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Geomorphic design and management of disturbed lands

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ABSTRACT Everyday human activities result in a wide variety of land disturbances. Some of these are inevitable, while others are merely convenient and lead to unnecessary environmental degradation. Regardless of the type of disturbance, it is proposed that each type can be evaluated in terms of three factors: (1) areal extent, (2) intensity, and (3) duration. Ultimately, society must render a judgment concerning the perceived severity and acceptability of a given disturbance and its impact.

The goal in design of a landscape for a disturbed area is to mitigate environmental impacts and re-establish dynamic equilibrium within the geomorphic system. The design of the landscape involves three phases: (1) analysis of existing environmental conditions, (2) formulation of a reclamation program, and (3) program implementation. The science of geomorphology is of powerful assistance, not only in the design of reclamation programs but in the evaluation of past reclamation successes and failures.

INTRODUCTION

There has evolved a growing awareness throughout the world of the human capacity for environmental destruction during the past few decades. Members of numerous disciplines within the earth sciences have mustered their expertise and directed their effort toward the documentation of the causes and consequences of land disturbances. More recently, their research has been called upon to provide the foundation for effective reclamation activities. It is the purpose of this paper to briefly discuss the contribution of one earth science, geomorphology, in the design and management of disturbed lands. It is recognized at the outset that this discipline draws upon other disciplines, such as atmospheric science, civil engineering, geology, hydrology, and soil science, in the development of its theory and practice.

EVALUATION OF DISTURBANCE

It is proposed that land disturbance may be rationally evaluated in terms of three factors: (1) areal extent, (2) intensity, and (3) duration. A geomorphic evaluation of disturbance is commonly process-oriented. Because accelerated erosion is usually a consequence of disturbance (Toy, 1982) and erosion control is central to the mission of reclamation (Toy, 1984), such an appraisal would examine the area over which erosion rates are accelerated, the extent to which they are accelerated, and the span of time during which they are accelerated. Each factor can then be assessed with some objectivity, and quantified in most cases. Ultimately, however, society must render a judgement concerning the perceived severity and acceptability of a given disturbance and constitutes a collective decision regarding its necessity, if not acceptability.

Table 1 summarizes a general assessment of environmental impact resulting from various types of land disturbances described in detail by Toy & Hadley (1987). If this evaluation is generally valid, then it appears that in the United States, at least, public perception and concern focus upon the intensity of disturbance while often ignoring the areal extent and duration. Certainly, the impact of grazing and other forms of agriculture has not produced the national outcry caused by surface mining.

Table 1 An assessment of environmental impact due to various land disturbance

Type of disturbance	Areal extent[1]	Intensity[2]	Duration[3]
Grazing	Large	Low	Long
Recreational vehicles	Small	High	Moderate
Surface mining/coal	Small	High	Short
Surface mining/uranium	Small	High	Short
Construction	Moderate	High	Short

(Source: Toy & Hadley, 1987)

[1] Areal extent: Small < $100 km^2$; moderate $100-500 km^2$; large > $500 km^2$.

[2] Intensity: Low, less than or equal to a two-fold increase in process rate; moderate, 2-10 fold increase; high, more than 10 fold increase.

[3] Duration: Short, few months to a few years; moderate, several decades; long > 100 years.

GEOMORPHIC DESIGN OF LANDSCAPES FOR DISTURBED AREAS

Geomorphic research has established a number of fundamental concepts that guide landscape design. First, the Earth's land surface is composed of a nested hierarchy of drainage basins that function as open, process-response systems with both positive and negative feed-back mechanisms (Chorley & Kennedy, 1971) and possessing both intrinsic and extrinsic thresholds (Schumm, 1973). These systems operate to create and maintain dynamic equilibrium. Disturbance to the system commonly results in a series of reactions or adjustments, collectively known as "complex response," and is the direct consequence of the integrated nature of the system. One adjustment toward the re-creation of dynamic equilibrium begets another and another, until several waves of change have passed through the system and an approximate balance between forces and resistances again prevail (Toy and Hadley, 1987).

The goal of geomorphic landscape design for disturbed areas is the re-establishment of dynamic equilibrium within the geomorphic system, and thereby, mitigation of environmental impacts. Three phases are involved in landscape design: (1) analysis of existing and probable or possible environmental conditions, (2) formulation of a reclamation program, and (3) implementation of the program. Following reclamation, the rates of geomorphic processes may be monitored on the disturbed site and management or remedial measures may be recommended.

Analysis of environmental conditions

Geomorphic process rates are a function of the environmental setting in which the processes are operating. The site characteristics of climate, geology, topography, soils, and vegetation cover determine the forces and resistances occurring on any land surface. Mathematical models commonly utilize these characteristics in some form as variables to estimate process rates. Sometimes, it is easier and more accurate to directly measure the process rates in the field.

Complete geomorphic analysis of environmental conditions should consider three time periods: (1) predisturbance, (2) active disturbance, and (3) postdisturbance. During the first period, landforms and processes are taken to represent natural conditions, although human activities and land use may invalidate this assumption. Geomorphic data collected during this period constitute the "baseline" and provides direction for eventual reclamation programs. Here, it is assumed that the magnitude and frequency of geomorphic processes affecting the disturbed site in the recent past provide an adequate basis for design.

The active disturbance period is a time of maximum disequilibrium between surface form and geomorphic processes. As a result, process rates are usually much greater than during the predisturbance period as the systems operate to re-establish dynamic equilibrium. Without effective control, the on-site environmental impacts can easily spread off-site.

The postdisturbance period follows reclamation. However, residual disequilibrium will persist because it is impossible to precisely reconstruct dynamic equilibrium with current knowledge and practice. Subsequent geomorphic processes will operate to "fine-tune" the system.

In most cases, reclamation procedures endeavor to produce environmental conditions similar to those of the predisturbance period and, to the extent that they are successful, should minimize the amount of adjustment necessary to achieve dynamic equilibrium. Accordingly, geomorphic process rates should be similar to those of the predisturbance period and considerably less than those during the active disturbance period.

When "geomorphic isolation" of buried toxic or hazardous materials is a reclamation objective, it is often necessary to predict or even speculate as to the magnitude and frequency of geomorphic processes that could effect a disturbed site during the next several thousand years. Schumm and Chorley (1983) discuss this issue in detail.

Formulation of the reclamation program

It is in the formulation of the reclamation program that the fundamental principles of geomorphology find direct application. As earlier noted, the Earth's land surface consists of a nested heirarchy of drainage basins; these in turn are composed of two primary landforms, hillslopes and channels. Extensive research provides essential design principles for drainage basins, hillslopes and channels.

Drainage basins The drainage basin is commonly considered a fundamental geomorphic, hydrologic and landscape unit (Chorley, 1971). Climate, geologic structure and lithology, and relief are regarded as the variables most influential in determining the morphology of drainage basins. Numerous investigations have established significant statistical relations among various features of the drainage basin and serve to validate the concept of the drainage basin as a complex, open, process-response system (Toy & Hadley, 1987). At least theoretically, it would be necessary to reconstruct all of these relations in order to produce drainage basins in dynamic equilibrium. Of course, this would likely be economically impractical, if technically possible.

Nevertheless, general guidelines may be offered for the design of the drainage network and land surface of the drainage basins. First, a dendritic drainage pattern should be appropriate wherever the disturbance has eradicated the pre-existing geologic structures and fragmented the strata. The drainage density of the reclaimed land should be higher than measured prior to disturbance in anticipation of lower infiltration capacities of the reclaimed surface materials. Melton (1958) contends that a drainage system is in equilibrium when:

$$F = 0.694\ D^2 \qquad (1)$$

Where: F = stream frequency
D = drainage density

Wells and Rose (1981) suggest that this relation has utility in the design of reclaimed drainage basins, although it probably requires additional examination.

Drainage area and relief are important attributes of the land surface. In the first case, drainage area is directly related to discharge (Leopold & Miller, 1956) and inversely related to sediment yield (Schumm & Hadley, 1961). Relief ratio (maximum relief/maximum horizontal distance along major stream) is directly related to sediment yield (Hadley & Schumm, 1961). Consequently, landscape design should seek to minimize both of these attributes to the extent feasible.

Hillslopes Hillslope form is a function of the geomorphic processes in operation on the surface and, again, the variables of climate, geologic structure and lithology, and relief are usually regarded as the most important determinants of form. The relation between hillslope form and geomorphic processes have been documented through abundant research, especially with regard to hillslope erosion by fluvial processes. Hillslopes are three-dimensional surfaces that may be dissected into plan forms and profile forms for analyses. Those possessing both concave plans and profiles are known as "valley-head" hillslopes (hollows), and here water tends to collect and converge in the downslope direction, leading to an intensification of the erosion process. Those possessing both convex plans and profiles are known as "spur-end" hillslopes, and here water tends to disperse and diverge in the downslope direction, leading to a constant or decreasing erosion rate.

In profile, hillslopes may be convex, concave, uniform (straight), or complex (including elements or segments that are combinations of the above). White (1966) suggests that the complex, convex-straight-concave, form represents the equilibrium profile. Experimentation by Meyer et al. (1975) and Meyer and Romkens (1976) indicate that a convex hillslope is more erodible than a uniform hillslope and a uniform hillslope will yield more sediment than a concave hillslope. Taken together, the "spur-end" hillslope is the preferred three-dimensional design while concavity is the preferred profile shape, with complex, uniform and convex profiles comprising a ranking of progressively lesser desirability.

It has long been known that there is a direct relation between hillslope gradient and length, and the rates of geomorphic processes, especially for the soil erosion process (Zingg, 1940; Musgrave, 1947). Here, "Hortonian Overland Flow" (Horton, 1945) is assumed, with an accumulation of runoff in the downslope direction and concomitant increases in the depth and velocity of flow.

Sometimes gradient and length are taken together in models to estimate soil loss. For example, Wischmeier (1975) offers the following equation:

$$LS = \frac{\lambda^{m}}{72.6} \; \frac{(430 \sin^2\theta + 30 \sin\theta + 0.43)}{6.574} \qquad (2)$$

Where: LS = topographic factor

λ = hillslope length
θ = hillslope gradient
m = exponent varying with gradient

Geometrically, there is a trade-off in the design of hillslopes, such that length increases, base increases, and height decreases, as gradient decreases for a given volume of material graded. Toy and Hadley (1987) provide a specific example, as shown in Figure 1, and demonstrate, based upon Equation (2), that grading to reduce hillslope gradient remains a desirable practice for erosion control on the reclaimed surface.

All factors considered, design hillslopes should possess a "spur-end" three-dimensional configuration, concave profile, gentle gradient, and short length. Frequently, it is not possible to accommodate all of these preferences. However, when design hillslopes depart from these shapes supplemental erosion control practices become increasingly important.

<u>Channels</u> Where the channel banks are composed of unconsolidated and erodible materials, as is often the case on disturbed lands, water and sediment discharge are the primary controls of channel morphology. The dynamic equilibrium, or graded form of the channel, is the morphologic expression of those variables, and in such a condition, the channel neither aggrades, degrades, nor otherwise

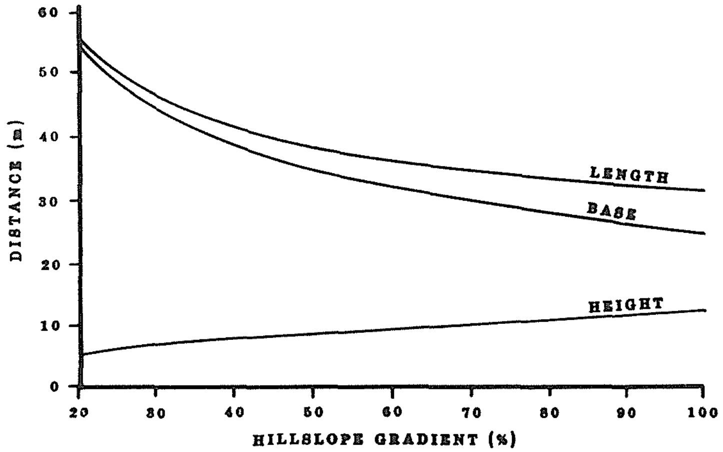

Fig. 1 Relation between hillslope gradient and base, height, and base.

progressively alters its channel dimensions. Usually, the water and sediment discharge of the stream can again be traced to the environmental setting, and especially to the climate, geologic structure and lithology, and relief.

Voluminous research has established the relation between channel dimensions and the water and sediment passing through it. These are discussed in detail by Schumm (1977) and summarized by descriptive equations showing that as water and sediment discharges change through a channel reach, there are usually changes in the width, depth, meander wavelength, gradient, sinuosity, and width/depth ratio of the channel.

Schumm (1977) also provides a series of equations to assist in the quantification of these relations. However, the two most common channel design procedures are (1) the permissible velocity approach and (2) the tractive stress approach. Recently, Schumm and associates have proposed a "geomorphic-hydraulic" approach; all three are discussed in Toy et al. (1987).

The most fundamental principal of channel design is that natural channels are formed by the waters that flow in them. Further, the design of channels for disturbed lands should rest upon the expected hydrologic properties of the reclaimed surface rather than the properties of the natural, predisturbance surface. And finally, the comment by Smith and Woolhiser (1978) is pertinent: "for reclaimed areas, the dynamic changes and interrelations of erosion, vegetal establishment, and surface hydraulics offers the greatest challenge to hydrology." Hadley et al. (1981) offer an example of a practical approach to estimating the hydrologic properties of disturbed and reclaimed surfaces. In light of the complexity of the hydrologic system and several uncertainties of parameter estimation, it seems prudent to over-design channels to a reasonable extent, so that they can serve as sediment sinks, rather than sediment sources, during the years immediately following reclamation. Enlarged channel dimensions and steepened channel gradients favor deposition.

Integration Drainage basins and their components, hillslopes and channels, function as open, process-response systems. In a natural, undisturbed setting, such systems operate to establish and maintain a condition of dynamic equilibrium through complex negative feedback mechanisms. Consequently, the components are integrated into the totality of the system. This is exemplified by significant statistical relations among the morphologic features of drainage basins, such as that reported by Strahler (1950):

$$S_g = 4S_c^{0.8} \tag{3}$$

Where: S_g = mean maximum hillslope gradient

S_c = stream channel gradient

This shows that there is a direct relation between hillslope and channel gradient; as one increases so does the other.

Likewise, reconstruction of all or parts of drainage basins requires integration of components and this must be considered during the design phase. Instability in one element can easily lead to instability in others. Accelerated erosion on hillslopes delivers large volumes of sediment to stream channels which will steepen their gradients in order to transport the load. This often leads to entrenchment of the channel and rejuvenation of the drainage network upstream.

From the foregoing, it is clear that complete geomorphic design of reclaimed lands rests upon numerous estimates of process rates and relations among components, and these vary with environmental setting. Perhaps, the best assemblage of information and equations to guide geomorphic design in various regions can be found in Hadley et al. (1985).

Implementation of the reclamation program

Reclamation failure can result from proper designs improperly implemented. Even subtle departures from design specifications can be problematic due to the complexity of geomorphic systems. For example, knickpoints, or abrupt changes in elevation along the longitudinal profile of a stream channel, may become loci of accelerated channel erosion and entrenchment, again leading to rejuvenation of the drainage network upstream. Most field geomorphologists can identify such departures, if on-site during landscape reconstruction, and recommend the necessary adjustments, thereby preventing future difficulties.

POSTRECLAMATION MANAGEMENT OF DISTURBED LANDS

Management refers to the control exercised over a parcel of land following reclamation. This includes three functions: (1) site monitoring, (2) remedial actions to repair site deterioration, and (3) decisions to minimize future deterioration. Monitoring often involves direct or indirect measurement of the work performed by geomorphic processes on the reclaimed land. Commonly, there is observational evidence of existing or potential problems. Deterioration of vegetation cover usually permits an increase in the sheet erosion rate and may eventually lead to rilling and gullying. Tension cracks across hillslopes suggest mass instability.

When deterioration becomes excessive, according to some standard, remedial actions are necessary to repair and forestall progressive damage to the reclaimed site, as well as off-site areas. If the cause cannot be traced to extraordinary circumstances or events, there may be serious deficiencies with the reclamation creating the disequilibrium detected. It may be necessary to regrade the hillslopes and channels in order to achieve stability. Although this entails considerable expense, it may prove economical in the long run when compared to periodic retreatment with unsatisfactory results. The geomorphic principles discussed above again provide guidance in the selection of remedial procedures.

Sometimes postreclamation land use is responsible for site deterioration. For example, excessive grazing intensity by livestock may produce deterioration in the vegetation cover. In such cases decisions must be made to minimize subsequent destruction. The number of animals can be reduced or the herd can be moved to another area for a time.

Nevertheless, management is essential and the reason, from the geomorphic perspective, is evident in the foregoing discussion concerning the integration of the geomorphic system. Frequently, instability begets instability; the adage, "a stitch in time saves nine," comes to mind. And from the foregoing discussion, it becomes clear that the science of geomorphology can provide powerful assistance throughout the reclamation process and thereafter.

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