Potential Evapotranspiration and Surface-mine Rehabilitation in the Powder River Basin Wyoming and Montana

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Abstract

Energy resource development in the Western United States must contend with the problem of water deficiency resulting from potential evapotranspiration rates which usually exceed precipitation rates. In this report the Blaney-Criddle method, with locally calibrated monthly natural vegetation coefficients, was used to estimate potential evapotranspiration (PET) for the Powder River Basin, Wyoming and Montana. In this area PET ranges from 15.02 inches per year to 26.76 inches. A radiation-based method for microclimatic adjustment of PET is presented. According to this procedure it might be expected that, for slopes of 20% inclination at 44° North latitude, annual PET is 17% less on northerly-facing slopes than a horizontal surface and 14% more on southerly-facing slopes.

The rehabilitation of disturbed lands must accompany energy resource development in the United States (U.S. Congress 1977). Erosion control is a primary goal of surface-mine rehabilitation because prolonged productivity of the land or aesthetic considerations are impossible if the soil is rapidly eroding. Erosion control is achieved through (1) proper surface contouring and (2) revegetation. The former is largely a mechanical exercise, while the latter is commonly a more difficult proposition in the Western United States, where much of the mineral and most of the coal reserves and resources lie within arid or semiarid climatic zones.

Discussions of mine-site rehabilitation potential typically include consideration of the climatic influences on revegetation. Frequently, however, evaluations of rehabilitation potential are based on incomplete information. A preoccupation with precipitation is often apparent (National Academy of Science and National Academy of Engineering 1974; Packer 1974), although the significance of precipitation lies in its relation to potential evapotranspiration (PET). Taken together, these two climate elements largely determine the amount of moisture available for plant use or, in arid and semiarid regions, the magnitude of water deficiency.

I submit that rehabilitation potential is inversely related to water deficiency. Therefore, PET data are necessary in order to evaluate the severity of drought, irrigation water requirements, and hence, rehabilitation potential. It is the purpose of this report to present estimates of PET for the Powder River Basi Wyoming and Montana, based on the Blaney-Criddle meth (1962), and utilizing crop coefficients for natural vegetation the Northern Great Plains. A radiation-based method for micr climatic adjustment of PET estimates is proposed.

Evapotranspiration, Vegetation Growth, and Rehabilitation

A brief discussion of evapotranspiration (ET) and its relati to vegetation growth illustrates the the significance of th parameter in rehabilitation studies and practice. ET is mai tained at the potential rate only as long as there is a plentifu nonlimiting supply of soil moisture. At some point during sc dehydration, ET falls below the potential rate. Chang (196 provides a summary of the controversy concerning the effect soil moisture tension on ET rates.

The assumption of nonlimiting soil moisture is rarely valid the Western United States. High mountain meadows an occasionally, valley floors, both with higher water tables ar subirrigated vegetation, are possible exceptions. In most case the concept of actual evapotranspiration (AET), resulting fro existing climatic and soil moisture conditions, is the appropria measure of surface water loss. Hanson (1973) developed model for estimating AET which includes a soil moistu parameter.

When AET is less than PET, plant productivity will be le than the potential maximum. Chang (1968) illustrates th generalized relation between yield and adequacy of wat application. Allison et al. (1958) show the relation between cro yields and water use for a number of crops grown in lysimeter

Current irrigation practices used in revegetation seem to b based on the relation between ET and soil moisture tensic proposed by Veihmeyer and Hendrickson (1955) and supporte by other researchers. According to their view, ET continues the potential rate up to the wilting point (15 bars) and fal sharply thereafter. However, work by Thornthwaite and Math (1955) indicated a linear inverse relation between ET and so moisture tension. Pierce (1958) concluded that ET continued the potential rate at low tension perhaps up to 0.4 bars and the rapidly decreased with increasing tension in curvilinear fashio If the relations proposed by either Thornthwaite and Mather Pierce are correct for species used in revegetation, then pla productivity is probably limited by the failure of curre practices to provide sufficient soil moisture to maintain ET the potential rate. Dwyer and DeGarmo (1970) found th production was greatest for selected desert shrubs and grasse

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with a field capacity soil-moisture level, and lowest at a moisture of one-third of field capacity for shrubs and at one-fourth of field capacity for grasses. However, water use per gram of dry matter produced (the measure of water-use efficiency) was highest at the field capacity soil-moisture level with the highest efficiencies of production occurring at one-third of field capacity. Under severe moisture stress (one-fourth field capacity), plants used more water and produced less dry matter. Since timely revegetation depends largely on plant productivity to produce a surface cover rather than efficiency of water use, it appears desirable to maintain soil moisture levels near field capacity, a condition allowing ET at the potential rate, at least until the plants have developed a significant root system. Unfortunately, in areas of extreme aridity, available water may be insufficient to maintain this level of soil moisture. In such cases, efficiency of water use gains importance. Plant survival, rather than biomass production, may be all that can be expected during some periods and effective rehabilitation will be delayed accordingly.

Irrigation and surface treatment techniques, employed to improve the probability of successful revegetation in surface-mined areas with extremely low and erratic precipitation, affect ET. The results of several irrigation experiments were reported by Aldon and Springfield (1977). As a consequence of irrigation practices, the normal irrigation applications are usually insufficient to maintain soil moisture levels near field capacity. Indeed, in one area, water was applied when vegetation showed visible signs of stress. Therefore, the amount of water evapotranspired was somewhere between the potential quantity and that which would have been AET under natural conditions. PET rates may be reached for short periods following irrigation applications or precipitation events.

Mechanical and chemical surface treatment techniques also alter the natural water balance of spoils piles undergoing rehabilitation. Hodder (1977) describes the effects of mulching, cultivation, top-soiling, deep chiseling, gouging, off-set listering, and excavation of doser basins. Aldon and Springfield (1977) describe the effects of water harvesting techniques utilizing the application of paraffin, silicone, or black polyethylene to the surface. The usual purpose of mechanical or chemical treatments is to increase the available soil moisture for plant use through a reduction of runoff and ET, an increase in infiltration, or by concentrating available water into a smaller area. The net effect of these practices is to increase the proportion of available moisture transpired to that evaporated from the soil surface. Additionally, AET from a treated surface will exceed that from an untreated surface because of the increased amount of soil moisture made available by these techniques. Experimental field plots are likely to be the only approach to measuring AET under the complex artificial conditions of rehabilitation.

Estimating Potential Evapotranspiration

Three factors favored the use of the Blaney-Criddle method for PET estimation: (1) availability of data, (2) effectiveness of these method when crop coefficients are locally calibrated, and (3) widespread acceptance of this method. The Blaney-Criddle method requires only mean monthly temperature, available at a large number of cooperative climate stations in the Powder River Basin, and station latitude as inputs. Burman et al. (1975) concluded that the Blaney-Criddle method, utilizing locally calibrated crop coefficients, appeared to be the most satisfactory of the 15 methods compared. Data for crop coefficient calibration were provided for use in the present study by Lauenroth and Sims (1976) and through personal communication; their use will be discussed in a subsequent section. Finally, the Blaney-Criddle method has provided estimates of PET in a variety of studies differing in purpose. The U.S.D.A. Soil Conservation Service (1970) uses this method as a part of its model for estimating irrigation water requirements. Burman, et al. (1975) acknowledge its widespread acceptance in water right transfer proceedings. Further, they note that the legal profession, lay personnel, and engineers not familiar with other methods understand the Blaney-Criddle method. This may be an important consideration when dealing with surface-mine revegetation and rehabilitation.

The Blaney-Criddle method estimates monthly consumptive use of water according to the formula:

$$u = kf \qquad (1)$$

where:

u=monthly consumptive use PET in inches
k=monthly crop coefficient
$f = \frac{t \times p}{100}$ = monthly consumptive-use factor
t=mean monthly temperature, °F
p=monthly percentage of daytime hours of the year (derived from tables and based on latitude)

The values derived for consumptive use by this method may be considered estimates of PET because the model assumes a nonlimiting water supply. Most investigators, including Cruff and Thompson (1967); Burman, et al. (1975); and Jensen, et al. (1973), have used the estimates in this way. Crop coefficients (k) have been experimentally determined for a variety of agricultural crops. In these studies, consumptive use was usually measured by lysimeter; and these values, together with those for f, were inserted into equation (1) such that $k=u/f$. The same procedure was used for determining monthly values for k in this research.

Crop Coefficient Calibration

The crop coefficients used for estimating PET in surface-mined areas should reflect the consumptive use characteristics of the vegetation species used in rehabilitation. Two strategies are possible for coefficient calibration: (1) use of consumptive-use measurements for revegetation species, such as western wheatgrass (*Agropyron smithii*); or (2) use of measurements for natural vegetation in the area. The latter strategy is based on the assumption that the most successful species to be used in revegetation will have consumptive-use characteristics similar to the species indigenous to the area. Availability of data will likely determine which of these strategies to use in practice.

PET estimates were made by Lauenroth and Sims (1976) using the water balance method at the Pawnee site of the U.S. International Biological Program Grassland Biome from 1971-1973. The natural vegetation at this site, east of Fort Collins, Colorado, is characteristic of a large portion of the shortgrass prairie and consists of blue grama grass (*Bouteloua gracilis*), fringed sagewort (*Artemisia frigida*), scarlet globe mallow (*Sphaeralcea coccinea*), plains pricklypear (*Opuntia polyacantha*), broom snakeweed (*Gutierrezia sarothrae*), and needleleaf sedge (*Carex eleocharis*). Lauenroth and Sims (1976) comment: "If the agreement between the data predicted by Penman's model and those arrived at by the water balance data from the water plus nitrogen treatment is accepted as evidence of the credibility of both, they may then be accepted as defining a range for potential evapotranspiration in the shortgrass prairie of northeastern Colorado." Nitrogen treatment

Table 1. Blaney-Criddle crop coefficients for natural vegetation in the Northern Great Plains.

	1971	1972	1973	k*
April		0.69	0.38	0.54
May	1.18	0.52	0.48	0.73
June	1.18	0.78	1.06	1.01
July	0.92	1.10	0.92	0.98
August	0.94	0.81	0.84	0.86
September	0.74	0.38	0.83	0.65

* Average monthly coefficient.

may enhance the utility of these data because rehabilitation sites are frequently fertilized.[1]

The consumptive-use data described above, together with the mean monthly temperature data obtained, were used to derive monthly crop coefficients during the growing season from 1971 to 1973 (Table 1). The variation of monthly crop coefficients from year to year reflects specific climate conditions prevalent during that period. For example, there were frequent thunderstorms during the first 2 weeks of June 1972, according to Dr. Lauenroth (personal communication, 1976). Consequently, the values in Table 1 suggest a range; all were included in the computation of the average coefficient because they are indicative of natural conditions. Figure 1 is a graphic portrayal of the average coefficients. The form of this curve is similar to that for other crops (U.S.D.A., Soil Conservation Service 1970).

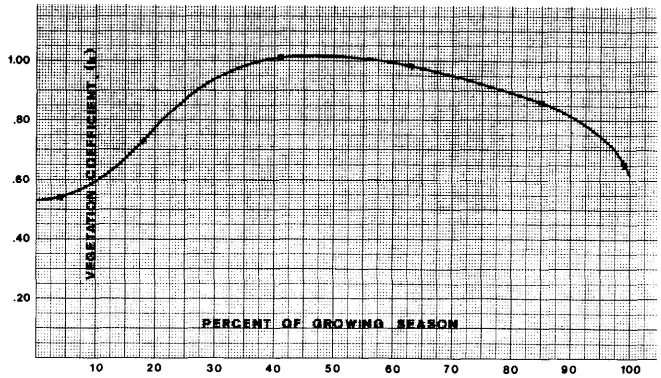

Fig. 1. *Average vegetation coefficients for natural vegetation of shortgrass prairie in Northern Great Plains.*

Potential Evapotranspiration in the Powder River Basin

Average growing-season PET was estimated for 63 climate stations in Powder River Basin using the Blaney-Criddle method with the average crop coefficients contained in Table 1 and mean and monthly temperature data for the period 1965-1974. The growing season was defined as the frost-free period, extending from the mean date of last spring frost to the mean date of the first autumn forest as advocated by Critchfield (1966) and supported by the U.S.D.A., Soil Conservation Service (1970). Soil Conservation Service program TR-21-V3 was used for the actual computations.

Figure 2 (Toy and Munson 1978) was produced by interpolating isopleths between the derived station values. This figure shows the variation in PET for natural vegetation throughout the Powder River Basin. Other things being equal, this is the amount of water required to sustain vigorous plant growth for revegetation of surface-mined areas during the entire growing season. Even in this rather geographically limited area, there is a PET range of 11.74 inches with Miles City, Montana, capable of losing 26.76 inches of water and Kirby 1S, Montana, losing 15.02 inches. The data contained in Figure 2 serve as a useful baseline for environmental impact statement preparation. Naturally, site-specific information must be collected on location; however, time constraints frequently preclude the collection of these data.

Topographic Influences on Potential Evapotranspiration

In semiarid regions natural vegetation development on hillslopes of southerly aspects tends to be more xeric than on northerly aspects. For the Cheyenne River Basin in east-central Wyoming, Hadley (1962) found that plant cover on southerly-facing slopes is only 28% of that occuring on northerly-facing slopes. This difference is usually attributed to greater moisture deficiencies on slopes of southerly aspect. This moisture deficiency is due to the higher rates of solar insolation received throughout the year resulting in higher rates of PET.

Chang (1968) and Jensen et al. (1973) note that the rate of PET is largely determined by net radiation in the absence of significant advected energy. Net radiation is defined as the difference between the incoming and outgoing radiative fluxes, both short-wave and long-wave. Unfortunately, net radiation data are collected at very few locales within the United States. Based on 14 stations throughout the world, Davies (1967) has found that net radiation can be estimated from total solar radiation (r=0.99):

$$Rn = 0.617Q - 24 \quad (2)$$

Rn = net radiation
Q = total solar radiation

Frank and Lee (1966) suggest that in the net radiation balance, diffuse sky radiation, thermal atmospheric radiation, reflected and thermal terrestial radiation components are largely self-cancelling over extended periods of time; and, hence, net radiation is proportional to direct beam solar radiation. Also noteworthy in this context is the comment by Chang (1968) that direct insolation is a function of both aspect and slope inclination, while diffuse radiation, being essentially uniform in all aspects, is affected only by the latter; a 10° northerly-facing slope receives just as much diffuse sky radiation as a 10° southerly-facing slope.

In the absence of collected radiation data for hillslopes of various inclinations and aspects, an indirect, if nonrigorous, method must be devised for adjusting horizontal surface PET estimates for topographic influences. If the following assumptions can be accepted as essentially valid for a period of several months' duration, then the data provided by Frank and Lee (1966) and the formulas devised by Davis (1967) can be used to make PET adjustments. The assumptions on which the procedure depends are: (1) PET is proportional to net radiation, (2) net radiation is proportional to direct solar beam radiation, (3) diffuse sky radiation is constant for slopes of the same inclination, and (4) the effect of the atmosphere in reducing potential direct beam radiation to that actually received at the surface is essentially constant for slopes of the same inclination but different aspects.

Table 2 shows the comparison of net radiation received on a northerly- and southerly-facing slope, both of 20% inclination, at 44° North latitude. These values were computed using potential direct beam radiation values provided by Frank and Lee (1966) with the Davies equation used to estimate net radiation values. Three time intervals are considered: (1) the full

[1] A word of caution to those using the data presented by Lauenroth and Sims (1976): There are errors in Table 1 of that report, and Figures 5 and 6 are switched (personal communication with Dr. Lauenroth, March 4, 1977).

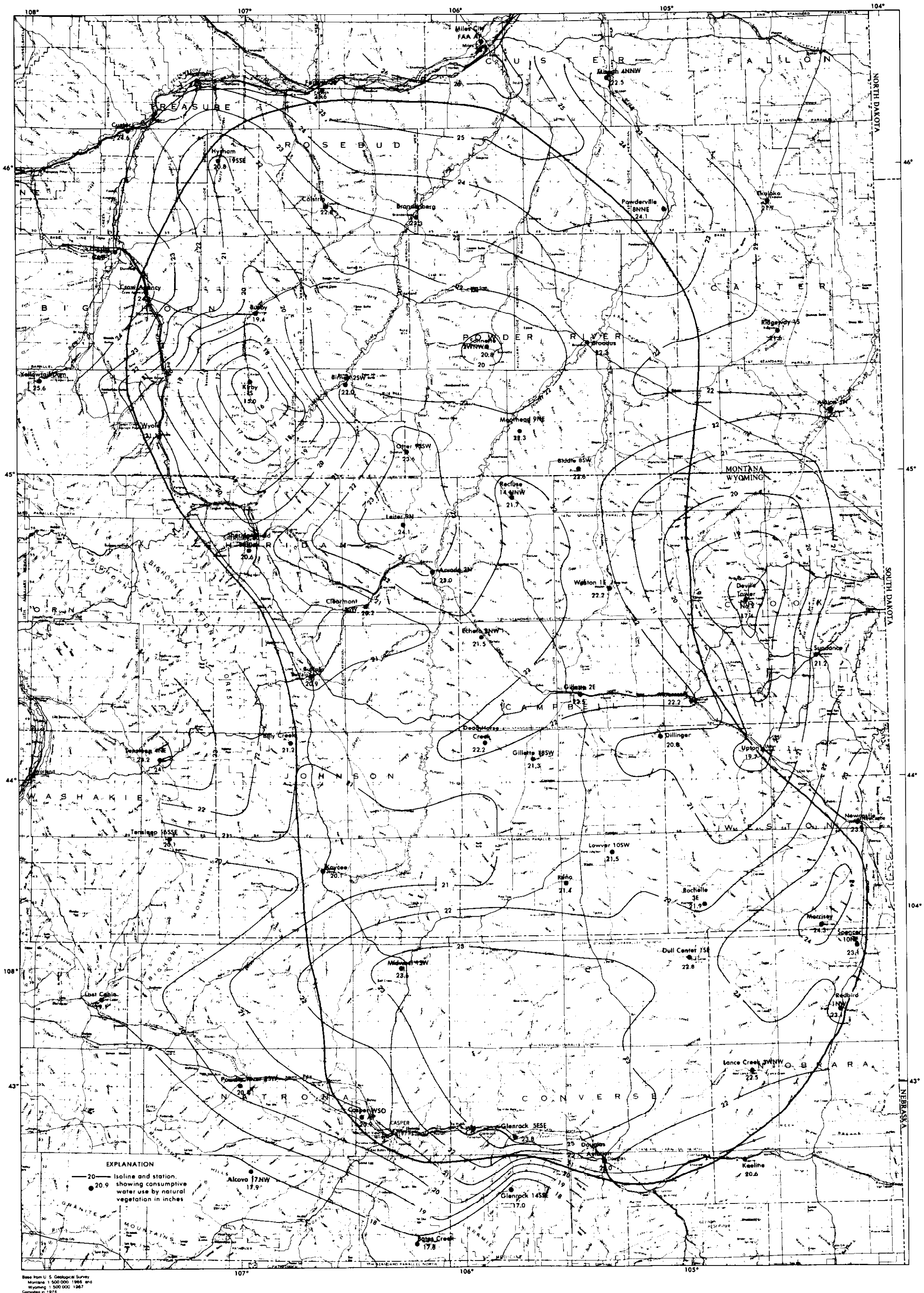

Fig. 2. *Isopleth map of consumptive water use in Powder River basin.*

year, (2) the pre-growing season period from the winter solstice to the beginning of the growing season, and (3) the growing season period. For the annual period, the northerly-facing slope receives 83% of the radiation received on a horizontal surface, while the southerly-facing slope receives 114% of that received on a horizontal surface. For the pre-growing season period, the northerly-facing slope receives 79% of the radiation received on a horizontal surface, while the southerly-facing slope receives 118% of that received on a horizontal surface. For the growing season, the northerly-facing slope receives 94% of the radiation received on a horizontal surface, while the southerly-facing slope receives 103% of that received on a horizontal surface. These ratios can be used to adjust measured solar radiation data, where such information exists, for use in radiation-based methods of estimating PET (Wymore, 1974), or adjusting PET estimates derived by other methodologies. In other words, for slopes of 20% inclination at 44° North latitude, it might be expected that PET is 17% less on northerly-facing

Table 2. Variation in energy receipt with slope aspect (20% inclination, 44° N. lat.).

	North-facing (N)	Horizontal (H)	South-facing (S)	N/H	S/H	N/S
Potential direct beam radiation (ly)[1]						
Pre-growing season (12/22-5/27)	73,931	94,094	111,367	0.79	1.18	0.66
Growing season (5/28-9/17)	98,868	105,172	107,932	0.94	1.03	0.92
Full year	199,035	240,588	274,472	0.83	1.14	0.73
Net radiation (ly)[2]						
Pre-growing season (12/22-5/27)	45,591	58,032	68,689	0.79	1.18	0.66
Growing season (5/28-9/17)	60,978	64,867	66,570	0.94	1.03	0.92
Full year	122,781	148,419	169,325	0.83	1.14	0.73

[1] Frank and Lee (1966).
[2] Davies (1967).

slopes than on a horizontal surface and 14% more on southerly-facing slopes for the annual period. Similar inferences can be made for the other time periods. The estimates of PET for horizontal surfaces provide adequate average estimates considering the accuracy of the estimating procedures themselves.

While the foregoing may be acceptable in theory, reality is, of course, more complex. It seems unlikely that the disparity in plant cover can be adequately explained by the difference (N/S=0.92, Table 2) in energy received during the growing season on northerly- and southerly-facing slopes. However, the difference (N/S=0.66, Table 2) in energy received during the pregrowing season period may well be significant, especially in areas where available moisture is near the minimum requirement for plant survival and development. Higher insolation rates on southerly-facing slopes prior to the commencement of the growing season result in increased winter evaporation losses, and reduced water supplies available for soil water recharge from spring snowmelt (Wymore 1974). Further, Wymore (1974) suggests that the growing season is initiated much sooner on slopes of southerly aspect, and Leopold (1974) notes that growing season length is the most important climatic characteristic governing water needs of vegetation. Exposure to prevailing winds also affects the amount of snow cover on the surface and hence soil moisture recharge in the spring. Observed differences in vegetation density along snow fences together with those on lee and windward slopes verify the significance of this factor. On-site experimentation and experience are necessary to measure precisely the influence of topography, although approximations and expectations can be obtained through the procedure described herein.

Discussion

PET is a frequently neglected component of the hydrologic system affecting surface-mine rehabilitation in the arid and semi-arid Western United States. Estimation of this component, however, is a prerequisite to an evaluation of the magnitude of water deficiency. While recognizing the importance of other environmental factors affecting vegetation growth, it is my contention that rehabilitation potential is inversely related to water deficiency. Indeed, the severity of drought may be a paramount consideration in the design of a rehabilitation program.

The information and procedures contained in this report can be used, together with precipitation records, to estimate irrigation water requirements. Irrigation during the initial period of rehabilitation (perhaps a year or two) can reduce the risk of revegetation failure due to insufficient precipitation. In some areas it may be essential; in others, merely insurance. The amount of water used for irrigation in most areas is likely to be a small percentage of that used solely for dust control. The cost of irrigation equipment may be amortized over an extended time period and, in the long run, may prove more economical than periodic retreatment of areas due to revegetation failure. According to Harley Meuret (personal communication, June 26, 1978), reclamation specialist at the Jim Bridger Mine in southwestern Wyoming, the cost of one reseeding is approximately equal to the cost of irrigation for the first season of reclamation.

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