about 0.8 miles per square mile, representing a total of about 5,000 miles of channel (and 11,000 heads). There are zones of very low or zero density, usually on wide plains or in forest reserves. But there are many zones of very high density that are associated with these factors:

1. Poor land management, the worst situation being unimproved pasture, with rotting tree stumps and sealed soils;

2. Landscape patterns that concentrate runoff, particularly onto very erodible soils;

3. Local zones of thunderstorms activity (e.g. the Colbinabbin Range);

4. In the case of scour gullies, long steep slopes.

For example, the district having the highest density of gullies (4.5 miles per sq. mile, around Landsborough), has factors 1 and 2 as extreme cases. In other localities where these two factors are less extreme, densities of the order of Colbinabbin Range, thunderstorms combine with long, steep slopes to yield scour gully densities of the order of 3.5 miles per sq. mile.

The factor "Landscape pattern" is complex and needs further explanation. It comprises the types of soil, alluvium, and rock present which determine the mechanisms of erosion), and also comprises the arrangement of these units in the landscape (which determines how they interact). Some common landscape patterns are described in detail in the forthcoming research publication on gully erosion, but it is worthwhile describing one here to serve as an example: the pattern around Crownlands and Landsborough. In this landscape, widely spaced, steep, rocky ridges are flanked by extensive bodies of impermeable, cemented gravel. Most of the valleys cut in the gravels are quite widely spaced, but narrow, so the high runoff from the ridges and gravels is strongly concentrated in the valleys. The valleys contain two main deposits of alluvium, both of which are very erodible. One deposit is thick, highly dispersible loam or clay which occurs as a terrace, and has solodic soils. This material is prone to tunnelling, which is a major mechanism of headward erosion, as well as A horizon sapping. The other alluvium is earthy, and cracks into columns. It is found in the bottoms of the valleys. This material is prone to scouring, and also to tunnel-sapping between the columns. One of its most important characteristics is the ease with which it is undercut, so gullies in it are often wide and irregular in plan.

But the landscape pattern is not simply a matter of topography. To some extent, the nature of the soils and mechanisms of erosion is governed by climate - essentially rainfall. Valley marsh soils are rarely found where the mean annual rainfall is less than about 25 inches. The columnar alluvial soils are found above 35 inch rainfall, while the upper limit for dispersible alluvium prone to deep tunnelling is about 30 inches.

This 30 to 25 inch zone is also the upper limit for catchment salting. It appears that under natural conditions, there was rarely any excess seepage where the mean annual rainfall was less than about 30 inches, so the effects of clearing caused radical changes. Above 35 inches, there probably was subsurface seepage under forests, and the soils were adjusted to frequent saturation, so, the effects of clearing were not as great.

ASSIGNMENT OF PRIORITIES FOR TREATMENT OF EROSION

Where resources are small compared with the job to be tackled, efficient planning requires a system of priorities. There is now some information available to assist such planning at the State, District and catchment levels. The allocation of priorities for treatment of gully systems depends on: (1) measurement of the extent and rate of progress of gullying; (2) policy decisions as to the relative importance of the various effects of gullying.

INFORMATION FROM STUDIES OF GULLY DISTRIBUTION

The easiest way of measuring the extent of gully erosion is to map gullies (see map enclosed). It is at once obvious that some Districts have a greater total length of gullies than others. This does not mean that some staffs are underworked - on the contrary, there is probably more than a lifetime's work in the Districts with the smallest amount of gullying. But it does mean that the effort is spread thinner in some Districts.

Within any one District, the map shows that certain areas or catchments have very high gully densities, while others have relatively low densities. Within that District, then, it could be argued that the catchments with high gully density are in the most urgent need of treatment.

As alternatives to gully length, there are three other measures of the extent of gully erosion: gully area, gully volume, and the number (or density) of gully heads. Each of these throws emphasis on slightly different aspects of the erosion problem. Gully area is a better measure than length of the amount of land taken from production. Gully volume empahsizes the sedimentation effects. The number of gully heads is more closely related to the amount of control work to be done. For convenience of discussion, however, gully length will be used for the present; bearing in mind that the other measures could be substituted.

A SEVERITY INDEX

Gully density is easy to measure, but it is not a very accurate way of expressing the degree of degeneration of the land. Most gullies occur in alluvial deposits and the soils developed on them, rather than on soils developed on bedrock. So the maximum possible density of gullying is set by the amount of alluvium in a landscape. Now there are two major alluvial landforms - fans and valleys. On the fans, the possible number of gullies is virtually unlimited. But an alluvial valley will usually only support one gully. So in areas where fans can be neglected, the maximum possible distribution of gullies is set by the distribution of alluvial valleys. The density of alluvial valleys varies, so the density of gullies will also vary for the same degree of degeneration. If separate areas are to be compared, it is therefore necessary to use the proportion of valley length that has been gullied as a basis. This fraction can be called the severity index:

$$\text{SI (gully length)} = \frac{\text{length of gullies in alluvial valley}}{\text{total length of alluvial valleys}}\ \%$$

For example, near Landsborough, where the gully density is around 4.5 miles per sq. mile, the severity index may be as high as 65%. But in parts of the Eppalock catchment, where a gully density of 4 miles per sq. miles is common, there are about 40%. So the state to which degeneration has proceeded at Landsborough is much higher than a comparison of densities suggests.

QUESTIONS OF POLICY

At this juncture a point of policy must be raised. The severity index shows the proportion of erodible land actually damaged. On this basis, the Landsborough district has a higher priority for treatment than Eppalock, if our policy is to treat the worst eroded land first and to save what little soil is left in those areas. On the other hand, the Eppalock catchment has a much greater potential for gullying, so if emphasis is placed on the effects of sediment coming from the gullies in future, then Eppalock has the higher priority.

If it is decided that it is more important to protect good land than to patch up badly eroded land, then the information on rates and distribution of gullies can be useful. It was shown in earlier chapters that certain types of gully, which can be ranked according to rate of erosion, are associated with particular types of soil and for alluvium. If the latter can be mapped, then predictions can be made about the relative rates of advance, width and depth of gullies in various parts of a catchment. Within a District, priorities could be assigned to various catchments on the basis of the area (or percentage area) of soil types with relative high rates of erosion that each contains.

Some other considerations in the allocation, of priorities should be mentioned for completeness, although they are purely points of policy. The main question is whether land within the highest economic value or potential should receive priority treatment, or whether all land should be viewed as having equal value. The latter point holds where a reservoir must be protected against siltation, and also if moral principles are invoked. But practical considerations are very important where landholders contribute funds, and it is usually the most productive land, which is economically worth preserving, and which has provided a high income, that can be treated thoroughly at present.

The other question is whether priority should be given to gullies or localities where we are most confident of success; leaving other areas where control is much more difficult and less likely to success until control measures are improved.

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L. E. Milton