Analysis and Guidelines for Watershed Rehabilitation

Burchard H. Heede[1] 1981

ABSTRACT

Analysis of gully networks and subsequent ranking of the network gullies for treatment priority leads to highest benefits for least cost. Ranking is suggested as a stepwise process consisting of determining stream order, number of tributaries, and stages of development. Development stages are interpreted in terms of present and expected future erosion rates.

INTRODUCTION

Since the 1930's and 40's, how to rehabilitate watersheds has been the subject of controversy. For some land managers, these controversies still exist, because they are unaware of the dynamics of the system.

Geomorphologic concepts can enhance our understanding of watersheds as dynamic systems in which all parts are interrelated, whether the fluvial system is perennial or ephemeral (whether flows run yearlong or during part of the year only).

Watershed rehabilitation efforts must consider the dynamic interrelationships, not only to be effective, but also to save money. Certainly, it is cheaper to work with the mechanics of a system than against it. For instance, the knowledge that aggradation in a master gully induced by check dams can lead to aggradation in its tributaries, may save the construction of unnecessary additional dams. Conversely, controlling only the headcut of a discontinuous gully, whose local base level dropped, eventually will lead to loss of the structure because future gully cuts will migrate upstream.

This paper will address some of the old controversies in light of more recently developed knowledge. It will demonstrate further how gully networks with confusing appearance can be deciphered for control purposes, and how rehabilitation funds can be saved by utilizing the dynamic interrelationships among gullies, i.e., working with gully dynamics.

Watershed rehabilitation problems are similar among different regions of the West, but the severity of the problems changes. The principles that will be discussed in connection with gully dynamics and control applications are valid regardless of physiographic region. Thus rehabilitation efforts in the Redwood National Park, other Pacific coastal regions, or watersheds of the interior West can be guided by these universal principles.

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WORKING WITH THE PROCESSES TOWARD REHABILITATION AND EROSION CONTROL

UPSTREAM VERSUS DOWNSTREAM CONTROL

A frequently heard issue in watershed rehabilitation is whether control should start and concentrate on the headwater area or the lower land. The argument for upstream control is that runoff originates in the high elevations, and if it is prevented from reaching the low land, the problems of erosion are solved.

First, this approach relies on the validity of Horton's overland flow model, and second, it neglects the geomorphologic processes. The Horton model differentiates only between above-surface and vertical (infiltration) flows, but does not include lateral flow. My observations and preliminary research suggest that lateral flow must be included as a possible source for above-surface flow. Indeed, it should be recognized that flow may alternate among the three components; i.e., overland flow may convert to lateral flow and the latter back to overland flow. Also, the vertical flow component, infiltration, may change to lateral and back to above-surface flow under certain conditions. This was also suggested by Zaslavsky and Sinai (1981) who described above-surface flow even on sand dunes in the Negev desert.

Thus water retained in the headwaters of a watershed by trenches, conversion ditches, or other structures, if not consumed in place, may reappear as overland flow at some location downstream.

The second and more serious argument against controls limited to headwaters, are the geomorphologic, dynamic relationships among the individual parts of a watershed. These are best illustrated by the base level concept. Assume that a stream cuts its bed deeply at the mouth due to deepcutting of the master stream or tectonic movement. As a result, a bed scarp will advance upstream and thereby lower the streambed. Eventually, the deepcutting will reach the headwaters and destroy the treatment, unless the bed scarp advance is controlled naturally by a bedrock outcrop or artificially by a gradient control structure (check dam). Thus, headwater control without downstream control cannot be successful. It also follows that channel system control work should proceed upstream to protect the local base level of the project area. Conversely, areal land treatments must proceed from the headwater area of the basin downslope to insure control of runoff. The issue is control of channel base level, which must be accomplished before on-site runoff and erosion control can proceed. Generally, this means successful treatments begin at the watershed mouth, unless substantial controls provide treatment starting points elsewhere.

HIGH DAMS VERSUS LOW DAMS

Another old erosion control issue is the question of whether to build a few high check dams or many low ones. Costs, sedimentation, structural stability, etc., were considered, but research results were not available to clarify the issue.

At the outset, it must be stressed that aspects of costs and sedimentation should be considered individually, because they cannot be lumped for determinations of effectiveness. For example, cost effectiveness may not be identical with sediment catch effectiveness.

A research watershed on the western flank of the Colorado Rocky Mountains, treated for rehabilitation for more than a decade, revealed functional relationships in structural gully control (Heede 1978). These relationships show that the answer to the question of high versus low dams depends on the specific objective of the treatment.

Furthermore, the project demonstrated that sediment is deposited above check dams on an upslope gradient. Sediment catch increases much faster than dam height. For example, the volume of sediment deposits behind a 1.2-m dam is seven times larger than behind a 0.3-m dam, or a four-fold increase in dam height causes a seven-fold increase in deposits (fig. 1).

During the large-scale pre-World War II rehabilitation efforts, zero sediment deposit gradients were assumed. Not only did this lead to overdesign in numbers of structures, but also to wasted sediment catch capacity of the dams, because upstream dams stopped the upstream extension of deposits.

We are able now to resolve the old issue as follows: Since high dams catch more sediment than low dams, the highest possible dams should be installed if sediment catch is the primary objective. Depth of streambed or stability considerations will set an upper limit for dam height.

Maximum possible dam height should also be selected in gully control where the number of dam sites must be limited, because the projected upstream extent of the sediment deposits above a dam determines the location of the next upstream dam. Increasing the dam height reduces the number of dam sites more in steep than in low-gradient gullies.

In the Colorado research project, loose rocks, wire mesh, and steel posts were the main construction materials. The functional relationships showed that, regardless of gradient or dam type, at a certain dam height material and cost requirements are lowest (fig. 2). Dams lower or higher than this optimum height have higher requirements of both. Under some conditions, other design factors such as structural stability and landscape aesthetics may override cost and material considerations.

ENGINEERING VERSUS VEGETATIVE MEASURES

An issue often raised by watershed managers is the choice of engineering versus vegetative measures in rehabilitation projects. The watershed manager must first evaluate the erosion potential of the area in question. Oversteepened slopes, high rainfall, and weak vegetative cover may indicate very high potentials for erosion. An example is found on the Redwood National Park, as well as many other Pacific coastal areas where plant growing conditions per se are excellent, but once the vegetative cover is disturbed, erosion rates are unusually high. Redwood Creek watershed in the Redwood National Park loses in excess of 2,800 metric tons of sediment per square kilometer per year (Redwood National Park 1981). On the Redwood

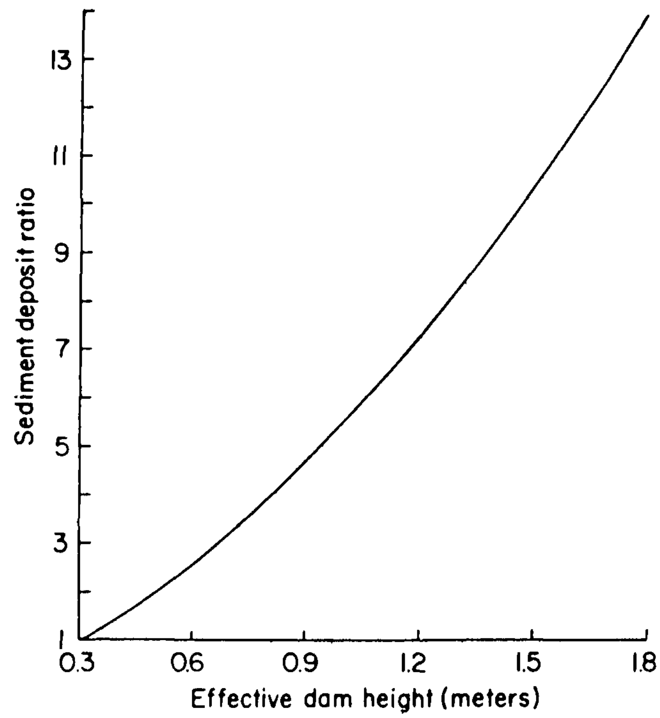

Figure 1. "Analysis and Guidelines for Watershed Rehabilitation" by Burchard H. Heede.

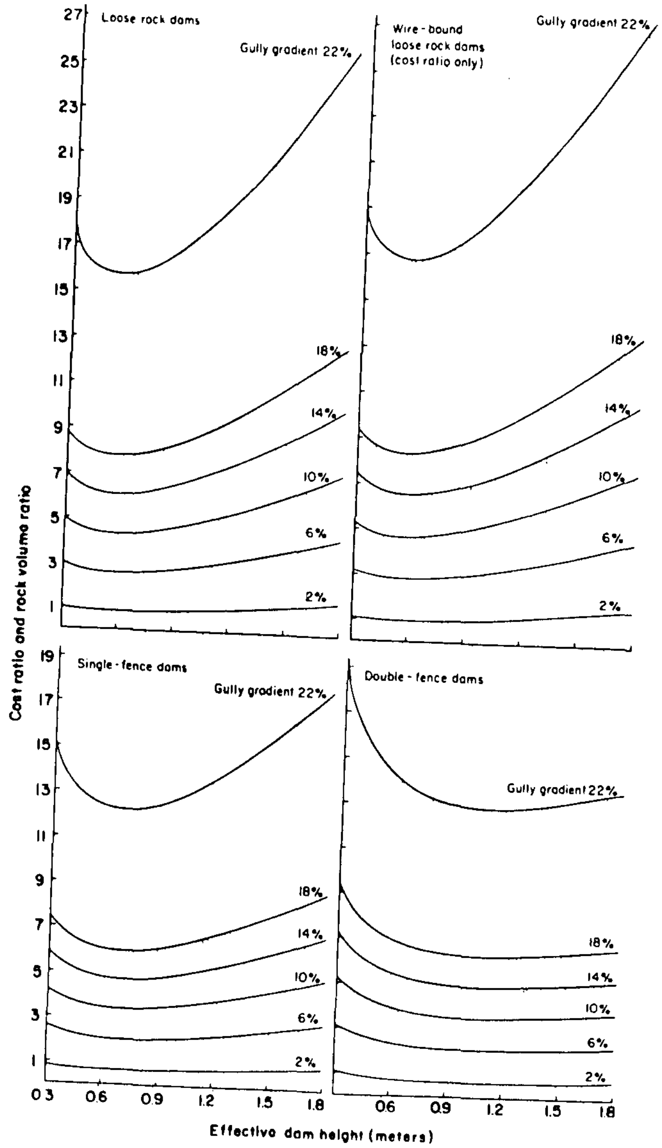

Figure 2. "Analysis and Guidelines for Watershed Rehabilitation" by Burchard H. Heede.

Creek watershed, 90 percent of the forests have been removed. This removal resulted in severe ground surface disturbances due to harvest methods in some areas, aggravating the problems of rehabilitation.

Based on rehabilitation projects in the Redwood National Park and in the Colorado Rocky Mountains, the issue of engineering versus vegetative measures can be resolved as follows: Where growing potentials are high and erosion potentials excessive--Pacific coastal areas--or where growing potentials are moderate and erosion potentials high--arid and semiarid interior West--engineering measures must be used to stabilize the ground surface; vegetation will enhance and perpetuate this stabilization. As will be shown in the second part of this paper, engineering works can be applied sparingly, if used at strategically important locations and in combination with vegetative measures.

For purposes of rehabilitation, engineered measures can be either structures or topographic reshaping. Both were successfully used in the Redwood National Park. Vegetative measures could be classed into three broad groups: 1) Improvement of existing cover by grazing reduction, enhancement of soil nutrients by fertilization, introduction of mulches, or other measures. 2) Planting of vegetation by seed or seedlings. 3) Establishment of wattles, representing a vegetative structure. These three groups were beneficially used in the Redwood Park rehabilitation projects.

Engineering structures are expensive. A methodology is therefore needed to determine which gullies require check dams, and to select those gullies where structural treatment will give greatest results. Such a methodology will be discussed in the following section.

RANKING NETWORK GULLIES FOR TREATMENT PRIORITY

GULLY NETWORK TYPES

Gully networks may appear confusing to the rehabilitation project planner, and questions arise such as: must all network gullies be structurally controlled? Or, which gully, when treated, offers greatest return? A systematic approach is therefore required that makes it possible to decipher gully networks and allow application of a process of elimination. The latter is important, if funds are a severely limiting factor. Generally, engineering measures require more funds than vegetative approaches.

Before considering the interdependencies in a network hierarchy, the types of gullies making up the network should be determined. Two types of gullies exist: continuous and discontinuous. Geomorphic gully processes differ with gully type and lead to different critical erosion locations within the gullies. Recognition of these critical locations is basic to a successful treatment design.

Critical locations are identified by a condition that not only induces instability at the location, but also transmits it into adjacent gully reaches and/or into the undissected watershed.

Continuous gullies begin their course in the headwater area with a gentle transition into the channel. At the gully mouth, where the bed gradient is low, flow velocities decrease and sediment is deposited. With time, this leads to gully widening at the mouth to convey larger flows through the gully cross section. Deposition and widening cause decreases in flow depth and increases in bed roughness (increased wetted perimeter). These in turn lead to further losses of flow velocities. At some point in time, deposits become excessively large, restricting high flows. Deep cutting of the bed at the gully mouth follows, which lowers the local gully base level. As a result, the whole gully will be deepened and ultimately widened. The mouth of a continuous gully is therefore its critical location.

Discontinuous gullies begin their course with an abrupt headcut that may be situated at any location on the watershed. This headcut advances toward headwaters and therby extends the gully upstream. Generally, discontinuous gullies begin their course at some point on the watershed, and an alluvial fan forms downstream from the gully mouth. Oversteepening of the fan by periodic sediment deposition causes the formation of a new discontinuous gully on the fan (Patton and Schumm 1975). This gully progresses upstream by headcutting into the pre-existing discontinuous gully, deepening and widening it. Thus the headcut and alluvial fan at the gully mouth are both critical locations in discontinuous gullies.

The compilation of aerial photograph overlays is very helpful in the determination of network types, because the images of independent discontinuous gullies, headcuts, and fused continuous gullies appear unobstructed by other terrain features. Based on gully types, four network types can be found:

- continuous gullies only;
- discontinuous gullies only;
- continuous and discontinuous gullies, the latter not fused with the network;
- continuous and discontinuous gullies of which some or all are fused with the network.

If a watershed has discontinuous gullies only, there is no network in the true sense of the term. The gullies may be located on the valley floor, resembling pearls on a chain, or they may occupy subdrainages adjacent to each other. If discontinuous gullies follow each other, they will eventually fuse (Heede 1967).

Discontinuous gullies that have fused with the network can be recognized by their headcut. Network fusion was attained by periodic gully processes on the alluvial fan, as described previously. At the location of fusion, a headcut develops, if a water overfall from the discontinuous into the network gully existed. Adjustment of the discontinuous gully to its new base level (network gully) follows by deep cutting. This may result in accelerated upstream advance of the main headcut. With time, the headcut may be eliminated by a gentle transition and a new continuous network gully is established.

STREAM ORDERING

Horton's (1945) stream order analysis demonstrates the relationships between network streams by assigning numbers (orders) to the individual streams, based on their network importance. The smallest streams, having no tributaries, are order (1), the next larger, having one or more tributaries of order (1), are order (2), etc., and the master stream of the network receives the highest order. This analysis is also well suited to gully networks with the exception that discontinuous gullies not fused with the network must be considered on their own, without an order, because interaction with other gullies cannot be established.

In gully ordering, we go one step beyond Horton's analysis, because for control objectives, it is important to know the number of tributaries dependent on a gully of a given order. We designate therefore each network gully by a letter, and use the number of tributaries as subscript (fig. 3). Examples of Figure 3 are gullies D and B_6, signifying that gully D has no tributary, while gully B_6 has six. Obviously, considering the local base level concept, gully B_6 has greater importance in the network hierarchy than gully D. A table should be established, separating the network gullies by stream order (Table 1).

Table 1.--Stream orders of gullies shown in Figure 3.

	Stream orders			
1	2	3	4	0*
A	F_3	B_6	K_{14}	I
C	N_1			Q
D	P_1			
E				
G				
H				
J				
L				
M				
O				

Subscripts indicate number of tributaries.

*Gullies not fused with network.

STAGES OF DEVELOPMENT

For control purposes, the importance of a gully in the network hierarchy is also given by its erosional stage, accelerating or inactive in extreme cases. Erosion may not be limited to the gully in question. By geomorphologic chain reaction, it may advance through the network. The next step in the network analysis will therefore consider stages of gully development.

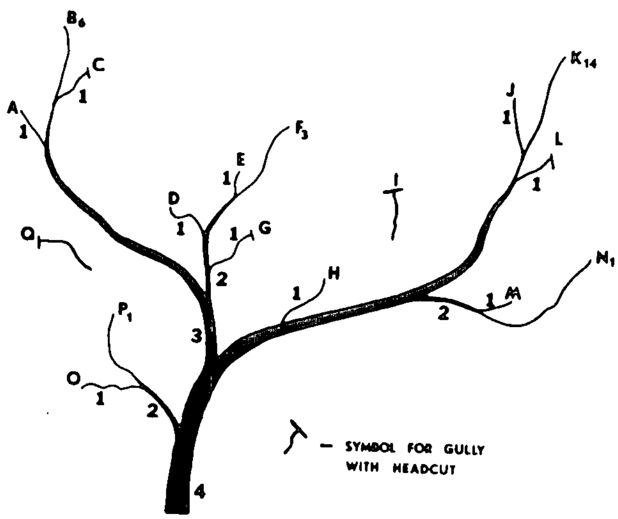

Figure 3. "Analysis and Guidelines for Watershed Rehabilitation" by Burchard H. Heede.

Stage designations should be based on erosional development alone, and should not necessarily represent the age of a gully. Thus, borrowing terms from classical geomorphology, an early erosional development is called young stage, a progressive development, mature stage, and the end stage of erosional development, old stage.

It is conceivable that network gullies are predominantly of one stage of development. In such a case, it may be desirable for purposes of differentiation to subdivide the proposed stages. An example is: early mature and late mature.

The proposed terminology also reflects the fact, suggested before, that gully age is not necessarily synonymous with development stage. A gully may be youthful by age but old in terms of development, or vice versa. For example, an unusual storm may create a gully, cut its bed down to hard bedrock, and leaves banks close to their angle of repose. Not much more future erosion could be expected, and old stage of development would be the correct designation.

On the other hand, a gully of old stage may cut through relatively hard bedrock, exposing soft bedrock in the geologic strata below. Accelerated erosion may begin, leading to processes that deepen and widen the formerly existing old stage gully. It has become youthful in its development.

These examples not only illustrate the dynamics of gully systems, that stages of development may not follow each other in sequence, but they indicate also that much knowledge can be gained by comparing the network gullies with each other.

Other examples of development stages are continuous gullies that adjust to base level changes. The adjustments will be indicated by frequent erosional scarps on the bed, often accompanied by channel widening at the location of the scour hole (plunge pool). The bedscarps advance upstream, deepening and widening the gully. It is youthful.

If a continuous gully has infrequent bedscarps and parts of the banks are stable, mature stage has been reached. Further development may lead to vegetation-lined gully bottoms, a few inconsequential bedscarps, and most banks in stable and vegetated condition. Old age is attained.

Table 2 presents commonly found indicators for determining stages of development. This table should not be taken as all-encompassing, because different indicators may exist as well as different combinations of them.

Table 2.--Commonly found indicators of stages of gully development.

Stage of development	Indicators
Young	Discontinuous gullies not fused with the network.
	Discontinuous gullies fused with the network. Their headcut

is located far below the watershed divide or other control point. The bed shows frequent erosional scarps. The farthest downstream bedscarp is close to the location of fusion with the network.

Continuous gullies with frequent erosional scarps on the bed, raw banks, and vertical incisons of at least 1 m depth, even if the remaining cross section is trapezoidally or semi-spherically shaped.

Mature — Discontinuous gullies joined with the network. Erosional bedscarps are infrequent but deeper than 0.6 m. The headcut still has to advance a substantial distance before a natural control is reached.

Continuous gullies with infrequent bedscarps. Half of all bank length is stable as indicated by an advancing vegetative cover. The bed shows signs of vegetation cover establishment.

Old — Discontinuous gullies fused with the network. The headcuts reached the watershed divide or any other natural or man-made control. Bedscarps are practically absent.

Continuous gullies with bed and banks well vegetated, or the bed rests on hard bedrock, or may consist of an armor of predominantly large loose rock. In the latter case, it is especially important that bedscarps are practically absent.

Table 3 presents development stage for the sample network in Figure 3.

Table 3.--Stages of development of gullies shown in Figure 3.

Young	Mature	Old
I	B_6	K_{14}
Q	C^6	A^{14}
	F_3	D
	G^3	E
	H	J
	N_1	L
	P^1_1	M
		O

TREATMENT PRIORITIES

The proposed method of ranking network gullies for treatment priorities assumes that the treatment approach combines structural and vegetative measures. The Colorado rehabilitation project has shown that not all gullies require check dams, if the vegetation on the watershed is managed for rehabilitation.

If check dams are built in a network gully, the base level of its tributaries will be maintained or raised. In either case, deepcutting is eliminated in the tributaries, vegetation cover can become established and the gullies stabilize with time.

On the Colorado research watershed, subsequent analysis showed one third of all gullies treated with check dams (expressed as total gully length) would not have required dams. Thus ranking network gullies for structural treatment priorities is an important tool for avoiding overdesign.

The stepwise approach to the analysis of gully networks for control and rehabilitation purposes has two major objectives. The first is to define the critical erosion locations within the individual network gullies. This is achieved by delineating the types of gullies that make up the network. The second objective is to determine the importance of the individual gullies in the hierarchy by establishment of stream order, number of tributaries, and stage of development. All these criteria must be considered in the final ranking for treatment priority. Regarding development stage, it must be emphasized that this stage not only expresses present but also the future erosion rates, and hence, it is an expression of expected returns from treatment.

Tables 1 and 3, based on the network schematically illustrated in Figure 3, will be used to demonstrate the final ranking step. We start with the main gully of the network K_{14}. Stream ordering showed that it has the highest order in the system, thereby controlling all other network gullies, a total of 14. Table 3 indicates an old stage of development, because the gully had reached bedrock in some places and was well vegetated in others. Also, the banks were predominantly stable as shown by plant invasions. If we would evaluate this gully as an entity by itself, we would assign the lowest treatment priority. But, of course, we have to evaluate this gully also in terms of its network importance, expressed by its control of 14 gullies. If the old-stage main gully remains stable in the future, and check dam installation can even raise the base levels for the other gullies, future benefits will be large. Table 4 shows that the designer ranked the main gully therefore as priority 1.

Table 4.--Ranking of gullies by treatment priorities

Priority 1	Priority 2	Headcut treatment only
I	F_3	C
Q		G
K_{14}		L
B_6		

Because gully B_6 has a high order, controls the second highest number of tributaries (Table 1), and is of mature development stage, (higher future erosion rates must be expected), it was also assigned priority 1.

The final ranking of discontinuous gullies I and Q offers no problems. Being without stream order because of network independence, and located on the watershed in locations that indicate large future headcut advances (young development stage in Table 3), they are ranked priority 1 (Table 4).

Within the priority classes of Table 4, ranking is also applied from top to bottom. Thus gullies I and Q rank before gully K_{14}, and that, in turn, before gully B_6. This means, if funds are severely restricted, the discontinuous gullies would be treated. But it is not advisable to consider gully control as a "one-shot" approach. Gully control activities can be spread out over time, if the concept of base level control is adhered to.

Table 4 shows gully F_3 ranked as priority class 2. The reason is that this gully controls the third highest number of tributaries. Structural treatment of all other gullies, with exception of the discontinuous gullies fused with the network, is judged to offer only small returns. Additionally, the watershed was evaluated to have high plant growth potentials, making effective ground cover establishment possible, once the main local base levels are stabilized.

The headcuts of the discontinuous gullies (C, G, L) that fused with the network must be treated, otherwise future headward extension of these gullies will take place. Generally, control of abrupt headcuts requires structures. Plants invade, after stabilization has been achieved, by selecting sediment deposits within and alongside the structure.

The examples discussed demonstrate that, in some cases, a step may be neglected for final ranking of treatment priority. Hence the question arises, could the stepwise approach sometimes be shortened? This is not advisable, because the information gained in each step must be established first, before its importance within the totality of all aspects can be determined.

SUMMARY AND CONCLUSION

Effective erosion control and watershed rehabilitation designs must recognize the dynamic interactions within the natural systems. Base level interactions tell us to proceed with a treatment from downstream toward upstream, to start at a location with a stable elevation that will not be lost during treatment life, and to omit certain network gullies from structural treatment, if the watershed vegetation is treated for rehabilitation. Land and vegetative treatments are the second step, and should proceed from headwaters downward to assure their functional integrity.

Where sediment catch is the prime objective, maximum possible dam height should be used. But if cost is the major constraint, the dam height that minimizes costs should be selected.

A treatment approach that combines engineering and vegetative measures not only hastens rehabilitation processes in many cases, but also reduces the number of structures required. Obviously, the Redwood National Park as well as other Pacific coastal areas, and the arid and semiarid watersheds of the interior West, fall into this category.

Networks can be differentiated by the type of their gullies: continuous, discontinuous, or mixtures of both. This network classification points to the main critical erosion locations within the individual gullies that must be recognized for control.

For treatment selection, gully networks must be further described by stream order, number of tributaries, and stage of development (treatment return expectancy). Establishment of treatment priorities can be summarized in general terms:

First priority--
- discontinuous gullies;
- main-stem gully;
- tributary gullies with largest number of tributaries of their own.

Second priority--
- tributary gullies controlling smaller numbers of tributaries.

Third priority--
- tributary gullies with excessive erosion rates.

The proposed systematic approach to ranking of network gullies for treatment priorities assures that, regardless of funding level, the highest return will be obtained for the least cost.

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Figures

Figure 1.--Expected sediment deposits retained by check dam treatment as a function of dam height. The sediment deposit ratio relates the volume of sediment deposits to the volume of sediment deposits at dam height of 0.3 m.

Figure 2.--Relative cost of installing check dam treatments and relative angular rock volume requirements in gullies with different gradients as a function of dam height. The cost and rock volume ratios relate the cost of a treatment to those of a treatment with loose rock dams 0.3 m high installed on a 2% gradient.

Figure 3.--A schematic gully network consisting of continuous gullies, independent discontinuous gullies I and Q, and discontinuous gullies fused with the network C, G, and L. Fused discontinuous gullies are indicated by the headcut symbol.