Gully Control in SAT Watersheds

Pathak P, Wani SP and Sudi R. 2005. Gully control in SAT watersheds. Global Theme on Agroecosystems Report no. 15. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 28 pp.

Background

Soil erosion is one of the major problems confronting agriculture worldwide. Although the problem is as old as settled agriculture, its extent and impact on human welfare and global environment are more now than ever before. A continuation of high soil erosion will eventually lead to a loss in crop production even though fertilizers and other inputs often result in increased yield in the short term. Soil erosion also leads to environmental pollution. It is the main source of sediment that pollutes rivers and fills reservoirs. A decrease in soil quality invariably leads to a decrease in water quality, and often in air quality. Globally, about 1.1 billion ha of land is affected by erosion. It is estimated that about 150 million ha out of the total geographical area of 328 million ha in India are subjected to serious water and wind erosion; 69 million ha are at the critical stage of deterioration due to water erosion and 32 million ha are prone to wind erosion (Katyal et al. 1995). Further, Dhruva Narayana and Sastry (1985) estimated that about 5,333 million t of soil is detached annually in India and 20% of this carried away by rivers into the sea. Nearly 10% of it is being deposited in surface reservoirs resulting in loss of 1 to 2% of the storage capacity annually. Gully erosion is geographically a widespread problem (Cooke and Reeves 1976, Lal 1992) and is the worst stage of soil erosion (Fig. 1). It is common in the semi-arid region, characterized by denuded landscape and flash floods. An estimated 4 million ha of land is affected by severe gully erosion in India. An additional 2.2 million ha are now susceptible to gully erosion in the semi-arid tropics (SAT) of India. In Africa about 29 million ha of land is affected by gully erosion. In Ethiopian highlands, gullies are particularly severe and widespread on 7.6 million ha of Vertisols (Brown 1981). Gully erosion is more difficult and expensive to control than sheet and rill erosion. It is also more spectacular than interrill erosion. Contrary to sheet and rill erosion, the damage done to land by gully erosion is permanent. Gully erosion also causes depreciation in land value by lowering the water table and depleting the available water reserves. Buildings and infrastructures are also undermined by rapidly advancing gullies.

Figure 1. Severe gully erosion in Guangzhon, China.

The objective of this report is to provide basic knowledge of gully formation and practical approaches for their control in the context of overall watershed development and management in SAT. The report will be useful to professionals, middle-level technicians and watershed managers in assessing gully erosion and in guiding the actual gully control measures.

Gully Erosion

Definition of Gully Erosion

Gully erosion produces channels larger than rills. These channels carry water during and immediately after rains and as distinguished from rills, gullies cannot be obliterated by normal tillage (Schwab et al. 1981). Thus, gully erosion is an advanced stage of rill erosion much as rill erosion is an advanced stage of sheet erosion. The Soil Conservation Society of America defines a gully as "a channel or miniature valley cut by concentrated runoff but through which water commonly flows only during and immediately after heavy rains; it may be dendritic or branching or it may be linear, rather long, narrow, and of uniform width" (SCSA 1982).

It is often difficult to differentiate between large gullies and small river valleys. Gullies have intermittent storm water flows of shorter duration compared to rivers with seasonal flows. Gullies, contrary to river valleys, are cut out rapidly and are generally restricted to easily erodable soils.

Causes of Gully Erosion

Most of the gullies are formed due to human activities. Some of the major causes of gully formation are overgrazing due to high cattle population, expansion of cultivation in steeper or marginal land, cultivation without taking care of surplus runoff water, deforestation due to clearing of vegetation, unsatisfactory waterways and improper design of culverts and other structures. Generally a gully is caused by a rapid expansion of the surface drainage system in an unstable landscape. Gully erosion is affected by several factors. Some factors determine the potential hazard while others determine the intensity and rate of gully advance. The factors affecting gully erosion can be categorized into two groups: man-made factors and physical factors.

Man-made factors

Improper land use

In developing countries, rapidly increasing populations usually migrate upland to occupy forests or rangeland. Most migrants cut trees, burn litter and grasses, and cultivate annual crops on hillsides without using appropriate conservation measures. After a few years, the productivity of the soil is lost because of sheet, rill and gully erosion, and the land is abandoned. This kind of cultivation is repeated by farmers on other hillsides until the land loses its productivity there as well. Thus, the whole of an area may be completely destroyed by gullying as the gully heads advance to the upper ends of the watershed.

Overgrazing

High cattle population and overgrazing constitute a major factor for gully formation in SAT Africa and Asia. Uncontrolled overgrazing leads to denudation of vegetation. Burning is another widely practiced system of pasture renovation. It leads to a rapid denudation and exposure of land to torrential rains. Cattle grazing in and around active gullies extends the nick point and dimensions of the gullies. Overgrazing removes much of the soils protective vegetative cover and trampling compacts the soils; thus the infiltration capacity of the soil is reduced. The increased runoff due to reduced infiltration produces new gullies or enlarges old ones.

Improper land development
Often the land development works, viz, construction of water storage structures, drains and bunding, are not done properly. Consequently failure of hydraulic structures or breaching of bunds occurs (Fig. 2) often resulting in sudden release of high volume of water. This results in the formation of gully particularly on steep lands.

Road construction
Road construction through steep lands, without adequate provision for drainage, is a major cause of gully erosion. Inadequate drainage systems for roads such as small number of culverts, insufficient capacity of road ditches, etc are some of the causes of gullying. Although the road-caused gully erosion may occur anywhere in the world, the problem is particularly severe in developing countries due to neglect in maintenance and the lack of provision for safe outlets for excess runoff.


Figure 2. Improper land development leads to damage of structure and gully formation as in Madhusudhangadh, Madhya Pradesh, India.

Livestock and vehicle trails
Gullies are also formed on livestock and vehicle trails that run along hillsides. Unplanned land use can disturb the natural drainage ways. Non-availability of water supplies in the rural communities necessitates villagers to walk to the springhead. Sunken footpaths made up-and-down the slope become the focus of concentrated flow that eventually turn into gullies. This leads to the development of new footpaths that also turn into gullies later on.

Physical factors

Gullies are formed by increased runoff which acts as a cutting agent. The main physical factors which affect the rate and amount of runoff are rainfall, topography, soil characteristics, profile characteristics and vegetative cover.

Rainfall
Rainfall is obviously an important factor. For a given condition, there is direct relationship between the rainfall and runoff. Big storms can cause severe gullying. Intense rains, coupled with soils prone to sealing and crusting, generate high runoff volume and concentrated flow (Lal 1992). The force generated by the runoff flow causes gully erosion especially in semi-arid regions characterized by scanty vegetation cover.

Topography
The size and shape of a drainage area as well as the length and gradient of its slopes have a major effect on the runoff rate, volume and flow velocity.

Shape and size of watershed
The larger the watershed, the greater the amount of runoff. Large watersheds have greater chances of gully erosion than small watersheds. The shape of the watershed has strong relationship with the time of concentration and peak runoff rate. If the time of concentration is high, peak runoff rate will be low.

Length and gradient of slope

The steeper the slope, higher the velocity and erosive power of the runoff. This is one of the most important factors for gully erosion. Also, if the slope length is long, the possibility of gully formation is high.

Soil properties

Some soils are more prone to gully erosion than others. A soil with a coarse-textured highly permeable surface horizon with an abrupt transition to slowly permeable subsoil is normally prone to gully erosion. The Vertisols with cracking properties are also highly susceptible to severe gullying (Fig. 3).

Figure 3. Gully erosion in SAT Vertisols due to cracks.

Vegetative cover

Vegetative cover intercepts rainfall, keeps the soil cover with crop canopy and litter, maintains soil structure and infiltration and provides resistance to runoff flow. Generally management and protection rather than the type of the vegetative cover determines its effectiveness in gully control. Any vegetation which is well adapted to local conditions and acceptable to the local community can be used.

Occurrence of Gullies

Gullies are more frequently found on bush and grasslands than on cultivated land because rills on cultivated land are removed by plowing and other recurrent cultivation measures. However, these rills continue to enlarge unhindered on grazing land and forest areas. Nowadays, even in cultivated areas, the number and size of gullies are increasing due to several factors. Gullies are mostly initiated during major storms. Once such gullies are formed, they tend to become further enlarged in subsequent years.

Development of Gullies

It is difficult to achieve gully stabilization without a full understanding of the erosion processes or stages of gully development. Otherwise, it would be risky because expensive measures taken would be unnecessary or ineffective.

Gullies are established by the deepening of rills and slumping of side slopes through the shearing effect of concentrated overland flow, increase in pore-water pressure, and decrease in soil strength along seepage lines close to the streams and rivers, and slumping due to excessive formation of tunnel or pipeflow. Once gullies are established, they form permanent locations for concentrating the overland flow. Consequently, progressive deepening and widening of the gully continues until the gully has adjusted to a new set of equilibrium conditions.

After its initial incision a gully usually extends backwards and sideways through the development of secondary gullies. Gully erosion is caused by headward advance, upstream migration of secondary nick points, widening of the gully channel by slumping and mass soil movement, and deepening by mobilizing or transporting sediments from the gully floor.

Start of erosion

In the initial stages of development when the gully cuts through the arable soil profile, erosion rates are low. As the erosion reaches down into the subsoil, rate increases greatly because the subsoils are generally prone to be more erodible. Consequently, the topsoil profile is undermined. A waterfall is created. The eroding action of the waterfall and its splash deepens a round pit into the subsoil, which acts as a plunge pool for the falling water. Due to successive undermining, the head of the gully moves up the slope. This headward cutting does not stop until the erosion reaches solid bedrock or the top of the slope.

Deepening erosion

The waterfall erosion usually creates a gradient downstream, which is less steep than the one above the waterfall. Therefore, the gully will be deeper as the waterfall erosion advances upstream. The deepening of the gully further downstream depends on the erosive capacity of the water flow through the gully. The side slopes of the gully become slanted by various erosion processes. Blocks of earth fall down due to tension cracks along steep walls of the gully. A rapid deepening of the gully occurs due to runoff flow, which keeps the side walls of the gully bare and unstable. Later, the cross-section of the gully appears U-shaped.

Retardation of vertical erosion

Vertical erosion continues until stopped by a base that can be of different types:

- Any plain where the velocity of the stream does not permit further erosion
- The water level of a lake or a river
- A solid sub-layer or solid bedrock

Eventually, a state of balance is reached between erosion and deposition even if the gully floor is not quite stable. The channel is deepened when the runoff volume and velocity are maximal. When the runoff flow drops, eroded material is deposited on the floor. As a result, the gully bottom becomes a wider floor and gets filled with sediments. The cross-section is not sharply V-shaped any longer, but more U-shaped. The state of equilibrium is often attained at a gradient of 2–4% in the longitudinal direction of the gully. If the sediments are coarse or appear in large quantities, the gradient can be high (4–12%). It is obvious that the U-shaped gully represents a stage of maturity and stabilization. On the contrary, one can recognize an active gully from its bare sides, and its more or less V-shaped cross-section.

Lateral erosion

In an active gully where vertical erosion has stopped, for instance, where bedrock has been reached, the flow energy is redirected on lateral erosion, causing widening of the gully. This widening is most dangerous in profiles susceptible to gully erosion, particularly in outer bends of such gullies. When large volumes of sand are transported by the stream, bars of sand can cause meandering. The banks of outer bends of the gully are then undermined and they collapse. The gully floor widens and the corresponding larger bars of sand are deposited when the stream decreases. During subsequent runoff events, erosion of the banks in the outer bends is accelerated, which undermines the land above the gully. This results in collapse of substantial blocks of soil profile into the gully.

Widening

The deep erosion makes the sides of the gully unstable and causes movement of earth from the sides of the gully to its bottom, where the earth is removed by the intermittent water flows. In this way the gully is not only deepened, but also widened (Fig. 4). A gullied area can also be widened through branches caused by tributary water flows. As these have a smaller volume of water than the main gully, they usually do not keep pace with the erosion of the main gully.

Figure 4. Widening of gully due to side cutting in Addis Ababa, Ethiopia.

Classification of Gullies

Gullies can be classified using several systems that are based on their different characteristics (FAO 1977).

Gully classes based on size, drainage and discharge rate

The simplest classification system is based on gully depth:

Small gully <1 m; medium gully 1–5 m; and large gully >5 m.

The size of a gully, however, often reflects its stage of development rather than the size of water flow. Therefore, a classification based on the flow rate is more useful for planning control measures:

Small gully $<0.3\ m^3 s^{-1}$; medium gully $0.3–2.0\ m^3 s^{-1}$; large gully $>2.0\ m^3 s^{-1}$.

Another gully classification system is based on depth and drainage area (Table 1).

Table 1. Gully classification based on depth and drainage area.

Gully classes	Gully depth (m)	Gully drainage area (ha)
Small gully	1	5
Medium gully	1–5	5–40
Large gully	5	40

Gully classes based on shape

Gullies are also classified according to the shape of their cross-section:

- U-shaped gullies are formed where both topsoil and subsoil have the same resistance against erosion. Since the subsoil is eroded as easily as the topsoil, nearly vertical walls are developed on each side of the gully.
- V-shaped gullies develop where the subsoil has more resistance than topsoil against erosion. This is the most common gully form.
- Trapezoidal gullies are formed where the gully bottom is made of more resistant material than the topsoil and subsoil because the erosion rate along the gully bank is greater than along the bottom.

Gully classes based on continuation

- Continuous gullies consist of many branch gullies. A continuous gully has a main gully channel and many mature or immature branch gullies.
- Discontinuous gullies may develop on hillsides after landslides. They are also called independent gullies. At the beginning of its development, a discontinuous gully does not have a distinct junction with the main gully or stream channel.

Gully Control

Principles of Gully Control

Generally, gullies are formed due to high runoff volume and peak runoff rate. Therefore, minimizing runoff volume and peak runoff rate through improved land use system is essential in gully control. The following three control measures should be taken in order of priority:

1. Improvement of gully catchments to reduce and regulate the runoff volume and peak rates.
2. Diversion of runoff water upstream the gully area.
3. Stabilization of gullies by structural measures and accompanying revegetation.

In some regions, the first and/or second methods may be sufficient to stabilize the incipient or small gullies. In tropical and subtropical regions, which receive large rains (monsoons, tropical cyclones, etc), all three methods may have to be used for successful gully control.

Controlling gully erosion can be an elusive process. The rate of success in such schemes depends on the planning, design and techniques employed. The ultimate success depends upon the proper diagnosis of the problem, steps taken to eliminate the causes, and drastic changes in land use to stabilize the ecosystem.

The benefit-cost ratio of gully control must be carefully assessed. Some gully control measures are extremely expensive, and resource-poor farmers cannot afford to invest in them. This means that gully preventive or control measures must produce short-term benefits in terms of increased yield, availability of more land for cultivation, and reliable crop yields through improved soil-water use. Above all, expensive measures of gully control and/or restoration have not been widely successful (Lal 1992).

Exact gully control rules are difficult to establish because gullies are not similar; one gully is never exactly the same as another one, even in the same area. Therefore, good judgment and experience are essential in assessing and solving the problem.

Placing loose brushwood, hay, tree branches, stone, etc in gullies does not help in stopping erosion. Refilling large or very large gullies with soil and without diversion of the water flow is not recommended. The refilled soils are generally not as well compacted as the natural soil layers, and can easily be eroded again. Side sloping of the very large gullies is not economical. The sides of a gully will get naturally slanted after some years.

Basic Gully Treatment Measures

Prevention of gully formation

Preventing the formation of a gully is much easier than controlling it once it has formed. Small gullies in initial stages can also be easily controlled (Fig. 5). Prevention is often more economical because cost of gully control and repair can be very high in relation to the value of the land. Therefore, in gully control, emphasis should be placed on the following practices.

Figure 5. Control of a small gully through small stone structure.

Proper soil, water and agronomic management practices

- Protection of the soil by good crop canopy during rains.
- Adoption of conservation-effective, improved soil, water and crop management practices.
- Control of sheet and rill erosion through proper land and tillage management practices.
- Specific slope treatment measures such as bunding, terraces and inter-bund land surface configurations.
- Maintenance of soil fertility through proper inputs, crop rotation and control of land degradation.

Proper management of field and community drains

- Control of grazing, and revegetation of community land and grassed waterways.
- Maintenance of field drains and community drains through proper shaping and installation of structures.
- Prevention of various activities which could lead to the formation of gullies such as dumping of weeds and other waste materials from neighboring fields into community drains.

Diversion of runoff above the gully area

In many cases, the simplest, cheapest and safest gully control method is to divert runoff before it enters into the gully (Fig. 6). This practice is particularly useful in forest land and grasslands. However, this is not practical in the cultivated land. The methods used for design of the diversion ditch are similar to those used for grassed waterways. If the runoff flow to a gully is small, the diversion ditch need not be large. Sometimes it is sufficient to construct a small ditch and a ridge using a plow. When diverting water, the outlet point must be safe from erosion, otherwise a new gully could form.

Figure 6. Farmers making diversion channel for controlling gully erosion in Ginchi watershed, Ethiopia.

If there are several gullies on a slope and it is difficult to find a suitable outlet point for discharging water, one of the continuous gullies can be used as a drainage way. Erosion must be checked in this drainage gully. If the catchment is too large, it might be possible to divert water to several waterways, each one with an acceptable flow.

The design and construction of a diversion channel involves the following steps:

1. Calculate the catchment area contributing the discharge to the gully.
2. Calculate the design peak runoff rate expected from the catchment.
3. Estimate the maximum permissible velocity considering the type of soil and vegetation.
4. Estimate the gradient, size and cross-section of the diversion channel (Hudson 1971).
5. Identify suitable outlet(s) for discharging water.
6. Assess the erosion conditions in the outlet drain(s) or existing gully.
7. Use the above information/analysis from steps 1 to 6 and take appropriate measures to stabilize the outlet drains or gullies.

The runoff volumes and peak runoff rates recorded from the watersheds at 16 locations in India are given in Table 2. The design peak runoff rates for each location are estimated considering the long-term rainfall and other climatic parameters.

Table 2. Measured runoff volume and peak runoff rate for benchmark watersheds in India[1].

Location	Annual rainfall (mm)	Runoff (mm)	Runoff as % of rainfall	Peak runoff rate ($m^3 s^{-1} ha^{-1}$)	Design peak runoff rate ($m^3 s^{-1} ha^{-1}$)
Rajasthan					
Goverdhanapura watershed (Bundi district)	436	37	7.8	0.107	0.22
Madhya Pradesh					
Lalatora watershed (Vidhisha district)	1046	273	26.2	0.092	0.35
Semli-Shyampura watershed (Dewas district)	1162	157	13.0	0.036	0.15
Kailashpura watershed (Guna district)	881	121	13.7	0.090	0.35
Ringnodia watershed (Indore district)	797	27	3.5	0.002	0.15
IISS watershed (Bhopal district)	843	160	15.8	0.050	0.20
Andhra Pradesh					
Adarsha watershed (Kothapally, Rangareddy district)	710	661	7.6	0.068	0.17
Appayapally watershed (Mahbubnagar district)	484	57	11.6	0.013	0.15
Malleboinpally watershed (Mahbubnagar district)	565	34	5.2	0.016	0.15
Mentepally watershed (Mahbubnagar district)	346	40	14.0	0.012	0.15
Sripuram watershed (Mahbubnagar district)	343	24	7.5	0.007	0.12
Kacharam watershed (Nalgonda district)	571	23	4.3	0.013	0.15
Tirumalapuram watershed (Nalgonda district)	474	11	2.3	0.022	0.15
Nemikkal watershed (Nalgonda district)	665	46	6.9	0.023	0.15
Devanakonda watershed (Kurnool district)	534	43	8.3	0.070	0.20
Karivemula watershed (Kurnool district)	323	17	5.3	0.021	0.15

1. Values are averages of long-term data.

Gully treatment measures

The objective of gully control is mainly to establish a good vegetation cover resisting erosion. This requires the stabilization of the gully floor and sides. Gully control embraces the following stages and conditions:

- Filling and shaping small gullies
- Prevention of bank erosion in bends

- Almost stabilized gullies with a U-shaped cross-section
- Check-dams
- Gully heads and other nick points

Filling and shaping small gullies

Small gullies can be stabilized by reshaping through cutting and filling. Rills and incipient branch gullies can be filled by a spade or plow. Small gullies can also be prevented from enlargement by filling tightly packed trash or earth covered with sods, or through stones laid with small voids (Fig. 7). Planting some grasses that are resistant to soil erosion is very important.

Figure 7. Loose boulder check with shrubs for controlling small gully.

Prevention of bank erosion in bends of wide gullies

A measure often recommended is lining/ filling the foot of the bank with stones and boulders. Such a rock fill must be laid in an excavation to prevent undercutting, and the stones/boulders must be large enough not to be carried away by the flow. A simple and cheaper method is to establish suitable vegetation along the foot of the bank. The seedlings should be planted densely in single or more rows. These can provide good resistance to even small or moderate water flows. Laying stones across the channel is useless in preventing erosion in gully bends.

Gullies with a U-shaped cross-section

Vegetation. In U-shaped gullies, with floors at least 1 m wide and with a bed slope of less than 3%, erosion is usually negligible and natural vegetation is established (Fig. 8). Sometimes the gully bed is not quite stable and natural vegetation is not established. Hence grass can be planted in strips across the channel, or all over the bed including the foot of the gully banks. Generally, napier grass is quite effective. Once a good grass cover is established, the channel can resist the stream velocity up to 1.5 m s^{-1}.

Figure 8. Gully stabilized through vegetation in Lalatora watershed, Madhya Pradesh, India.

Structures. If there is no equilibrium between erosion and deposition of sediments, then the gully bed needs stabilization through a simple and cheap physical measure. Usually wood or stones are used for construction of gully control structures. The choice depends on the local conditions and, above all, on the availability of material. The wooden structures are less durable than structures constructed with stones.

A wooden structure consists typically of a single row of small poles (diameter around 5–7 cm) with branches plaited between the poles. The idea is to slow down the runoff velocity and thereby decrease the risk of erosion. The height should not be more than 0.5 m, and the depth of poles inside the ground at least the same as the height above it.

If stone material is used, it acts as a threshold and prevents erosion. Such an alignment consisting of stones placed in a single or double row must be laid in an excavation in the ground and should not reach much above the adjacent ground level. The diameter of stones used should preferably be not less than 10–15 cm. A vertical interval of 2–7 m is recommended and depends on the water flow and the gradient.

Check-dams

The most commonly applied engineering measure is the check-dam. Forces acting on a check-dam depend on design and type of construction material. Non-porous dams with no weak holes, such as those built with concrete and steel sheet, receive a strong impact from the dynamic and hydrostatic forces of the flow. These forces require strong anchoring of the dam into the gully banks to which much of the pressure is transmitted. In contrast, porous dams release part of the flow through the structure, and thereby decrease the head of flow over the spillway and the dynamic and hydrostatic forces against the dam. Much less pressure is received at the banks than at non-porous dams. Since gullies, generally, are eroded from relatively soft soils, it is easier to design effective porous check-dams than non-porous ones (Heede 1977).

Basic considerations. In active gullies the objective of gully control should be to reduce the gradient and dissipate the energy of the flowing water. In nature, this is achieved through erosion down to base levels. To control a gully, a series of local base levels can be established through check-dams. The difference in height between the crests of successive check-dams should be such that the filled-up basins form steps with a mild slope. In this way, a steep erosive gradient is replaced by a stairway of gentle and non-erosive steps.

It is important to first determine whether the check-dams are capable of discharging the expected runoff from the catchment area. The size of the check-dam and its spillway decide the discharge capacity as shown in Table 3. Irrespective of the material used for the construction of check-dams, the following rules should be followed:

1. Construction of check-dams should normally start at the downstream end of the active section of a gully.
2. Check-dams should not reach up to the level of adjacent land. This can cause runoff and flood fields on either sides of the gully. The height of outflow should not be higher than 1 m. The lower the check-dam, the smaller the risk of collapse, and the need for repair. An ideal height of the spillway is often 0.5–0.6 m. It is better to build two such low dams instead of one high dam.

Table 3. Discharge capacity through a parabolic or trapezoidal spillway.

	Discharge capacity ($m^3 s^{-1}$)						
Depth of spillway (m)	0.6 [1]	1.2	1.8	2.4	3.0	3.6	5.2
0.15	0.05	0.10	0.15	0.20	0.25	0.30	0.35
0.30	0.10	0.25	0.40	0.50	0.60	0.75	0.90
0.45	0.20	0.50	0.70	0.90	1.20	1.40	1.50
0.60	0.35	0.70	1.10	1.50	1.80	2.20	2.50
0.75	0.50	1.00	1.50	2.00	2.50	3.00	3.30
0.90	0.60	1.30	2.00	2.70	3.30	3.90	4.70

1. Average length of spillway (m).

3. The crest of a check-dam should not be level but lower in the center. Thus, the spillway will draw the stream to the middle to prevent erosion of the gully sides.
4. A check-dam should reach into an excavation of the gully floor and into the sides of the gully. This ‘keying’ is to prevent erosion scouring and tunneling under the check-dam or around it. The depth of the ‘keying’ depends on local soil conditions but should usually be 0.3–1.0 m, more so in the unstable sides of a gully.
5. The gully area immediately downstream of a check-dam must be protected from erosive forces of falling water through an apron. In the absence of an apron, the check-dam will be undercut and will eventually collapse. The length of the apron should be 1.5–2 times the height of the check-dam. The length of apron is also linked to the slope of the gully. The higher the slope, the greater should be the length of the apron. The floor as well as the sides, from the height of the spillway to the downstream end of the apron, should be protected.

Types of check-dams. Several types of check-dams are used for gully control. Some of the common types are described.

Loose rock. Loose rock can be used in different types of check-dams (Figs. 9 and 10). Dams may be built of loose rock only, or the rock may be reinforced by wire mesh, steel posts (Fig. 11) or other materials. The reinforcements may influence rock size requirements. The basic design of a loose rock check-dam is illustrated in Figure 12. The volumes of excavation and of rocks required in the construction can be calculated from Figure 12.

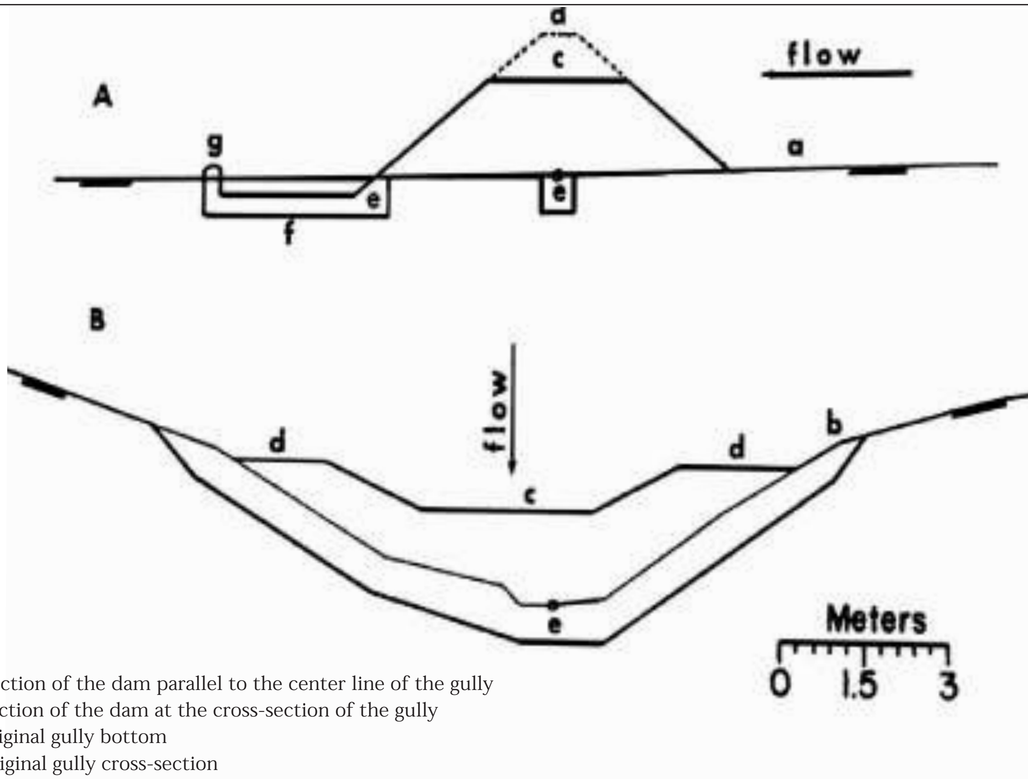
Figure 9. Loose rock check-dam for gully control in Ginchi watershed, Ethiopia.

Figure 10. Loose rock drop structure for controlling gully erosion in Mittimari watershed, Karnataka, India.

Figure 11. Rock reinforced with wire mesh and steel posts for controlling gully in Lalatora watershed, Madhya Pradesh, India.

Since loose rock dams are not reinforced, the angle of rest of the rock should determine the slopes of the dam sides. This angle depends on the type of rock, the weight, size and shape of the individual rocks and their size distribution. If the dam sides are constructed at an angle steeper than that of rest of the rock, the structure will be unstable and may lose its shape during the first heavy runoff.

Loose rock has proved to be a very suitable construction material if used correctly. Often it is found on the land and thus eliminates expenditure for long hauls. Machine and/or hand labor may be used. The quality,



A = Section of the dam parallel to the center line of the gully
B = Section of the dam at the cross-section of the gully
a = Original gully bottom
b = Original gully cross-section
c = Spillway
d = Crest of free board
e = Excavation for key
f = Excavation for apron
g = End sill

Figure 12. Construction plans for a loose rock check-dam.

shape, size and size distribution of the rock used in construction of a check-dam affect the success and life span of the structures. Obviously, rock that disintegrates rapidly when exposed to water and atmosphere will have a short structural life. Further, if only small rocks are used in a dam, they may be moved by the impact of the first large water flow, and the dam quickly destroyed. In contrast, a check-dam constructed of large rocks that leave large voids in the structure will offer resistance to the flow, but may create water jets through the voids. These jets can be highly destructive if directed toward openings in the bank protection work or other unprotected parts of the channel. Large voids in check-dams also prevent the accumulation of sediment above the structures. In general, this accumulation is desirable because it increases the stability of structures and enhances stabilization of the gully.

Double-row post-brush dam. This is also known as wooden check-dam or brushwood dam (Fig. 13). This type of check-dam is ideally suited for gullies with small catchments. They are not meant to resist large flows, eg, channel flows larger than 1 $m^3 s^{-1}$. It is a temporary measure, which can last up to 10 years, provided it is properly maintained.

The height of the spillway should preferably not be more than 0.8–1.0 m. The distance between the check-dams is dependent on the gradient of the gully. The recommended spacing as a function of gradient is given in Table 4 (Geyik 1986). Construction of a wooden check-dam should start with at least 0.5–0.6 m excavation into the sides of the gully. The posts should have a pointed lower end. The double row of posts is hammered across the floor. An auger type tool is required to make post holes in hard earth. The post should be driven into the ground so that the depth below the ground is equal to 0.6–0.8 times the height above the ground. The wooden posts should be rot resistant and termite proof. The posts should be cut in such a way that they form a curved line, which is deepest in the middle. After putting down the posts in their holes, an apron of brushwood should be made. The brushwood must not be dry and breakable. It should have branches, preferably with leaves, which are straight, flexible and long. The design and various construction details of the double-row post-brush dam are shown in Figure 14.

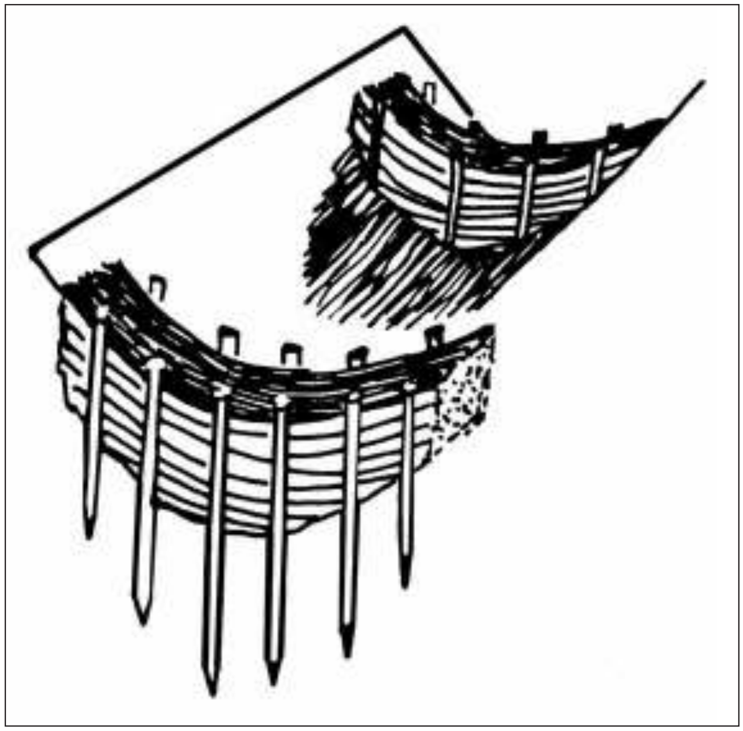


Figure 13. View of two double-row post-brush dams: the lower one denuded of earth and the upper one viewed in the gully.

The apron should not be placed directly on the ground, but on a bed of straw, weeds, mulch or similar materials (15–30 cm thickness), to prevent scouring erosion under the brushwood. The tree branches are laid between the two rows of posts across the gully, and thoroughly packed. There is a risk of the brushwood being removed by flowing water. Therefore, it is necessary to fix the brushwood with rope or wire. When doing so, two or more persons should stand on the brush to press it down. Upstream of the wooden check-dam, sods can be laid and packed to prevent direct flow into the apron brush. This helps in filling gullies through sedimentation at the upstream end of the apron brush (see Figure 14 for details).

Double-row post-stone dam. The design and most of the dimensions of this dam are similar to the double-row post-brush dam. Instead of brush, stone-fill can be used between two rows of posts. On the downstream from this post-stone structure, there should be an apron or stilling basin filled with

Table 4. Spacing between check-dam for different gully gradients and check-dam heights.

	Spacing (m)			
Gully gradient (%)	0.3[1]	0.6	0.9	1.2
4	18.75	37.50	56.25	75.00
6	9.38	18.75	28.75	37.50
8	6.50	12.88	18.75	25.00
10	5.00	9.63	14.38	18.75
12	4.00	7.88	11.63	15.00
14	3.38	6.63	9.75	12.50
16	2.88	5.75	8.38	11.13
20	2.25	4.63	6.75	8.88

1. Height of check-dam (m).

stones. If only small stones are available, a welded mesh can be placed between the rows of posts and filled with small stones. The spacing of this type of check-dam is the same as for post-brush dams. The double-row post-stone dam is more resistant to water flow than the double-row post-brush dam. However, the durability in both cases greatly depends on the quality of the posts.

Single-row post-stone dam. It is also known as post-stone dam (Fig. 15). This type of structure can be used in gully sections with a steep gradient of 30–100%. It is also suitable when the gully is used as a footpath, and in gully heads or other nick points.

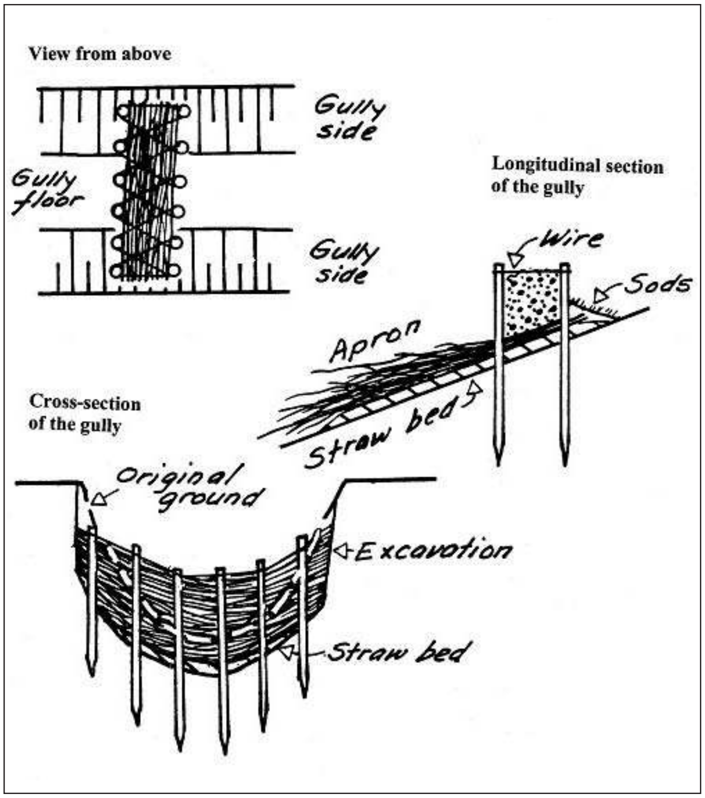


Figure 14. Design of a wooden check-dam, a double-row post-brush dam.

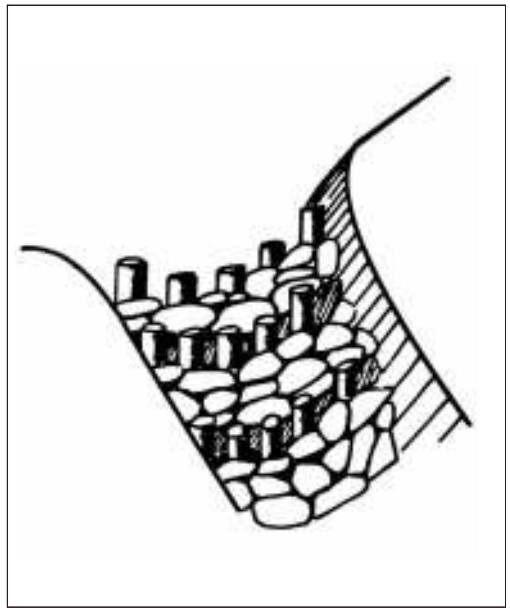


Figure 15. Single-row post-stone dam.

The posts must be placed 0.40–0.65 m deep into the bed of the gully. They should be cut such that about 10 cm remains above the surface of the boulder-stone material. Stones and boulders are arranged in steps supported by rows of posts, ideally 0.3 m high, and preferably not higher than 0.5 m. There should be a layer of small stones at the bottom of the excavation so as to provide a layer of transition between the stone structure and the ground.

Stone wall dam. Stone wall dams are also known as stone check-dams or stone dams. The dam structure is a wall built of stones and boulders laid down carefully so that voids are reduced to a minimum (Fig. 16). The lowest central part of the stone wall must not reach above the surface of the adjacent land. The ideal height of the spillway is about 0.75 m and it should not exceed 1 m. On steep slopes (>20%), stone wall dams with sloping faces can be placed at 10–30% greater spacing than the double-row post-stone dams. The spacing of stone wall dams is similar to that of double-row post-dams up to 20% gradients.

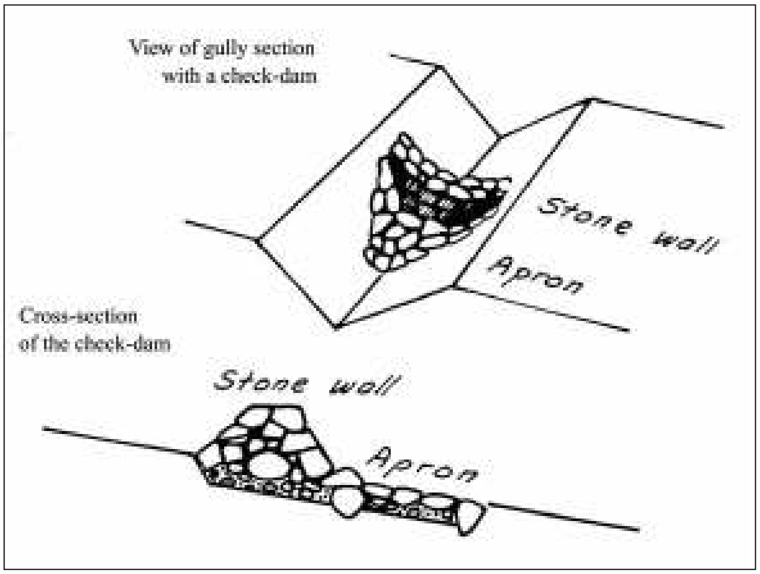


Figure 16. Stone wall check-dam.

The crest of the wall should be 0.3–0.5 m wide and the slope from the crest to the floor should be 1:2–1:1 (length:height). The downstream face of the wall should reach down into a trench. The upstream face may be almost vertical, as it is expected that sediments will fill up the basin sooner or later. The crest must be slightly lower in the middle. Usually it is a curved line, successively lower from the sides of the gully. Spillways can also have a trapezoidal cross-section.

The large boulders should be placed at the crest to form the downstream face of the wall. The size of the boulders should be large enough to resist even high stream velocities. Spherical and smooth surface stones should be avoided or laid inside the stone wall because they can easily roll out of the structure, if pushed by flowing water. If large stones are not available, the stone wall can be encased with wire mesh to prevent stones from being washed away.

Figure 17. Series of stone wall dams for controlling gully in Bundi, Rajasthan, India.

Construction of a stone wall dam should start with the excavation into the sides and the floor of the gully. To prevent scouring and tunneling erosion around the ends of a check-dam, a trench (0.3–0.6 m) should be dug into the sides of the gully and later filled with stones as a continuation of the stone wall. To prevent piping and undermining, the trench should be continued over the bed of a gully to a depth of around 0.3 m. Alternatively, the bed of the gully can be excavated to a depth of about 0.3 m within an area where the stone wall and the apron will be constructed. The excavated earth should be replaced by small stones, pebbles and gravel, if the soil is very susceptible to erosion. Some small variation in the design of stone wall dam is quite common (Fig. 17).

Masonry check-dam. Masonry check-dams are permanent structures used for both controlling gully erosion and water harvesting (Figs. 18 and 19). They are very popular in India. The cost of construction is generally quite high. Proper investigations, planning and design are needed before construction of masonry check-dams. These structures are required to meet the following functions (Mal 1994):

- Should handle peak runoff rate at safe velocity.
- Design should be based on topographic and storage-height considerations.

Figure 18. Masonry check-dam for controlling gully and water harvesting in Adarsha watershed, Kothapally, Andhra Pradesh, India.

Figure 19. Masonry check-dam for controlling gully and recharging groundwater in Bundi, Rajasthan, India.

- Should be able to stabilize the gully.
- Selection of site should be appropriate in terms of economical and most feasible construction benefiting maximum number of farmers.

These structures are preferred at sites where velocity of runoff water flow in streams/gullies are very high and stable foundation considerations (hard murram or rock) are encountered and where construction of earthen embankment is costly and unstable. In locations where runoff velocity is very high some additional support to the structure may be required (Fig. 20). These structures check the velocity of water flowing in gullies, affect the deposition of flood load, decrease the erosive force of water, moderate bed slope, and increase the contact time of water with land surface and thus increase the groundwater recharge (Murty 1994).

Figure 20. Masonry check-dam with additional support for stability in Madhusudhangadh watershed, Madhya Pradesh, India.

Mini-percolation pit/tank. Mini-percolation pits/tanks are quite useful in controlling gully erosion and recharging groundwater. These are small, low cost and simple design structures constructed in series along the gully benefiting more number of farmers across the watersheds (Figs. 21 and 22). These structures are cost effective and check runoff velocity while increasing water percolation to improve the soil moisture regimes and groundwater levels. These structures are quite popular because of the equitable benefit to farmers along the toposequence.

Earthen check-dam. Earthen check-dams are very popular in India for controlling gully erosion and for harvesting runoff water (Figs. 23 and 24). The structure is constructed using locally available materials. Generally the cost of construction is quite low.

Figure 21. Mini-percolation tank for recharging groundwater and controlling gully erosion in Kothapally watershed, Andhra Pradesh, India.

Figure 22. Sunken pits in the gully bed at Kothapally watershed, Andhra Pradesh, India.

Figure 23. Earthen check-dam with stone pitching for water harvesting and gully control in Lalatora watershed, Madhya Pradesh, India.

Figure 24. Earthen check-dam with outlet in Kothapally watershed, Andhra Pradesh, India.

Earthen check-dams, designed on the basis of engineering principles, are constructed across streams for creating water reservoirs and for reducing the runoff flow velocity. The following aspects are considered as basic requirements for designing the earthen dams:

- Hydrologic data
- Information on soils and geology
- The nature and properties of the soils in the command area
- Profile survey and cross-sectional details of the stream or gully

To arrive at a proper design of the earthen dam, site selection is very crucial. A narrow gorge should be selected for erecting the dam to keep the ratio of earthwork to storage at minimum. Runoff availability for the reservoir should be computed on the basis of rainfall and runoff relationship for the locality. Depending upon the assumed depth of ponds and the corresponding area to be submerged, suitable height of the dam may be selected to provide adequate storage in a given topographic situation; such dams are constructed with height ranging from 5 to 15 m (Katyal et al. 1995).

The cross-section of dam and other specifications are finalized considering the following criteria:

- There should be no possibility of the dam being over-topped by flood-water.

- The seepage line should be well within the toe at the downstream face.
- The upstream and downstream faces should be stable under the worst conditions.
- The foundation shear stress should be within safe limit.
- Proper spillway should be constructed to handle the excess runoff.
- The dam and foundation should be safe against piping and undermining.
- The upstream face should be properly protected against the possible wave action (stone pitching or with grasses).

Side slopes of the bund are governed by the material used for construction. Minimum side slopes are 3:1 on the upstream side and 2:1 on the downstream side; steeper side slopes may sometimes be adopted in case of lower bund heights but these should be restricted up to 2:1. A minimum free board of 1.5 m is usually provided. The check-dam should be provided with spillway to remove designed peak rate of runoff. These can be masonry structures in case suitable site is not available for locating a vegetative emergency spillway.

The earthen check-dams are used for multiple purposes. They are used as surface water storage structures as well as for recharging groundwater. These structures have been found beneficial for improving the groundwater (Figs. 25 and 26).

Figure 25. A defunct well recharged after construction of check-dam and more area brought under cultivation in Dewas, Madhya Pradesh, India.

Figure 26. A recharged well near a gully control structure in Mudhsudhangadh watershed, Madhya Pradesh, India.

Gabion. A gabion check-dam consists of prefabricated wire cages that are filled with loose rock (Fig. 27). Individual cages are placed beside and onto each other to obtain the dam shape. Normally, this dam is more esthetically pleasing, but it is more costly than loose rock or wire-bound rock check-dams. Gabions are particularly suitable for Vertisols where cracking is a major problem.

Figure 27. Gabion structure across a big nala *in Dewas watershed, Madhya Pradesh, India.*

Gully heads and other nick points

An eroding waterfall (a gully head or any other nick point) can be treated in three ways:

1. Dam construction downstream of the fall

2. Sloping the head and protecting the channel
3. Construction of drop structures

Sloping the head and protecting the channel. Sloping the head is the most common and rather simple measure, provided the height of the fall is less than 1.5 m. The gully head and other nick points of a longitudinal section can be sloped back to an acceptable gradient for stone pavement or check-dams. One possibility is sloping through excavation, another is to cut down the head only to half the depth and use the excavated material for filling a slope, so half the channel will be excavated, the other half rests on earth fill. Even if the fill is trampled or pre-compacted, there is a risk of further compaction as well as movement of the slope fill at a later stage. This damages the structure part on the slope. Proper compaction is often difficult. It requires watering with careful moisture control.

The sloping channel needs to be shaped and protected from erosion. Four alternative materials can be used for protection: (1) Sod; (2) Brushwood; (3) Stones and boulders with or without posts; and (4) Chute or pipe. The selection depends on the size of the flow rate and channel gradient.

Sodding. The sloped nick point can be protected through a carpet of sods. Some of the sods should be pegged, so that the sod is not so easily removed by flowing water. Sodding is a cheap and effective measure if good grass turf is available and if the waterfall is small. The structure fits best in new gullies without a pronounced head and waterfall erosion.

Brushwood. If the head (>1.3 m) and the flow are large, brushwood can be used. The waterfall erosion of the flow is stopped through a protective carpet of two piled beds: one straw bed and another bed of brushwood.

Stones and boulders. The following structures can be used: stone pavement or brick lining; and single-row post-stone dam.

A stone pavement is recommended if flat stones are available. The stones must be placed closely on edge. A transition layer of gravel, pebbles and small stones is needed between the pavement and the earth, if this is susceptible to erosion.

Large flows require the construction of check-dams and stone wall dams as already described. However, in narrow or very steep channels, single-row post-stone dams are recommended.

Drop structures. Waterfalls can be managed by permanent structures of reinforced concrete, bricks or other materials. A common structure is the drop spillway. There are several designs available on drop structures. All are expensive and need engineering assistance in planning, design and construction. This type of structure is not much used in agricultural areas.

Selection of structure

The selection of structure depends upon the following:

- Size of catchment and peak runoff rate
- Stage of gully erosion, especially gradient
- Required durability of structure
- Availability of materials for construction
- Costs

Size of catchment and peak runoff rate

Wooden check-dams can resist flows less than 1 $m^3 s^{-1}$ in V-shaped gullies. Gullies with larger flows and steep gradient require post-stone dams or stone-wall dams.

Stage of erosion and gradient

Gradients of 0–3% usually represent a stabilized stage. The cross-section is more or less U-shaped, and natural vegetation is established. Large flows in erodible earth, however, can cause lateral erosion, which needs planting or stone packing along the gully bank. Gradients of 3–5% are often near stabilization, which means that grass can be planted on the gully floor. Gradients of 5–10% may need support by wooden check-dams. In gullies with small flows single-row post-brush dams might be sufficient, and in larger gullies with modest flows double-row post-brush dams are required. Gullies with gradients of 10–50% and with medium flows usually need stone check-dams.

Durability

The goal of most gully control measures is revegetation. Temporary structures such as wooden check-dams and post-stone dams often create conditions necessary for the establishment of a good grass cover. The useful life of these check-dams depends on the quality of the posts and maintenance. For longer durability, stone structures are needed. Structures in concrete are considered to be permanent and free from maintenance. However, on Vertisols also, these require regular maintenance.

The approximate useful life of the various structures is:

Earthen dam - 5 years; double-row post-brush dam - 5–10 years; double-row post-stone dam - 5–10 years; single-row post-stone dam >10 years; and stone wall dam >10 years.

Availability of materials

If no stone or wooden material is available locally, the earth of the site can be packed in sacks and used. If only small stones are available, iron netting is needed.

Costs

Cost is an important consideration. It needs to be worked out carefully considering earthwork involved, cost of various materials, transport, labor charges, etc for the cost obviously depends on site and region. The most economical and most effective measures should be adopted.

Steps for Restoring Land Degraded by Gully Erosion

A sequence of steps recommended (Lal 1992) for restoring land degraded by severe gully erosion is as follows:

1. Assessment of current situation
   - Rainfall characteristics
   - Vegetation
   - Current land use
   - Land capability
   - Soil properties
   - Catchment area and slope
   - Drainage pattern
   - Runoff volume and rate

- Gully heads
- Gully bed slope gradient

2. Identification of the conservation needs for different landscape units
3. Protection of gully heads and area from overgrazing
4. Diversion of water from the gully
5. Change of land use in the catchment using land management treatments and cover crops
6. Use of biological and other simple measures for controlling gully
7. Installation of engineering structures (if needed)
   - Check-dams
   - Drop structures

Maintenance

Damage by erosion in a grass cover may be healed by its regrowth, but even a small break in the gully structure enlarges rapidly. Collapse of one check-dam will sooner or later affect other structures through headward erosion. If the repair is postponed, the damage will be larger, and more expensive. Delayed maintenance can result in the collapse of all gully control structures made.

In conclusion, gully control should always be carried out to safeguard future maintenance. Damage must be checked after every rainy season, and also after every large runoff event.

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