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THE USE OF COST-EFFECTIVENESS AS A TECHNIQUE TO EVALUATE AND IMPROVE WATERSHED REHABILITATION FOR EROSION CONTROL, REDWOOD NATIONAL PARK

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Abstract. Traditional cost-benefit analyses cannot be routinely applied to rehabilitation practices because soil and many other watershed amenities have little net economic value. Consequently, the success and effectiveness of restoration practices are best evaluated by the extent to which carefully formulated objectives are met. Controls on cost-effectiveness are, by definition, twofold. Cost is influenced by such factors as program goals, indirect expenses, professional judgment and treatment design standards. Erosion control effectiveness is influenced by temporal changes in vegetative and structural treatments, erosional mechanisms and the relative timing of erosion control work with respect to the original land use disturbance. Quantitatively predicting and evaluating cost-effectiveness are the two most valuable tools for best achieving erosion control objectives. In the park, over three orders of magnitude difference exists between the most cost-effective primary technique and the least cost-effective secondary procedure. Even treatments designed to control similar problems display cost-effectiveness differences of over one order of magnitude. Whether in conjunction with the original land use or as a part of subsequent rehabilitation activities, prevention is clearly the most cost-effective technique for minimizing sediment production and yield.

INTRODUCTION

The effectiveness of watershed rehabilitation, like any other work, is primarily dependent upon the degree to which stated goals have been obtained. Success can only be judged when clearly defined objectives have been established against which results can then be compared and evaluated.

In isolated situations where the end-product of such work has an immediate and directly quantifiable market value, a cost-benefit analysis will help determine the advisability of initiating, continuing and/or modifying restoration activities. For example, in-stream habitat improvement which results in increased salmonid fishery production may be economically justified on the basis of its positive net economic return (Everest, 1978; Ward and Stanley, 1979). Unlike an industrial setting, however, the chief economic benefactors of such improvement work are generally not those

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who expend the funds at the restoration site. Thus, while the sportsman and the fishing industry may gain from habitat improvement accomplished on private or public forest lands, the economic benefit does little to stimulate private incentive for such work.

Similarly, while nearing the end of an era marked by abundant (albeit diminishing) natural resources, justifications for watershed rehabilitation based on long-term economic returns have not yet been seriously considered in the market place. For example, there is a loss of growth sites on commercial forest lands resulting from inadvertant but avoidable soil loss (e.g. landsliding and gullying). However, this loss has not yet been determined serious enough to warrant substantial procedural changes, such as self-imposed, modified logging practices or post-harvest corrective work (erosion control), solely for the purpose of maximizing future timber yield (California Board of Forestry, 1980).

As a consequence of these limitations, rehabilitation effectiveness must be judged on the qualitative degree to which stated goals have been or are expected to be attained rather than on economic return. Since unitless cost-benefit ratios for such work would require the assignment of unique monetary values to project benefits, cost-effectiveness ratios may be used instead. In this manner, various techniques used to attain a given goal may be compared on the basis of the cost and the relative effectiveness of each method attaining all or some portion of the desired end result. Thus, while cost-benefit analyses may be used to justify the expenditures of funds in classical economic situations, an evaluation of the relative cost-effectiveness of watershed rehabilitation work will only describe which methods are best helping to achieve the goals with the least expenditure of funds. Depending on the stated goal(s), the land manager may wish to maximize effectiveness, minimize cost or maximize overall cost-effectiveness.

This paper will describe the use of cost-effectiveness as a tool to improve watershed rehabilitation practices. The examples used in the following pages are based on experiences and data accumulated over five years of rehabilitation for erosion control. The first section, describing controls on cost-effectiveness, and those on predicting and evaluating cost-effectiveness, are primarily taylored to the subject of erosion control. However, most of the discussions and techniques are broadly applicable to a wide range of management actions involving natural resources; especially where traditional cost-benefit analyses are not possible. The paper concludes with our current analysis of the cost-effectiveness of specific techniques and procedures used for controlling sediment production and sediment yield on logged lands in the park.

CONTROLS ON COST-EFFECTIVENESS

The controls on rehabilitation cost-effectiveness are derived from three principal sources. First, the goals of the program are of greatest overall importance in determining how cost-effectiveness will be measured and evaluated. The other two controls are, by definition, those factors which influence the effectiveness of treatments and work procedures, and those factors which determine project costs. The remainder of this section will describe the more important variables which influence each of the three controlling elements, especially as they relate to erosion control work at Redwood National Park.

Goals

The two fundamental goals of the park's watershed rehabilitation program are: 1) to restore the acquired area to a natural, self-functioning redwood forest ecosystem, and 2) to reduce accelerated erosion rates and sediment yields which continue to impact park resources (United States Department of Interior, 1981a). Although revegetation and restoration of the biological system are important elements of the program, primary emphasis has been placed on the reduction of accelerated sediment production and delivery. With this objective for the park's erosion control program, cost-effectiveness is measured, and techniques are evaluated, on the basis of treatment costs and the amount of sediment removed or prevented from entering active channels where it could be transported downstream. The measure of cost-effectiveness used in the park's program (and in this paper) is the unit cost-per-volume of sediment "saved" from sediment yield ($/yd^3) over a specified period of time[1].

Although the primary goals of any rehabilitation program may not vary through time, other factors will frequently control short-term objectives and thereby influence levels of cost-effectiveness. For example, in the park's program initial emphasis was necessarily placed on experimentation and development of new erosion control techniques at the potential expense of effectiveness (Madej, <u>et al</u>., 1980). As methods were developed and refined, the focus shifted to those critical areas where sources of accelerated erosion could be easily and inexpensively treated. In this manner, major sources of sediment were rapidly controlled or eliminated at a comparatively small cost. Currently, as the most cost-effective work is completed, rehabilitation efforts are concentrated on those features which remain significant sediment producers, yet may require greater costs to effectively control. As a consequence, costs may rise and cost-effectiveness may decrease substantially. Treatments in the future will be directed toward areas of potential accelerated sediment production (e.g. intact logging roads), and the objective will become one of erosion prevention rather than erosion control. In practice, erosion control work on a single rehabilitation unit in the park typically involves two or more of these elements simultaneously.

The dynamic nature of immediate goals in a long-term rehabilitation program sometimes makes cost-effectiveness evaluations most applicable to limited, short-term objectives. For example, in the park's program, the immediate goal of erosion-control technique-development temporarily supplanted the long range goal of minimizing increased sediment yield (Sonnevil and Weaver, 1982). Thus, in 1978, rehabilitation sites were selected to provide numerous opportunities for controlling a wide variety of erosional problems. As previously defined, cost-effectiveness during this experimental phase was not of overriding importance in determining work site locations or technical prescriptions for erosion control. Where objectives and other conditions do not change through

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[1] Other resource rehabilitation projects could measure cost-effectiveness in a number of ways. Depending upon the goal, these might include: $/ft^2 increase in spawning area or $/ft^2 increase in useable, summer fish-rearing habitat; $/planted shrub or tree surviving after some time interval; $/newly established and inhabited nesting site for some desirable bird species; among others.

time (as has been the case in the park program since 1979), technical improvements, increased efficiency and experience aid in improving effectiveness, decreasing costs and raising overall levels of cost-effectiveness.

Effectiveness

By definition, factors which influence the effectiveness of erosion control work also partially determine the cost-effectiveness of these techniques. Many treatments may show little or no change in their effectiveness through time (e.g. road outsloping, channel excavations, waterbars, rock armor). Other treatments, however, exhibit temporal variability that ultimately affects the effectiveness (and cost-effectiveness) of erosion control work. For example, successful revegetation will provide additional stability and protection to a disturbed site as the plants increase in size and number (Reed and Hektner, 1981). It thereby represents an erosion control treatment whose effectiveness increases through time. In areas where natural revegetation is hindered, planting a variety of native or stabilizing species may be ineffective for immediate or short-term erosion control, yet its effectiveness gradually increases through time, without the need for additional expenditure. This makes revegetation one of the most cost-effective long-term treatments. In direct contrast, some erosion control treatments tend to become less effective through time, especially mulches and structural devices such as wood check-dams, flumes, and water ladders. Even though these measures provide highly effective, immediate protection against accelerated erosion, their limited life-spans result in continuing maintenance costs and generally decreasing levels of effectiveness.

Rehabilitation treatments can be applied to account for these temporal changes. For example, at an excavated stream crossing, the sideslopes may be seeded or planted with coyote brush, alder, and conifer seedlings, and then covered with straw mulch. The bare, newly exposed channel can be check-dammed and inplanted with willow cuttings or alder seedlings along the bed and banks. In this fashion, straw and check dams should provide immediate protection against rilling and channel erosion. On the sideslopes, straw mulch will deteriorate over several years, but brush and/or willow and alder will grow to provide litter and direct groundcover. As they, in turn, reach the end of their life spans and begin to senesce, conifers will have reached a size where their foliage and root systems provide continually increasing protection. In the stream channel, properly designed and maintained check dams will continue to provide protection for years (Kelsey and Weaver, 1979). However, as they begin to deteriorate, the expanding root network of woody vegetation planted in and along the channel will have a compensating, stabilizing effect. Rapid or large adjustments of the restored stream channel can be avoided. These same techniques, applied individually, might provide negligible short-term protection (e.g., planting conifers) or provide little or no long-term benefits (e.g., straw mulch). The proper application of a combination of appropriate treatments can provide overall protection of essentially unchanging or increasing effectiveness.

In addition to changes in the effectiveness of erosion control work through time, the type and magnitude of erosion processes can also exert substantial control on the effectiveness (and cost-effectiveness) of watershed rehabilitation (e.g. see Kelsey, *et al.*, 1981). Some erosional processes (e.g. raindrop and sheet erosion) are highly amenable to treatment and effective control, yet their relative contribution to sediment production and yield may be minimal. On the other hand, deep-seated mass movement features, while perhaps contributing a proportionately larger quantity of sediment directly to the stream system, could require huge expenditures to treat. In many cases, these sediment sources may not even be controllable. Because of this, cost-effectiveness should not be the only management tool used to influence the decision-making process. Either cost or effectiveness may be of overriding importance depending on the importance, relative size and complexity of the delivery mechanisms.

Perhaps the greatest single factor determining the ultimate effectiveness (and cost-effectiveness) of watershed rehabilitation relates to the relative timing of the original land use or ground disturbance and the onset of erosion control activities (Kelsey, et al., 1981). A simplified, schematic representation of this concept is shown in Figure 1. Some erosion features may be so far advanced by the time treatment is contemplated that they are either beyond one's ability to effectively treat or they are no longer generating significant quantities of sediment. For example, in the Copper Creek drainage basin, eight years after logging, nearly 50 percent of the gully systems were no longer active (Weaver, et al., 1982). Those gullies which still carried their channel-forming discharges were probably yielding sediment at only a fraction of the initial rate following management-related disturbance.

Depending on the timing of major storms, if roads are not maintained, and cutover hillslopes and erosional features in the park are allowed to remain untreated for long periods of time (approximately 10-20 years), the disturbance to soil and newly established vegetation caused by rehabilitation activities could potentially outweigh the benefits derived from these erosion control efforts (Figure 1). This results from rapid revegetation and a rapid rise, and then decline, in rates of elevated fluvial sediment production following timber harvest and road construction in the coastal region of northern California. Where logging roads could continue to cause stream diversions and consequent gullying in the park, treatment benefits may still outweigh impacts for several decades. For these reasons, it is critical either to plan and conduct land-use practices in a fashion to strictly minimize subsequent erosion, or to initiate rehabilitation and erosion control work immediately upon completion of operations. In this manner, treatment costs can be substantially reduced and the bulk of erosion may be altogether avoided (Figure 1).

Costs

Unlike factors which control the effectiveness of rehabilitation work, those elements which influence costs are more amenable to quantification and manipulation. In practice, realistic project objectives are frequently developed only after available financial resources have been determined. The stated program goal(s) indirectly assign a desired minimum level of erosion control protection the land manager is willing to accept. Specific objectives to work towards the goal(s), as well as the intensity of work activity, are then established in relationship to the funding available. Such goals could include the revegetation of all bare soil areas, a measurable increase in suitable fish spawning habitat, a reduction of accelerated erosion rates, decreased sediment yields, improved stream-bank and stream-bed stability, or a complete return to pre-disturbance conditions, among others. Successfully attaining these end results involves and requires the employment of a variety of different techniques, intensities of effort and monetary expenditures.

Several other considerations which directly affect the cost of rehabilitation work include: 1) the magnitude of indirect costs (access, administrative overhead, profit, supplies and materials, etc.) which do not specifically result in attainment of objectives but which represent unavoidable costs; 2) subjective professional judgment used to outline the problems and the desired methods of rehabilitation; and 3) in the case of erosion control work, the size or intensity of hydrologic event which treatments, structures and excavations are designed to successfully withstand.

Under some circumstances, indirect costs can become prohibitively large. Depending on the method of contracting, costs not directly involved with on-site labor and heavy-equipment erosion control work can exceed 50 percent of total rehabilitation expenditures for an area (Kelsey and Stroud, 1981). Similarly, but on a smaller scale, re-opening abandoned road systems to treat continuing erosion problems along or adjacent to the roads can also increase costs and have an adverse impact on the cost-effectiveness of the overall effort.

Errors or differences in professional judgment (generally the result of a lack of relevent experience) can also result in rapid cost escalations which thereby significantly reduce rehabilitation cost-effectiveness. For example, in 1977, and to a lesser extent in 1978, project supervisors in the park perceived surface erosion to be a critical problem on rehabilitation sites. Extensive treatments were applied to control this source of soil loss (Madej, et al., 1980). In actuality, after close measurement and subsequent field observations it was not found to be as significant a process as originally thought (Weaver and Seltenrich, 1981). While the treatments may have been effective, they were also of very low cost-effectiveness ($/yd^3 "saved").

Other professional judgments applied during field operations can also affect levels of cost-effectiveness. For example, the use of drag-line cranes or hydraulic excavators to perform stream-crossing excavations may be needlessly expensive if the same jobs could be done with equal effectiveness and at a lower cost by more efficient machinery (e.g. bulldozers). Similarly, most stream crossings in the park, if excavated with 30 percent channel sideslopes, show few, if any, post-rehabilitation slope-stability problems. However, if the sideslopes would have been equally as stable at 50 percent steepness, significantly less soil could have been excavated at no measurable loss of effectiveness. Reductions in cost-effectiveness attributable to errors in professional judgment can be largely eliminated through increased experience, and regular and repeated peer review conducted before, during and after field operations.

Due to the nature of physical and meterologic processes in north-coastal California, and high rates of sediment production and yield, the ultimate test of erosion control effectiveness is the large hydrologic event. To account for this, treatments must be designed to accommodate geomorphically relevant flows while still minimizing project expenditures. In the park, channel protection devices and stream channel excavations are currently constructed to withstand the calculated 20-year return period runoff event.

Significant increases in costs commonly associated with small increases in treatment design standards or minor improvements in effectiveness will lower rehabilitation cost-effectiveness. For example, 1500 cubic yards of fill might be excavated from a stream crossing at a total cost of $5,500. Assuming that all 1500 cubic yards would have been eroded if the crossing had not been treated, the cost-effectiveness of this excavation was $3.70 per cubic yard. To stabilize the new channel and prevent local downcutting and bank erosion, rock armor or check dams can then be placed in the stream bed. To prevent an estimated additional loss of 100 cubic yards, $2,500 might be spent on this protective treatment. The comparable unit cost (cost-effectiveness) is then $25 per cubic yard "saved" from erosion. Clearly, the added protection is accomplished at significantly reduced levels of cost-effectiveness. The decision to pursue such costly measures depends on a number of factors including, but not limited to, the nature of downstream or on-site resources being protected. In the park such decisions are not strictly based on quantitative determinations of cost-effectiveness ($\$/yd^3$). A number of factors are evaluated prior to intiating erosion control work. These are listed and discussed in the following section.

PREDICTING COST-EFFECTIVENESS

Areas which display advanced erosion problems may have evolved to the point where erosion control work is no longer justified (e.g. see Figure 1). It is important, therefore, to predict or estimate the cost-effectiveness of rehabilitation work before it is conducted. In this way, the greatest results can be achieved with the available funds. Areas which have progressed beyond cost-effective treatment can also be objectively recognized.

The prediction process involves five basic steps. They include: 1) delineating active versus inactive erosion features; 2) identifying potential sources of future erosion; 3) defining those problems which are technically treatable; 4) delineating those active or potential erosion sources which are accessible by heavy equipment, or whatever tools are needed to treat the problems; and 5) estimating the cost-effectiveness of the proposed treatments. The listed order of these steps is one which logically follows the intensive geomorphic mapping and erosion inventory which must precede rehabilitation. Of the currently active or potential erosion sources identified in a watershed, it is likely that only a fraction of these will be both accessible and controllable, and many may no longer be cost-effectively treated.

In erosion control work, prior determination of cost-effectiveness and the decision whether or not to treat an area hinges on an evaluation of: 1) the potential volume of sediment to be lost to erosion; 2) the probability of occurrence for this sediment release; 3) the expected rate of delivery or amortization period over which soil loss would occur; 4) the expected delivery ratio (the ratio of sediment yield to sediment production); and finally, 5) the cost associated with access and effective treatment. Although many of these factors can only be subjectively and qualitatively determined for many sites, recognition of their importance and usefulness in predicting the cost-effectiveness of proposed erosion control work is paramount to making educated decisions and defensible plans for watershed rehabilitation.

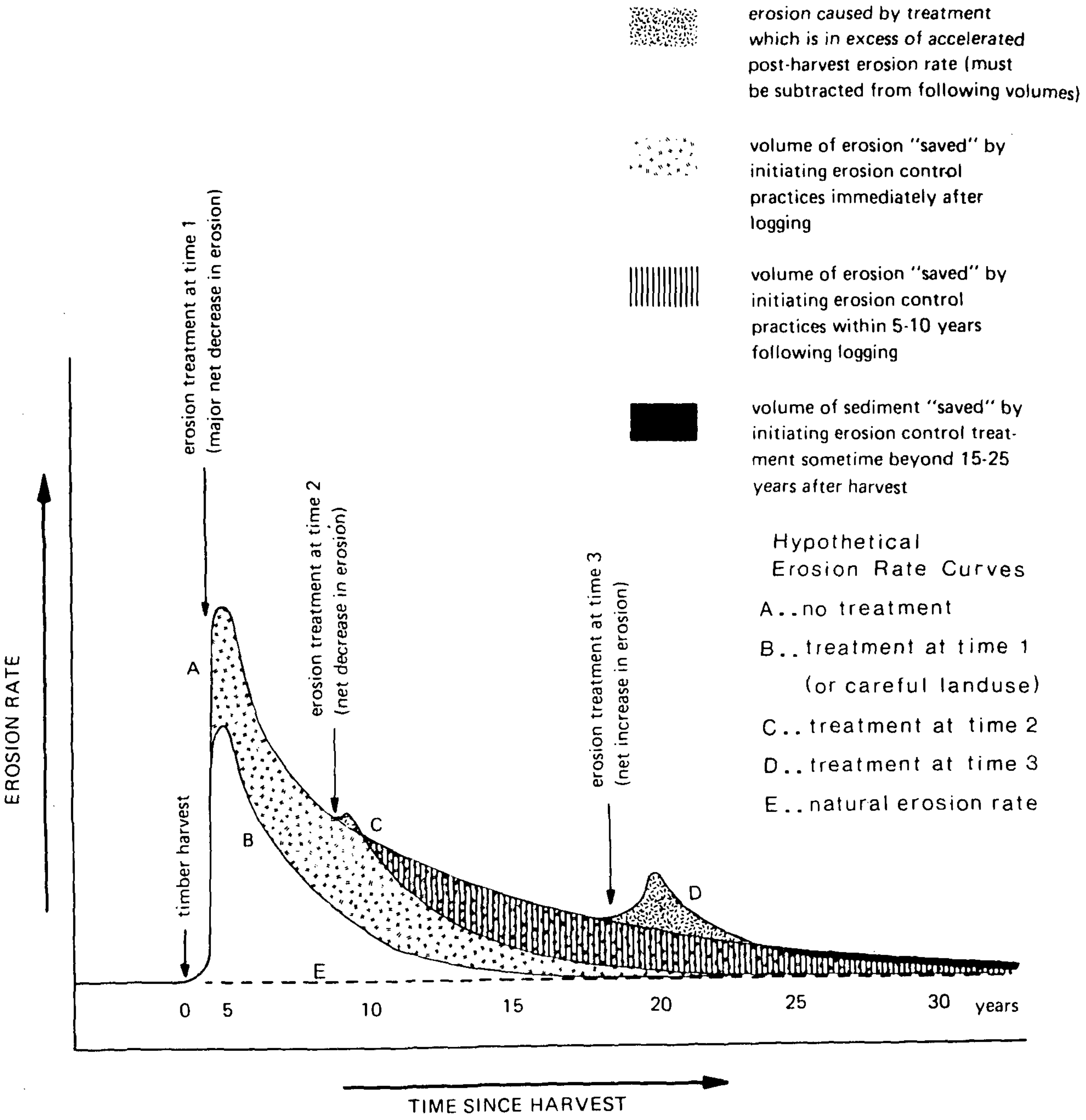

Figure 1. Schematic representation of fluvial erosion rates as affected by erosion control. Diagram is simplified for illustrative purposes. It excludes such factors as the effect of major storms and the delayed occurrence of mass movement processes following timber harvest. All else constant, the greatest rates of post-harvest erosion are expected in the first five years following land use. Time scale is included only for general reference. Depending upon erosional processes, climatic conditions and land use history, each area will display unique sediment yield curves.

On most erosion control work-sites in the park, "erosion potentials" are calculated and cost estimates are made to provide a pre-work estimate of cost-effectiveness. For example, at skid-trail and logging road stream crossings, the potential volume of sediment which could be eroded is determined by graphically reconstructing original channel sideslopes and the configuration of the pre-logging stream profile (depth to thalweg). The assumption is made that, eventually, all material contained in a fill crossing will be eroded and carried downstream. Subjective evaluations are also made to show which crossings have a distinct probability of causing future stream diversions (e.g., through culvert plugging) and developing hillslope gully systems. As a preventive measure, crossings which show a potential for diverting streamflow are routinely excavated.

While it is certian that material introduced into an active stream channel will eventually be eroded and moved downstream, the rate of material transport is highly variable. In the park, factors used to evaluate this rate include: 1) the amount (percentage) of the fill which has already been lost to erosion; 2) the magnitude of storms and runoff events (discharge) which have occurred on the site since the fill was emplaced; 3) the calculated, 20-year return-period discharge at the crossing site; 4) channel geometry and 5) the condition of other fill-crossings upstream and downstream within the same channel or in nearby streams. These "indicators" are used to estimate the residence time of the fill material. The same observations, with a close look at current and potential sediment storage sites in downstream reaches, allow a good estimation of the sediment delivery ratio to be expected over various time frames. On potential hillslope or logging-road work-sites located at some distance from active streams, estimated delivery ratios drop significantly and become an important consideration in cost-effectiveness predictions.

The final step, predicting cost-effectiveness, requires an accurate estimate of project costs, including the expenses of accessing the work site and effectively treating the erosion problems. Contractors can provide valuable assistance in determining proper types of earth-moving equipment, suggesting approaches to specific tasks and estimating job costs. Labor costs for various erosion control practices can be derived from literature reviews or estimated on the basis of sample applications on nearby areas. If carefully documented, previous work can be an invaluable tool for assessing future treatment costs (e.g. Bundros, et al., 1982; Teti, 1982). In the park, the ultimate decision to proceed on a project or a particular work site is generally based on an objective analysis of the expected costs, the potential for future erosion and sediment yield and the probability for successful control or prevention. Quantifying these factors for the purposes of predicting cost-effectiveness is an important part of assuring successful and efficient erosion control work.

EVALUATING COST-EFFECTIVENESS

Post-rehabilitation evaluation of completed work is the greatest available tool for improving the effectiveness and cost-effectiveness of general approaches and specific techniques for erosion control. For maximum benefit, it is thus critical to maintain detailed accounting of work performance and costs during every readily distinguishable phase or element of a project. During the heavy equipment phase of rehabilitation work in the park, project supervisors keep hourly and daily records of where work is being done, the pieces of equipment used, the job tasks (e.g., outsloping, waterbar construction, etc.), the rate work is completed (e.g., ft/day, yd^3/hr, etc.), the cost of each task (e.g., $/$yd^3$), and overall task performance and quality (see Bundros, 1980; Hagans, 1980; Teti, 1981; Spreiter and Johnson, 1981; Wosika, 1981). These detailed records are used to determine the pieces or combinations of equipment which are most cost-effective for each task and the operators who are most adept at this work.

Similarly, work and cost documentation are integral parts of all labor-intensive rehabilitation work performed in the park (e.g. United States Department of Interior, 1981b). Each labor contract contains a bid item which requires the contractor to keep accurate work records on forms provided by the park. Each task is broken down into as many component parts as are needed to clearly delineate actual unit expenditures. Unit bid prices (e.g., $/check dam) are not always considered valid indicators of actual costs to complete the various tasks. They are estimates which typically involve a variety of other complicating factors.

The most useful tools for evaluating the effectiveness of work procedures and erosion control techniques are those derived from field data and experience. Repeated photo-documentation, written notes and sketches based on field observations collected during storms and periods of high runoff, and group discussions and recommendations generated during organized peer review sessions are methods of evaluation which commonly result in changes in operating procedures. Technical changes in erosion control work generally evolve in response to a quantitative evaluation of physical processes. Techniques which have been used to measure erosion and evaluate the physical effectiveness of erosion control work in the park are straight-forward and numerous. For example, surface erosion on treated and untreated sites has been documented through various techniques including detailed hillslope cross-sections, grids of erosion pins, and rainfall-runoff/erosion plots involving the use of sediment collection troughs. Pre- and post-rehabilitation channel erosion is measured with detailed cross-sections and longitudinal profiles, accurate morphologic maps and winter-storm sediment sampling. Additionally, detailed checklists have been used to document the effectiveness of measures used to prevent or control both hillslope and channel erosion. Accurate topographic surveys, stake lines, groundwater wells, piezometers and detailed mapping have been used to monitor the response of mass movement features to rehabilitation and other environmental controls.

A modest program designed to measure the absolute or relative effectiveness of various procedures and techniques can pay for itself many times over. In the Redwood National Park rehabilitation program, less than five percent of the total budget is allocated to an evaluation program, yet the results of monitoring costs and effectiveness have provided a substantive basis for making major changes in the direction, approach and details of on-the-ground restoration over the last three years (Sonnevil and Weaver, 1982; Hektner et al., 1982).

RELATIVE COST-EFFECTIVENESS OF REHABILITATION WORK AT REDWOOD NATIONAL PARK

Erosion control work in Redwood National Park is divided into primary and secondary treatments. Those elements designed to provide for the immediate reduction of management-caused sediment production or yield are considered primary treatments. They are most closely associated with the ultimate objectives of erosion control and landscape rehabilitation. Most primary erosion control practices used in the park from 1978 to 1980 were accomplished at a cost-effectiveness of from one to ten dollars per cubic yard ($/yd^3) of sediment removed or prevented from entering local channels and being transported downstream (Table 1).

Disregarding the fact that the sources of increased erosion are associated with a variety of failure probabilities and subsequent delivery ratios, the cost-effectiveness of treating these erosion problems can vary over a range of two orders of magnitude, or more. For example, by excavating fill-crossings on natural stream channels, each cubic yard physically removed represents an equal volume saved from future erosion and sediment yield. However, in diverting streams out of rapidly eroding gullies and back into their natural channels, each cubic yard excavated at the diversion point could ultimately result in 10, 100 or more times the savings in potential future erosion that might have been generated by the untreated, active gully system. Large, rapidly eroding gully systems can be totally dewatered through simple, comparatively inexpensive excavations at the source of the diversion (Teti, 1982). It may also be technically possible to treat some large landslides at cost-effectiveness levels better than $1 - $10 per cubic yard. However, stabilization is typically difficult and/or prohibitively expensive regardless of overall cost-effectiveness.

Secondary erosion control practices are those designed to minimize erosion from areas disturbed during primary treatment. They typically consist of a variety of labor-intensive erosion control and revegetation techniques, as well as heavy equipment work needed to transport and place channel armor. A listing of average costs and the range of relative cost-effectiveness of secondary erosion control techniques used in Redwood National Park is shown in Table 2 and Table 3. Perhaps the most important information to be gleaned from these tables, in comparison to each other and to Table 1, are the relative ranges of cost-effectiveness. Primary erosion control techniques used in the park are from one to three orders of magnitude more cost-effective than secondary treatments, except where the primary work done was of inherently lower cost-effectiveness. Similarly, on logged lands in Redwood National Park, secondary treatments used to control channel erosion (Table 2) are generally much more cost-effective than treatments to control surface erosion (Table 3). This difference reflects the greater importance and contribution of erosion from post-rehabilitation channel scour and adjustment as compared to surficial soil loss from bare areas.

It is significant to note that even among methods designed to treat similar erosion problems (e.g., sheet or rill erosion), there may be well over an order of magnitude difference in their relative cost-effectiveness (Table 3). This usually arises from large variations in the cost of application rather than major differences in effectiveness. For example, in the park, straw mulch and jute-secured straw mulch have provided comparable protection to bare slopes under 70 percent in steepness. However, the high cost of installing jute makes this a much less cost-effective treatment. By definition, maximizing cost-effectiveness entails a trade-off between maximum effectiveness and minimum cost. In addressing erosion control problems, it must be recognized that maximizing cost-effectiveness may result in unwarranted compromises.

Table 1. Cost-effectiveness of primary erosion control treatments used to prevent or minimize sediment production and yield in Redwood National Park, 1978-1980.

Treatment	Average Cost Paid in Park ($)(1)*	Cost-Effectiveness Range ($/yd^3 "saved")(2)
Road ripping (decompaction)	350-450/mi	unquantified(3)
Construction of cross-road drains (4)	1000-3000/mi	unquantified(5)
Waterbar construction on skid-trails		
machine constructed	5-50 ea (6)	unquantified(5)
hand-labor constructed	30-300 ea (7)	unquantified(5)
Forest road outsloping for erosion control (8)	2500-9500/mi(9)	1-10(10)
Prairie road outsloping	~7000/mi(11)	unquantified(12)
Excacavation of skid-trail stream crossings	125-1350 ea(13)	1-10(10)
Excavation of logging road stream crossings (14)		
under 750 cubic yards	~2000 ea	1-10(10)
750-1500 cubic yards	3000-3500 ea	1-10(10)
those requiring endhauling	~4000 ea	1-10(10)
Rediversion of stream flow from gullies back into natural stream channels	125-4000 ea(15)	0.1-0.5(16)
Gully stabilization(17)	variable	variable
Prairie gully obliteration	variable	unquantified(12)
Removal of perched debris from the perimeter of yarder pads and cable landings	1000-5000 ea(8)	1-10(10)
Large landslide excavations(18)	20000-30000 ea(19)	1-10(10)(20)

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*see succeeding page for footnote explanations

Footnotes to Table 1:

1. Cost based on 1978, 1979 and 1980 unpublished data. "Average" depends on site conditions.

2. Primary goal of Redwood National Park program is to minimize management-related sediment production and yield (i.e., to "save" soil from moving into stream channel systems and, eventually, downstream); no time frame for the eventual occurrence of the erosion has been specified for these calculations although complete loss is anticipated over a period from one decade, or less, to one century. Cost-effectiveness calculation assumes total loss, without reference to time.

3. Treatment results in increased rate of revegetation and reduced surface runoff, and produces an unknown decrease in road surface, ditch, gully, and downslope stream channel erosion. Road fill failures are also reduced by an unknown quantity.

4. Assumes construction every 150 feet, on average; cost range dependent on type of equipment (tractor, backhoe and hydraulic excavator, in order of increasing unit costs)

5. Treatment results in reduced concentration of surface runoff and an unknown reduction in road surface, ditch and gully erosion from adjacent hillslopes.

6. Tractor-constructed waterbars, $5 to $20 each; backhoe-constructed waterbars, from $5 each for areas with good access and requiring little travel time between work sites, to $50 each where access is poor (e.g., on steep slopes) and results in high travel time.

7. Average cost was $60 each; range dependent on length and substrate hardness at each waterbar location.

8. Costs depend upon the concentration of organic debris and the amount of endhauling required; generally, up to 75 percent of the cost may be in debris removal while the remaining 25 percent is taken up by actual outsloping of the landing.

9. Narrow roads using only tractor, $2500/mi; narrow roads using tractor and backhoe, $3000-$4000/mi; roads across moderately steep terrain using tractor and hydraulic excavator, $5000-$7750/mi; roads built across steep, unstable ground using a dragline crane and tractor, with some endhauling required, up to $9500/mi (all figures include ripping costs, but do not include the expense of stream crossing excavations).

10. Assumes sediment production would have occurred had the excavation not been performed, and that erosion would have been translated into sediment yield in adjacent stream channel systems. Does not include benefits realized from preventing future stream diversions, and associated gully erosion, which might have occurred without treatment.

11. Full outsloping utilized tractor and hydraulic excavator.

12. The dual goals of rehabilitation on prairie or grassland areas include: (1) erosion control and prevention, and (2) scenic or site restoration of a high visitor-use area; thus the measure of cost-effectiveness used in this table does not apply.

13. Costs dependent upon site accessibility; $\bar{x}$ = $400 for tractor and backhoe combination; $\bar{x}$ = $300 for tractor and excavator tandum.

14. Excavations primarily performed by tractor and hydraulic excavator; some completed with drag-line crane.

15. Cost of re-diversion is typically associated with stream crossing excavation at point of diversion.

16. Assumes diverted stream flow would continue to cause increased erosion and had not yet formed a stable, non-eroding channel. Results derived from Teti (1982), Weaver et al. (1982) and unpublished Redwood National Park data.

17. Treatments include armoring, check dams, bank protection and gully headcut stabilization. Costs and cost-effectiveness dependent on type and extent of treatments applied, their effectiveness, and the expected rate of erosion had the erosion control work not been accomplished (see also Table 3 for a more detailed discussion of the cost-effectiveness of these methods).

18. Streamside landslides in the size class of 60,000 to 100,000 cubic yards, of which approximately 4500 to 7000 cubic yards (7%) are excavated from the crown region. Other remedial measures may also be employed on a site-specific basis, but those figures are not included in this analysis.

19 Cost includes endhauling a short distance to a local storage area (0.25 mile).

20. Assumes a one-to-one soil loss potential; that is, each cubic yard of material excavated from the slide mass is considered one cubic yard "saved" from eventual delivery to an adjacent stream channel.

Table 2. Cost-effectiveness of secondary erosion control treatments used in Redwood National Park to minimize or eliminate short-term post-rehabilitation channel scour(1)

Channel Treatment(2)	Cost-Effectiveness Range(3) ($\$/\mathrm{yd}^3$ "saved")	Comments
Water ladders(4)	20-70(5)	for short reaches
Brush check-dams(6)	10-30(7)	short lived; for small gullies
Small board check-dams(4)	10-30(8)	highly effective;may require maintenance
Large board check-dams(9)	30-50(10)	very expensive; require maintenance
Hand-placed rock armor(6)	20-70(11)	limited to small channels; low flows
Machine-placed rock armor	10-50(12)	very effective; requires good access

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1. In certain circumstances, these techniques may also be considered primary treatments. In the park, they are typically employed at excavated skid-trail and logging-road stream crossings.
2. The treatments listed here are not interchangeable; each technique is best suited to a particular situation. Thus, treatments are not directly comparable in terms of cost-effectiveness.
3. Assumes treatment is 100% effective; most methods provide 60% to 90% effectiveness in the first year of average rainfall, and a reduced effectiveness with time (with the possible exception of machine-placed rock armor). Cost-effectiveness would therefore be somewhat lower than that listed (i.e. higher $\$/\mathrm{yd}^3$ value). Figures refer to first year cost-effectiveness.
4. As used in the park, structures work best when confined to channels which carry a 20-year peak discharge of 6 cfs, or less.
5. Average cost=$700 (1978 data) for 30 ft. structure; erosion prevented = 10-40 yds^3. A more cost-effective treatment would be to excavate a small channel.
6. As used in the park, treatments work best with flows of 2 cfs, or less. Brush dams used mostly in narrow gullies, not in excavated stream crossings.
7. Treatment cost for 60 ft. channel (9 dams) = $135.(1981 wage rates); erosion prevented = 5-20 yds^3.
8. Average cost for a 60 ft. channel (9 dams) = $320.(1978-1979 data); erosion prevented = 10-40 yds^3.
9. As used in the park, large-board dams work best when used on channels which carry a 20-year peak discharge of 20-30 cfs, or less.
10. Average cost to treat a 200 ft. channel = $9450. (13 dams on a 1980 work site; includes first year maintenance costs); erosion prevented = 200-300 yds^3, based on nearby untreated crossings.
11. Average cost to armor a 60 ft. channel = $370. (1978-1979 data); erosion prevented = 5-20 yds^3. Cost assumes rock is available on-site.
12. 1980 cost to rock a large, 275 ft. channel = $4180.(includes blasting and rock delivery; size = 6-18 in.); erosion prevented = 200-300 yds^3. Mean cost to treat 12 crossings (avg.65 ft long) = $530.; erosion prevented = 10-40 yds^3.

Table 3. Cost-effectiveness of secondary treatments used to control surface erosion in Redwood National Park.

Slope Treatment	Mean Cost (1) ($/10,000ft^2)	Cost-Effectiveness (2) (3) ($/yd^3 "saved")	Relative Effectiveness (4) (1 = most effective)
Contour trenches (5)	430	40-80	6
Wooded terraces (5)	590	60-120	9
Wattles (5)	2500	250-500	10
Ravel catchers	668	70-140	7
Grass seed with fertilizer	99	10-20	8
Hydroseed	600	60-120	4
Straw mulch (6)	180	20-40	3
Jute-secured straw mulch (7)	2360	240-480	1 (8)
Excelsior blankets (7)	1970 (9)	200-400	1 (8)
Wood chips (5)	950	100-200	5

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1. Based on 1978 and 1979 data.
2. Computations based on treating a 100-foot-long stream crossing excavation with bare, 50-foot-long side-slopes at a 50% gradient (total area = 10,000 ft^2). Volume of erosion from this area is assumed to be 5 to 10 yds^3 (all of which leaves the slopes and enters the adjacent stream channel system) until living ground cover is established. These figures are well in excess of erosion rates measured from plot and trough studies from similar settings within the park and produces conservative or "better-than-probable" values of cost-effectiveness.
3. Assumes treatment is 100% effective. Most methods have been shown by independent tests to be from 30% to 80% effective in the first year. Cost-effectiveness would not be expected to be as good as indicated.
4. As measured in plot studies or as inventoried on rehabilitation sites.
5. Use of this method was discontinued in 1979.
6. Dominant treatment used to control surface erosion, 1980 to present.
7. Dominant treatments used to control surface erosion on steep slopes (over 70%), 1980 to present.
8. Jute-secured straw and excelsior blankets are of roughly equal effectiveness.
9. Based on 1980 purchase data and 1979 installation costs.

Some techniques may be only marginally effective yet their cost-effectiveness is high. Grass seeding, an inexpensive erosion control treatment, is one such example (Weaver and Seltenrich, 1981). If the objective is controlling surface erosion, a slightly more effective, less cost-effective method could be chosen (e.g. straw mulch). Likewise, jute-secured straw mulch may be the most cost-effective technique in circumstances where other treatments provide an unacceptably low level of effectiveness (e.g. on slopes steeper than 70 percent; see Weaver and Seltenrich, 1981).

In general, secondary treatments are characterized by one or more factors which significantly limits their ultimate cost-effectiveness. They include: (1) the volume of potential erosion being prevented is usually small when compared to the volume treated during primary or heavy equipment rehabilitation work; (2) by nature, the total cost of a task performed by manual labor can be extremely high when compared to costs for performing the same types of work with machines; and (3) the products of labor techniques are commonly plagued by either limited life-spans, limited capacity or resiliency or, in the case of revegetation, delayed effectiveness. If program objectives demand short-, immediate-, and long-term protection, such practices can be justified. If short-term increases in sediment production would endanger downstream riparian or aquatic resources in need of protection, then labor-intensive treatments are essential (Teti, 1982). However, if ultimate concerns are only focused on the long-term reduction of accelerated sediment yields, many of the secondary treatments listed in Tables 2 and 3 would not be cost-effective.

Other factors have significantly affected the costs and, hence, cost-effectiveness of primary and secondary treatments used in the park. An unskilled or inefficient heavy equipment operater can more than double the price of stream channel excavations. Similarily, the selection of an improper piece of earth-moving machinery for any given job can result in cost increases of over 50 percent. An example is the utilization of a hydraulic excavator or backhoe in instances where a crawler tractor could perform the same task at a cheaper rate and in a shorter time period. Recognition and timely correction of inefficient procedures is dependent on the experience and ability of the project coordinator, and is enhanced by a system of technical peer review.

The cost-effectiveness of labor-intensive work is primarily controlled by: (1) the selection of proper techniques designed to treat the actual (as opposed to perceived) erosion problems; and (2) the method of accomplishing the work (contracts, in-house labor, etc.). Initially, surface erosion from park lands was perceived to represent a significant source of increased sediment yield and wattles were judged to be an appropriate treatment for bare soil areas (Madej, et al., 1980). However, quantitative studies and detailed field observations soon revealed surface erosion to be far less significant than channel or gully erosion, and wattling to be far more costly and less effective than a variety of other techniques available to treat sheet and rill erosion (Weaver and Seltenrich, 1981). Cost-effectiveness can be optimized by ensuring that: (1) each manageable erosion process is treated in relation to its actual importance in affecting sediment yield; and (2) both cost and effectiveness considerations are quantitatively evaluated in light of the variety of techniques available to treat each problem. Technique selection, which dictates both the overall level of cost and the effectiveness with which erosion is controlled, is based on professional judgement and experience. Utilization of the best available information on erosion processes and erosion control techniques, quantification of erosion potentials, and a critical field-review of proposed work elements by peers or experienced practitioners are the best methods to minimize the inclusion of unnecessary, ineffective and typically expensive procedures (Sonnevil and Weaver, 1982).

Labor costs, the second major factor affecting the cost-effectiveness of labor-intensive erosion control work, can represent a large percentage of watershed rehabilitation expenditures. On four 50-acre to 200-acre cutover areas treated in 1978 and 1979, labor costs alone ranged from $20,000 to over $80,000 each and comprised from 75 percent to 95 percent of the total project cost (Madej et al., 1980; Kelsey and Stroud, 1981). Four methods have been used to complete labor work in the park (Sonnevil and Weaver, 1982). In order of increasing cost-effectiveness, they are: (1) request for proposal (RFP),cost-reimbursement contract; (2) request for proposal (RFP),fixed price service contract; (3) direct labor hiring (if done on a temporary or part-time basis); and (4) invitation for bid (IFB),fixed price service contract. Although the incentive to do a rapid, inexpensive, and effective job is greatest with the competitively bid, IFB, fixed price service contract; administrative delays and legal requirements can sometimes make their use impractical when erosion control work must be completed prior to the commencement of winter rains. Hiring a part-time labor force allows the application of secondary treatments immediately following heavy equipment operations. However, the need for training and a comparatively lesser incentive to maximize work efficiency can increase the costs of this method. Thus, in-house labor must be temporary, well trained and well supervised or motivated to be cost-effective.

SUMMARY AND CONCLUSION

A number of factors have affected the cost-effectiveness of erosion control work conducted at Redwood National Park. Here, as elsewhere, cost-effectiveness can only be evaluated in terms of achieving clearly defined objectives within the framework of overall program goals and available funds. Controls on cost-effectiveness have been shown to depend upon the static or dynamic nature of short-term objectives and long-term goals, the mechanisms and "controlability" of sediment sources, and a variety of factors which show variation through time. These include the protection provided by revegetation and structural erosion control measures, and rates of post-disturbance sediment production and yield. Erosion control treatments can be selectively prescribed to provide short-, intermediate- and long-term protection to a site. Applications which ignore any of these time frames may fall short of meeting the primary objectives.

Prevention is clearly the least costly and most effective method for minimizing increased erosion and sediment yield. However, where corrective work is needed, quantitative predictions of erosion control cost-effectiveness can result in significant savings. Only those projects which can be completed within acceptable levels of cost and with beneficial results need be carried out. Cost-effectiveness calculations used in the park's program allow short-term comparisons between measures as widely divergent as the dewatering of gully systems, stream channel excavations, channel armoring, check damming, mulching and wattling.

Evaluations of the cost-effectiveness of specific primary and secondary treatments used in Redwood National Park show in excess of three orders of magnitude potential difference between the various techniques. Due to this large variation, extra efforts are now taken on park projects to complete the cost-effective primary treatments to the fullest extent possible. This reduces the amount of secondary protection needed to attain maximum overall cost-effectiveness. In many cases, adequate primary treatment may actually obviate the need for further protection at little or no loss of effectiveness.

Work at the park has shown that a successful erosion control program requires a rigorous evaluation and monitoring program which continually feeds information and findings back into ongoing rehabilitation work. Acceptable levels of cost-effectiveness can only be assured through the quantitative documentation of erosion processes and erosion control effectiveness. Accurate, detailed accounting of procedures, work elements and associated unit costs can then be used to establish the cost-effectiveness of watershed rehabilitation for erosion control.

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