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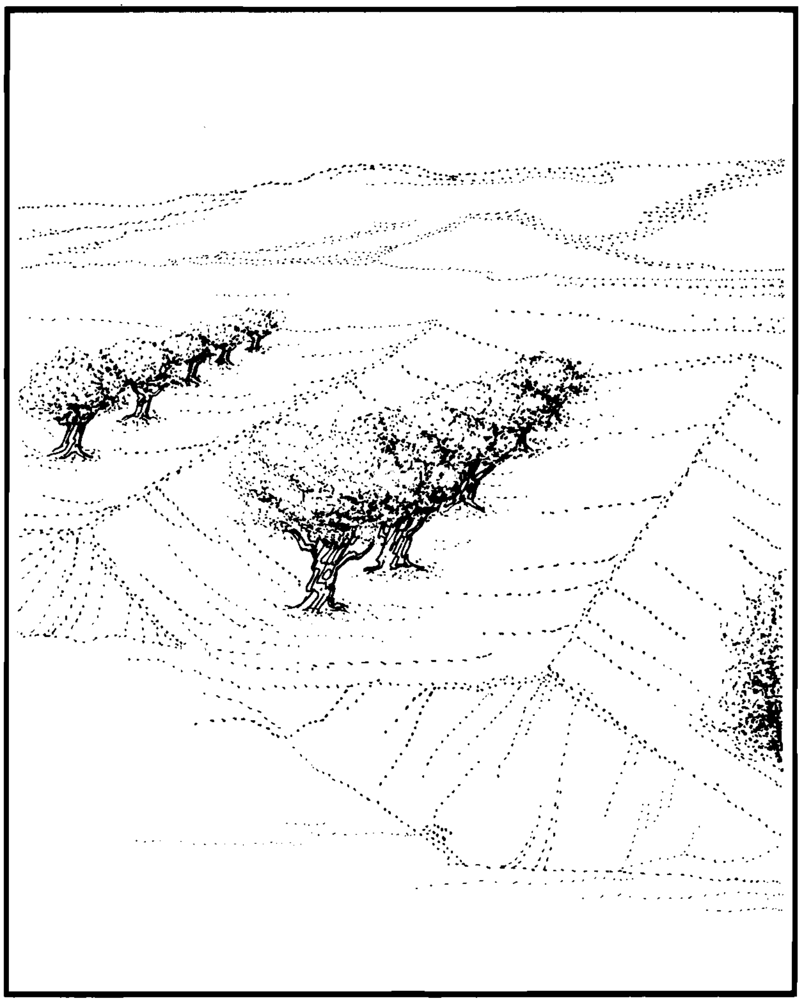
December 1982



Prepared for the U.S. Department of Energy
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RESTORATION OF SURFACE MINED LANDS WITH RAINFALL HARVESTING

R.H. Sauer
W.H. Rickard

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Pacific Northwest Laboratory
Richland, Washington 99352

EXECUTIVE SUMMARY

Strip mining for coal in the arid western U.S. will remove grazing land as energy demands are met. Conventional restoration usually includes leveling the spoil banks and covering them with top soil, fertilizing, seeding and irrigating with well or river water. This report provides an overview of research on an alternate method of restorating this land. From 1976 through 1981, Pacific Northwest Laboratory conducted studies on the use of water harvesting, the collection and use of rainfall runoff, to restore the vegetative productivity of strip mined lands in arid regions. These studies tested the technical and economic feasibility of using partially leveled spoil banks at strip mines as catchment areas to collect and direct runoff to the topsoiled valley floor where crops were cultivated.

Information was collected on the efficiency of seven treatments to increase runoff from the catchment areas and on the productivity of seven crops. The experiments were conducted in arid areas of Washington, Arizona and Colorado.

It was concluded that water harvesting can replace or augment expensive and inadequate supplies of well and river water in arid regions with a suitable climate. These studies showed that some treatments provided adequate runoff to produce a useful crop in the valleys, thus making this alternative approach to restoration technically feasible. This approach was also potentially economically feasible where the treatment costs of the catchment areas were low, the treatment was effective, the crop was productive and valuable, and earthmoving costs were lower than with conventional restoration involving complete leveling of spoil banks. It was also concluded that water harvesting can be made more effective with further information on catchment area treatments, which crops are most adaptable to water harvesting, the optimum incline of the catchment areas and climatic influences on water harvesting. Water harvesting has the potential for reducing the costs and increasing the effectiveness of restoring the vegetative productivity in arid surface mined lands.

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INTRODUCTION

Energy demands in this country are focusing interest on coal. While underground mining in the eastern United States is likely to provide much of the coal, an increasing amount will come from western surface mines, where thick seams are within a few hundred feet of the surface and the growing seasons are hot and dry. The premining vegetation of such areas frequently consists of grazed shrub and grasslands of relatively low productivity. The return of mined lands to a productivity level equal to or greater than premining conditions has been legislated by Congress and is intended to reduce the impact of the mining process upon the people in the area and upon the landscape (1,2).

The problem of restoring vegetative productivity to mined lands results in part from the low quality, even toxic, spoil expected to act as a rooting substrate and in part from the absence of adequate water to support a vigorous soil-building vegetation (3). The aridity of the western U.S. coal bearing regions and the slow soil formation rate produce an environment in which a self-maintaining vegetation of desirable native species cannot quickly be established.

This harsh environment is usually ameliorated by leveling the spoil banks and covering them with topsoil (or the best soil) (4). The vegetative cover is started by planting as seeds or young plants a mixture of native and alien species selected on the basis of desirable properties and ability to withstand the severe conditions. Fertilization and irrigation often follow seeding to increase chances for vegetation establishment. Specialized seed bed preparation consisting of furrows or small basins can be used to provide microsites of more favorable habitat for the young plants (4). In the arid southwest U.S., grazing species are usually planted to satisfy legal requirements and to provide a practical vegetative cover (5). The problems of restoring the vegetative productivity of mined lands in the arid southwest are discussed by Green (6).

The problem with the conventional approach to arid mined land restoration is that it uses the valuable resources irrigation water and soil to produce a relatively low value crop or product, such as livestock forage. In cases where either irrigation or fertilization are not practiced, undesirable alien weeds such as Russian thistle (*Salsola kali* L.) may become established. Even with irrigation to establish desirable species, weedy species may invade once irrigation is stopped.

The charge to return a mined area to premining conditions requires that the premining native vegetation be reestablished. Without man's assistance, however, this process could take an unacceptably long time. Reestablishment of predisturbance vegetation under desert power lines or on unpaved streets wasn't completed after 33 years (7,8). Return of predisturbance vegetation over a pipeline buried in the California desert could take millenia (9). The greater disturbance caused by surface mining would probably extend natural recovery beyond these estimates. We have the choice of accepting the costs of using valuable soil and water to return the arid mined land to the original low value vegetation, leaving the land in its disturbed, non-productive form, or changing our concept of restoration.

An alternative means of restoring the vegetative productivity of arid mined lands uses water harvesting to provide irrigation water for desirable crops. Water harvesting, the gathering of runoff for agricultural or domestic use, was used successfully as early as 2000 B.C. to supply agricultural and domestic water in the arid mideast (10) and was the subject of a recent symposium (11). Water harvesting is used in Australia and the U.S. at present to supply livestock water (12,13). The potential of water harvesting is large; in Nevada as much as 250 liters of water per square meter per year would be available (14).

Irrigation with water harvesting is the focus of a program at the Pacific Northwest Laboratory (PNL), sponsored by the U.S. Department of Energy. In this unconventional approach to restoration, smoothed spoil banks are utilized as catchment areas that collect and direct precipitation to topsoiled areas between the spoil banks (Figure 1). The spoil banks are slightly graded to reduce the slope angle to a stable configuration. Topsoil is placed in the valley between the catchment areas. Thus, a 5 mm rain event which would ordinarily be lost to surface evaporation would be increased to a 20 mm rain event in a 100% efficient catchment area four times the width of the topsoiled valley floor. In this way, the resources in short supply in arid regions, water and good soil, are concentrated in the valleys between the spoil banks. The advantages of this approach are:

- A smaller fraction of precipitation is lost to soil surface evaporation because the larger effective storm size results in a greater proportion of water percolating past the zone of surface evaporation.
- The catchment areas (spoil banks) can reduce air movement and evapotranspiration, further reducing water stress.
- Less energy is expended because the catchment areas do not require cultivation.
- Smoothing and partial leveling of the spoil banks requires less earth moving than return to a level contour.
- Energy, materials and equipment to obtain and distribute irrigation water are not required.

The purpose of this research program was to determine the technical and economic feasibility of using water harvesting to reestablish useful vegetation on surface mined lands in dry regions. Specifically, this program investigated, a) the effectiveness of different slope treatments in producing runoff, b) the adaptability of different crops to water harvesting agriculture, c) the effect the catchment areas or spoil banks have on the crop environment, and d) the relationship between crop productivity and slope treatments. Data and conclusions from the Hanford Site in Washington, the Kayenta coal mine at Black Mesa in Arizona and the Nucla coal mine in Colorado will be presented here. The results of this research, if adopted by mining companies and recommended by regulatory agencies where appropriate, would result in a savings in energy, time, water, and reclamation costs.

METHODS

Water harvesting reclamation was studied in three dry regions; the Hanford site in Richland, Washington, the Peabody Kayenta coal mine on the Navajo Nation Reservation at Black Mesa in Arizona, and at the Peabody Nucla coal mine in southwestern Colorado.

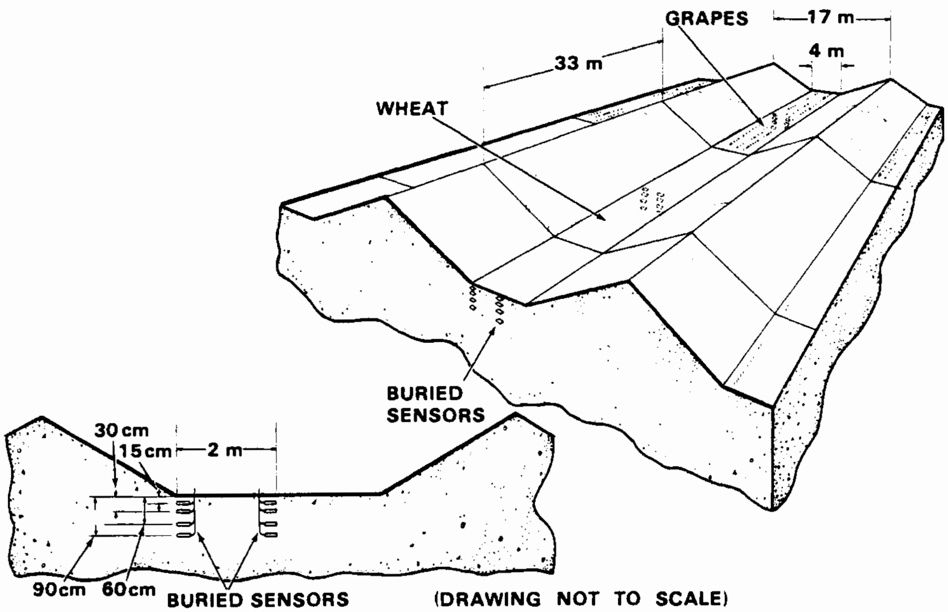


FIGURE 1. Diagram of research site at Hanford. (The slopes are the catchment areas; Crops are planted in the topsoil between the catchment areas, and soil water content is monitored at four depths in the topsoil.)

HANFORD SITE

The Hanford site was established to test methods and materials before putting them in use at more distant, operational coal mines. This test site, located on the Department of Energy's Hanford site at a 120 m elevation, receives an average of 130 mm of precipitation per year, about one-half as snow. Winters are cool, with minimums occasionally as low as -25°C; summers are rainless, with temperatures frequently over 35°C. The soil is Burbank sand, consisting of approximately 65% sand, 30% silt, and 5% clay. Cobbles make up approximately one-half of the soil mass, resulting in a low water holding capacity. This climate and soil provide a challenging environment for testing water harvesting reclamation.

An abandoned waste area near the Columbia River was modified with a small dragline to resemble the smoothed spoil banks of a coal mine; cobbly alluvium of the Columbia River served as spoil. Seven areas were prepared, three with valleys that ran north to south, and three with valleys that ran east to west; one area was prepared without adjacent slopes to simulate leveled spoil banks. The north-south valleys were protected from the strongest winds in the region, while the east-west valleys were parallel with the strongest winds. The valleys were each 90 m (300 ft) long by 18 m (60 ft) wide at the top of the catchment areas ("spoil banks") and 4 m (13 ft) wide at the surface of the topsoil, with a 33° angle of repose for each slope. For slopes such as these, the catchment ratio on a 100% efficient catchment surface would be approximately four to one, making each storm four times larger than on level ground.

Slope Treatments

The runoff efficiency of any surface can be improved by applying a porefilling or waterproofing substance to the surface. The slope treatments that were applied at Hanford were rubber sheeting, paraffin, asphalt-rubber, bare slope control and no adjacent slopes (flat control).

The rubber sheeting was 1.59 mm (1/16 in.) thick EPDM (butyl rubber) installed in September 1976 in one NS valley (For convenience, north-south valleys are designated NS, east-west valleys, EW). Butyl rubber has been used for domestic water impoundments for some time and has excellent stability in sunlight and temperature extremes. This treatment was intended to provide a 100% efficient runoff catchment area for comparison with the other treatments.

Paraffin (approximate melting point 53°C) was melted and sprayed at the rate of approximately 1 kg/m^2 on the cobbly catchment area of a NS valley in May of 1977 and on the smooth catchment area in an EW valley in September 1977. Paraffin, relatively low in cost, is easy to apply and has shown promise elsewhere (15,16).

Asphalt-rubber, a mixture of ground rubber and asphalt, is used as a crack sealer on roadways and as a liner for reservoirs (17). The mixture is sprayed on hot and cools to a tough, sunlight-resistent, flexible coating. This treatment was applied to catchment areas of an EW valley in September of 1977 at the rate of 4 to 8 l/m^2. The dark-colored material may provide the higher temperatures or longer growing season required by some crops to mature. Catchment (slope) treatments at Hanford included:

- Flat Control - NS oriented area with no adjacent slopes or catchment areas.
- Rubber sheeting - NS valley with rubber sheeting on catchment area
- Asphalt-rubber - EW valley with asphalt-rubber on catchment area
- Paraffin NS - NS valley with paraffin on catchment area
- Paraffin EW - EW valley with paraffin on catchment area
- Bare surface NS - NS valley with no treatment on catchment area
- Bare surface EW - EW valley with no treatment on catchment area

Physical Environment

Microclimatic parameters were recorded to identify and explain differences in vegetative performance between valleys. Insolation, air temperature, wind travel and precipitation were measured at a distance of 1 m from the ground surface in the middle of each of the three control valleys. Precipitation was recorded with standard 15 cm gages next to the insolation instruments. Weekly maximum and minimum temperatures measured at canopy height (30 cm) were taken at midlength in each valley.

Daily insolation and wind travel observations were combined into monthly means. The weekly observations (maximum-minimum temperatures in the wheat canopy and precipitation) were combined into quarterly (3-month) means. The individual observations in each period were considered replicates in an analysis of variance used to assess statistical differences ($p \leq 0.05$) between stations. Only data from days without instrument failure were used in the analyses.

Soil water content was monitored to determine if we were meeting our objective of increasing the water content of the cultivated soil. To measure the effectiveness of our approach, gypsum conductivity blocks (18) (sensors) were buried at four depths (15, 30, 60, 90 cm) at six stations in each valley, as shown in Figure 1. The length of the valley was divided into thirds. Two stations were located at midlength in each third, one next to the slope, and one at midwidth. This arrangement was intended to give data on soil water content at four depths near the source of the runoff and in the middle of the width. Unstable soil structure prevented deeper emplacement of the sensors.

The electrical resistance of each of the 156 sensors was measured weekly on an instrument designed and fabricated under the sponsorship of this program (19). This instrument compensates for capacitance of the long (up to 200 m) leads used to connect all blocks to a central reading station (a patent is pending). The electrical resistance of each sensor was converted to a percent water value with a calibration curve (r^2 of each individually calibrated sensor ≥.95). Percent water was converted to soil water potential with a water release curve. We used soil water potential as a measure of soil water status, rather than percent water, because soil water potential is directly related to a plant's water status.

To obtain a single value that would represent soil water status for the entire growing season, the soil water potentials of the four sensors at each station (Figure 1) were integrated over depth and time as follows. The value of -15 bars, usually taken as the limit of soil water availability, was subtracted from the soil water potential of each sensor to obtain an estimate of available water. Negative values of available water were set to zero. To integrate over the depths of the sensors, the distance (cm) halfway to each adjacent sensor were summed and multiplied by the available water (bars). Thus, the available water potential of the sensors at 15 and 30 cm were each multiplied by 22.5 cm, and the available water potential of the sensors at 60 and 90 cm, by 30 cm. The total depth of instrumented soil was assumed to be 105 cm or 90 + 15 cm. The values for the four sensors were summed to represent the available soil water potential in the profile at the station for one day (bar•cm). To integrate over time, the number of days from one observation to the next was halved and added to half the number of days from the following observation. This time span was multiplied by the available soil water (bar•cm) to obtain the available soil water for that sample period (bar•cm•days). Finally, for each station, the bar•cm•days was summed from the soil water observation date at wheat emergence to the last date before harvest (the growing season), to obtain a single value, T, that represents the available water for the growing season.

These calculations are summarized in the following equation

$$T = \sum_{k=1}^{m} \sum_{i=1}^{4} \Psi_i - (-15)^{+} \cdot L_i \cdot D$$

$$D = \frac{t_0 - t_{-1}}{2} + \frac{t_{+1} - t_0}{2} \qquad \text{(Eq 1)}$$

$$Li = \frac{B_i - B_{i-1}}{2} + \frac{B_{i+1} - B_i}{2}$$

$$B_0 = 0$$
$$B_5 = 105$$

Where:

T represents soil water in bars•cm•day for the growing season,
Ψ_i is the soil water potential at depth i,
B_i is the depth of sensor i, (B_0 = 0 cm and B_5 = 105 cm)
t_0 is the current observation date in calendar days
t_{+1} is the next observation,
t_{-1} is the previous observation and
m is the number of soil water observation periods from wheat emergence to harvest.

The season values of available soil water at the four stations in each valley planted to wheat were averaged to represent the soil water status of the wheat crop.

Test Crops

The test crops were wheat, grapes, apples and alfalfa. Wheat was chosen because it is widely planted on irrigated and dry land in Washington. Nugaines, a soft white winter wheat was broadcast at the rate of 100 Kg/ha and covered by discing in two-thirds of the valley length in October 1977. In June 1978, wheat yield in each valley was estimated from 48 clipped plots, each 0.5 x 4.5 m. The plots were located in two sets of 24, and were laid out so that six plot widths covered the width of the valley and the lengths were parallel with the length of the valley. The grain was harvested by plot, thrashed, dried, and weighed.

Grapes were chosen because they can use water as deep as 13 m and are a high value crop. The ability to use deep water is important; concentrating rainfall by 4 to 1 can result in a significant portion of the water percolating deep into the soil and, therefore, out of reach of shallow-rooted crops. In the remaining third of the valley length, three individuals for each of four varieties of grapes (Concord, Gewurtztraminer, Chardonnay and Pinot noir) were planted. Grape production was expected to begin in 1979 when the vines were three years old; however, unusual winter cold and grasshopper damage in 1978 killed all but one vine. The vines were replaced in 1979 with an expectation of harvesting fruit in 1982.

The wheat was replaced in 1981 with apples (red and golden delicious) in the middle third of each valley length (4 red and 2 golden per valley) and alfalfa in the other third. The alfalfa varieties, chosen for drought resistance (Norsman, Spredor II, Ladak 65 and BC 79), were recommended by Dr. Richard Peden at the Prosser, Washington agricultural experiment section.

BLACK MESA SITE

The Black Mesa site is located on the Navajo Indian Reservation in Northern Arizona at an elevation of 2,100 m on Peabody Coal Company's Kayenta Mine N-1. Average annual precipitation is 280 mm, ranging from 174 to 477 mm (20) with high month to month variation. Summer rains are intense and localized. Winter rains fall uniformly over large areas, often as snow which usually melts in a few days. Temperatures are moderate, seldom reaching over 30°C in the summer or falling below -10°C in the winter. Evapotranspiration exceeds precipitation during the growing season.

Undisturbed soils on Black Mesa are primarily classified as Natragias. They are generally shallow and poorly developed, with very low organic matter and an abundance of rock outcrops. The mine spoils, 10 to 30 m deep, consist of shale, sandstone, siltstone, and mudstone which have been crushed, mixed, and regraded. The size distribution of spoil material ranges from very fine clay particles to rocks about 45 cm in diameter. The mine spoil tends to puddle when wet and forms a surface crust after drying.

Construction of the Black Mesa site began on March 22, 1979. The site selected consisted of three uninterrupted rows of ungraded spoil adjacent to an active pit. The final site had an area of 2 ha and consisted of two parallel valleys, 260 m long and about 5 m wide, between three rows of spoil which had been graded to form precipitation catchment areas. The distance between valleys averaged about 40 m.

The site was shaped with bulldozers, scrapers and graders. The original slopes (about 50 percent) of the spoil rows were reduced to a final average slope of about 15 percent, with slope lengths of about 20m. The grading technique consisted of bulldozing along the peaks of the spoil rows, pushing the spoil to either side into the valleys and then bulldozing at right angles to the rows to achieve a uniform hill and valley system. Final shaping of the slopes and valleys was done with graders. The scrapers were used to haul, deposit and level topsoil in the valleys to an average depth of 25 cm. The soil was unavoidably compacted during the topsoiling operation by repeated passes with the scrapers, but was subsequently loosened with a soil ripper.

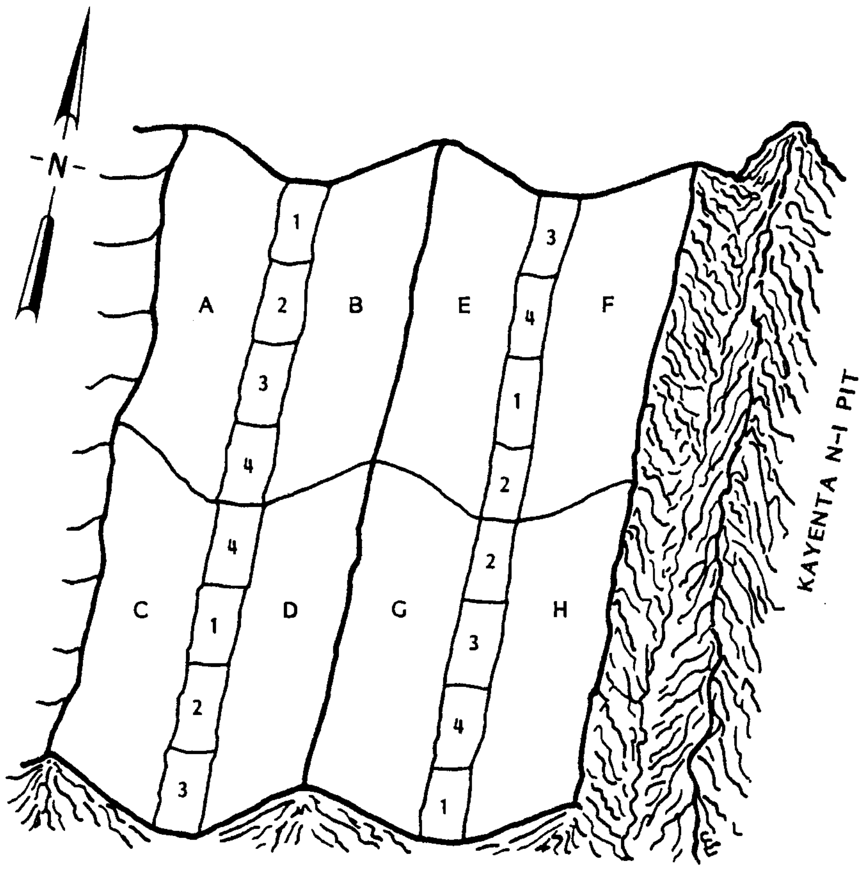
Slope Treatments

Four treatments were applied to the catchment slopes in 1979 - 1980 (See Figure 2):

1. Seeded and fertilized - slopes A and B were fertilized in the same manner as the valley bottoms and seeded with a mixture of yellow sweet clover (15 Kg/ha), crested wheatgrass (10 Kg/ha), western wheatgrass (15 Kg/ha), and four-wing saltbush (10 Kg/ha).
2. Untreated - slopes C and D were not treated after shaping was completed.
3. Compacted - slopes E and F were compacted using three scrapers with full loads running back and forth on the slopes for about 20 minutes.
4. Compacted and salted - slopes G and H were compacted in the same manner as E and F. Salt was distributed evenly over the slopes at a rate of 10,000 Kg/ha using an E-Z flow spreader pulled by a tractor.

For 1980, catchment slope treatments were maintained but the plot design of the previous year was abandoned in favor of seeding the valleys uniformly.

In 1981 (Figure 2), sod forming grass species were planted on the catchment slopes to control dust and erosion, and to comply with reclamation regulations. The catchments had become heavily invaded by Russian thistle and other noxious species and the sod cover could help control these invasions. The slopes were cleared of noxious plants by hand and planted in the winter of 1981 with a mixture of fairway crested wheatgrass, nordan western wheatgrass, and buffalo grass at a rate of 30 Kg/ha.



1979:

CATCHMENT AREA TREATMENT: AB = SEEDED AND FERTILIZED, CD = UNTREATED, EF = COMPACTED, GH = SALTED AND COMPACTED.

TEST CROPS: 1 = YELLOW CLOVER, 2 = CRESTED WHEATGRASS, 3 = FOUR-WINGED SALTBRUSH, 4 = WESTERN WHEATGRASS.

1981:

ALL CATCHMENT AREAS PLANTED UNIFORMLY WITH FAIRWAY CRESTED WHEATGRASS, NORDAN WESTERN WHEATGRASS AND BUFFALO GRASS AT 30kg/ha.

TEST CROPS: 1 = SORGHUM, 2 = ALFALFA, 3 = CORN, 4 = PINYON PINE.

FIGURE 2. Slope treatments and test crops at Black Mesa in 1979 and 1981

Physical Environment

Soil moisture was measured gravimetrically, a method advantageous in its applicability to both wet and dry ranges and small instrumental error. Difficulties with the method include inherent errors in destructive sampling, transporting, and repeated weighings.

In the first year of the study (1979), samples were taken monthly from the center and at the edge of each plot along a transect that crossed each of the 16 vegetation plots. A depth of 8 cm was selected because most plant roots early in the study were restricted to this layer. In 1980 the depth was narrowed to the 4-8 cm layer, but with the same sampling scheme used in 1979. On two dates, moisture profiles were determined by taking samples at intervals of 2 cm for the 8 cm sampling depth.

In 1982, monthly samples were taken at two depths, 3-6 cm and 15-20 cm, to allow better characterization of soil water storage. Two stations were monitored at both depths in each of the 16 vegetation plots and on each slope treatment for a total of 74 samples in the valleys and 32 samples on the slopes. On some dates, samples were collected from ridge tops and from an adjacent area that was reclaimed by Peabody with conventional methods.

Erosion measurements were made with four transects of nails and washers, established on each treatment area of the catchment slopes. Each transect consisted of eight to 10 nail/washer stations at 3 m intervals up and down slope for a total of 382 stations. A 2.5 cm space was left between the head of the nail and washer. Measurements were taken at the end of each growing season for the three years of study.

Soil chemical and physical properties were analyzed using composite soil samples, taken in January, 1981. Both surface topsoil and subsoil (mine spoil) were tested. Subsamples were taken in each of the 16 vegetative plots; all four samples for each slope treatment were mixed to obtain a composite sample. Routine soil analyses conducted by the University of Arizona Soils Water and Plant Tissue Testing Lab tested for soil fertility and potential growing problems.

Test Crops

In 1979, four species believed adaptable to local conditions were tested. The second year (1980) was devoted to achieving maximum production of the most promising species from the results of the first year. Plants that could yield greater economic returns were tested during 1981.

In 1979 the valleys were fertilized with a pelletized mixture of 6-12-6 (%N, %P, %K), at a rate of 120 Kg/ha and laid out into sixteen, 30 m long test plots, four plots to each slope treatment (Figure 2). Each of the four plots within a slope treatment was planted with either yellow sweet clover (15 Kg/ha), crested wheat grass (10 Kg/ha), western wheatgrass (15 Kg/ha), or four-winged saltbush (15 Kg/ha). These species were recommended for their adaptation to the site and usefulness as forage species by the Plant Materials Center of the Soil Conservation Service in Tucson, Arizona. The seeds were broadcast with a cyclone seeder at rates recommended by the supplier, Valley Seed Company in Phoenix, Arizona.

In the early spring of 1980 all of the valley areas were reseeded with a mixture of four-winged saltbush, crested wheatgrass, and western wheatgrass at a rate of 88 Kg/ha. This high rate (Peabody's reclamation uses roughly 30 Kg/ha) was used to insure germination because the seed was a year old and germination had been poor the previous year. Sweet clover was not included in the mixture because of its poor performance the previous year. The valleys were fertilized with NH_4SO_3 at a rate of 160 Kg/ha and with a 16-16-16 commercial mixture at a rate of 96 Kg/ha.

Flooding and ponding due to low infiltration rates was a problem in portions of the valleys. Compaction by heavy machinery may also have contributed to low infiltration rates on some plots. Consequently, an attempt was made to improve infiltration and tillage on one-half the valley area by plowing a 5 cm depth of straw mulch into the soil.

The species selected for the 1981 planting were sorghum, alfalfa, pinyon pine (Pinus edulis) and Indian corn. Sorghum was chosen for its high water use efficiency and its value as livestock feed. Alfalfa (variety Ladak) is more valuable as feed, but does not produce as well as sorghum under drought conditions. Pinyon pine is indigenous to the area and was chosen because of its potential commercial value and interest. Peabody was unable to reestablish pinyon in the area, in part because of the moisture requirement. Indian corn was chosen because of its high social value. It is considered the most important crop by the Indian farmers on the Mesa.

Pinyon pines (150) were planted in March, on a 1 m x .6 m spacing. At the same time, extra seedlings were also planted on the same spacing in a reclaimed area adjacent to the site. Pinyon pines grow slowly, and even at this close spacing would probably not be competing for several years. Since first year survival is all that could be measured under the time constraints of the project, interspecific competition was not believed to be a problem. The entire site, including catchment and slopes, was fertilized with 16-48-0 commercial mix at a rate of 180 kg/ha at the time of planting.

Indian corn, sorghum and alfalfa were planted by hand in May, following replowing for weed control. Indian corn seed was supplied by the Southwest Traditional Crop Conservancy Garden and Seed Bank, from seed obtained near Hopi on Black Mesa. Corn was seeded with six seeds per hill at a depth of 6 cm and spacing of 2 m x 2 m per hill. The sorghum chosen was a sorghum x sudangrass hybrid (DEKALB SX-17), which was developed at the University of Arizona for dry areas. Sorghum seeds were also planted in hills, with four to eight seeds per hill at a depth of 5 cm and spacing of .5 m x 1 m. Alfalfa was planted in rows about .3 m apart, smoothed over, and firmed in by foot. Part of each new vegetation type was fenced as additional protection from livestock.

Plant performance was monitored throughout the three years of study. Vegetation density (number of plants per square meter) was measured each month and plant production (grams of dried biomass per square meter) was measured at the end of each growing season.

In 1979, three transects 15 cm wide and extending across the width of valley areas were established on each of the 16 vegetation treatment plots, for a total of 48 transects. Measurements were made monthly for plant density and growth. New 1 m x 4 m transects were established in 1980. These were placed across the center of each of the 16 vegetative plots, on the AB fertilized and seeded catchment area and on Peabody's topsoiled reclaimed area (Figure 2). Plants were grouped into two classes, those planted in 1979 and those planted in 1980. Plots were monitored monthly for density and growth progress. Near the end of the growing season, 1 m^2 samples, were collected on all areas to determine annual production of aboveground biomass (g/m^2).

In 1981, five transects each .2 m by 4 m (.8 m^2) were established on the eight unchanged vegetative plots in the valleys and on each side slope treatment, for a total of 80 transects. This increased number of samples was used to take into account the patchiness of vegetative cover. The transects were monitored monthly for density and height.

Several methods were used to monitor the newly established higher value plant plots. Alfalfa was monitored on five transects (.2 x 4 m), and checked for plant density and growth. Pinyon pine seedlings were checked for survival. Individual corn and sorghum plants or hills were monitored for germination and growth.

NUCLA SITE

The Nucla site, established July 1980, was located in Montrose County, southwestern Colorado, on Peabody Coal Company's Nucla Mine, elevation 1,900 m. The water harvesting study area consisted of a spoil site and a topsoil site. The spoil site was "Y" shaped and consisted of two converging valleys about 75 m long, with the slopes at a 14% grade and the valley at a 7% slope. The topsoil site was a 75 m single valley with the slopes at a 7% grade. Both the topsoil and spoil sites were "V" shaped in cross section. Site construction consisted of moderately reshaping the existing configuration to achieve as uniform a slope as possible for the catchment areas. The grading, however, was not as precise as was done for the Black Mesa site since only bulldozers were available.

The climate of the area is similar to Black Mesa. Average annual precipitation is 300 mm, with three quarters occurring in the winter as snow. Summer storms occur as small convective cells, resulting in localized intense precipitation. Average annual air temperature is 8°C and average frost-free season is 110 to 130 days.

The natural vegetation of the area is Utah Juniper and pinyon pine, with an understory of galleta, blue gramma, fendler threeawn, Indian rice grass, needle and thread, douglas rabbitbrush, and broom snakeweed. When the range condition deteriorates, fendler threeawn, wheatgrass, plains prickly pear and broom snakeweed increase.

Undisturbed soils in adjacent areas are generally torriorthents, with little or no soil development. Mine spoils are derived from shales and include many pieces of coal. Unlike the Black Mesa mine spoils, the Nucla spoils are generally quite permeable and do not exhibit surface crusting.

Slope Treatments

Unlike the Black Mesa work, the objective at Nucla was to determine the benefits of a modified water harvesting system that would also meet the requirements of strip mine regulations. Accordingly, a uniform treatment was applied on both the catchments and the valleys to determine if overall production of the configuration could be increased over that of conventional regrading.

Physical Environment

Monthly measurements (May-August 1981) of soil moisture were obtained gravimetrically as at Black Mesa. Samples were taken from the 3-6 cm and 15-20 cm depths. On the spoils site, 24 sampling stations were used each month, eight on the east slopes, eight in the center, and eight on the west slopes. These stations are about 16 m apart along the orientation of the valley. At each station, samples were taken at both depths, for a total of 48 samples. The topsoiled area was monitored in the same manner but with samples taken at this site only in July and August.

Erosion was monitored with nail and washer erosion transects, consisting of 60 nail/washer stations established at 1.6 m intervals along the transect and across the valleys and catchments. Ten transects of four to seven nail and washer stations each were monitored at the end of the growing season.

Test Crops

In February 1981, both valleys and catchments were raked by hand and planted to species recommended by the Soil Conservation Service in Norwood, Colorado. The seed mixture was galleta grass (*Hilaria jamesii*), Indian rice grass (*Oryzopsis hymenoides*), side oats grama (*Bouteloua curtipendula*), crested wheatgrass (*Agropyron cristatum* var 'Nordan') and alfalfa (*Medicago sativa*). The first three species on the list were supplied by the Norwood Office; alfalfa seed was that used for the Black Mesa site, and crested wheatgrass seed was obtained from local seed supplies. Seeds were broadcast with a cyclone seeder at a rate of 14.6 Kg pure live seed per ha and raked in by hand.

Vegetation at Nucla was monitored monthly for plant density and growth and in August for biomass production. Quadrats, each 1 x 1.5 meters, were established on the spoils site in May 1981. Eight of these quadrats were set in each valley bottom and each side slope for a total of 16 valley quadrats and 32 slope quadrats. During the growing season plant density was monitored by counting individual plants in the plots each month. Plant production was measured in August by clipping and drying.

On the topsoiled site, plant density was measured in quadrats the same dimensions as the spoils site, with eight quadrats in the valley bottom and eight on the side slopes. Measurements of naturally seeded vegetation were taken in July and August. Aboveground biomass production was measured in August by clipping and drying.

ECONOMIC ANALYSIS

The economic feasibility of the water harvesting reclamation system hinges on whether or not its net benefits exceed those of conventional reclamation. A preliminary analysis assessed the net private benefits of each system using cost and income data specific to the Kayenta mine area in Navajo County, Arizona.

To compare the alternative reclamation systems, the present value of direct net benefits (income from subsequent land use minus production and reclamation costs) was calculated for grazing (conventional reclamation) or for cropping (water harvesting reclamation). In calculating the net present value of each system, all costs and prices were converted to 1979 dollars using the Consumer Price Index and a real discount rate of 4 percent.

In the absence of direct experience, the analysis necessarily used several important assumptions and must therefore be considered only preliminary. These assumptions include: a) 50% of the precipitation will run off the slopes and be relatively evenly delivered to crops in the water harvesting valleys; b) crop yield levels with water harvesting and no supplemental irrigation are equal to or greater than 50% of normal yields with flood irrigation, and c) typical crop production methods and costs apply to the water harvesting "strip farming" configuration. In the light of subsequent experience at Black Mesa, these assumptions appear reasonable; nevertheless, a fully functioning water harvesting cropping operation would be required to demonstrate their validity fully.

RESULTS

Results of the studies at Hanford, Black Mesa and Nucla are presented below, along with the results of the economic analysis.

HANFORD SITE

Physical Environment

Insolation differences between valley direction were studied to determine if EW or NS valleys received more sunlight. The consistent order (FC, EW, NS) of monthly means of insolation (Figure 3) suggest the presence of a difference between the sites, but the means for any one observation period are not significantly different ($p \leq 0.05$). It was initially thought that shading by the slopes would decrease available sunlight in the NS valleys. However, the presence and orientation of the slopes had no significant effect on the amount of sunlight received by the cultivated areas.

Wind run (Figure 4) was studied to see if differences between valley direction could be related to differences in soil erosion or evaporative losses. Monthly means of wind run in the NS valleys and flat

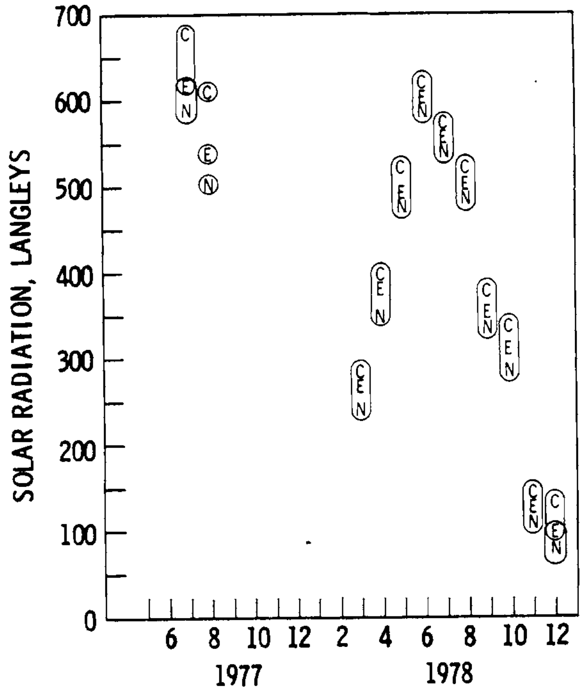


FIGURE 3. Monthly means of solar radiation (Langleys) at the Hanford site, means within circles are not different ($p \leq .05$). C = flat control, E = east west valleys, and N = north south valleys.

control frequently were greater than the EW valley, but no specific seasonal pattern is evident. Wind direction would seem to be a factor in increasing the wind speed down a valley by a channeling effect of the slopes, but the monthly averages obscure the effect of a variable wind direction. The wind environment in the valleys was, thus, unpredictably different.

Air temperatures in the vegetative canopy (Figure 5) were studied in each valley to identify differences that could be attributed to slope treatment and valley direction. Maximum and minimum canopy (30 cm high) air temperatures were read weekly. Neither maximum nor minimum air temperatures differed between valleys, suggesting the air temperature variable need not be considered when choosing valley orientation or slope treatments.

Precipitation (Table 1) was recorded to insure that each valley received the same amount of water. Monthly precipitation totals for the 1978 growing season (October 1977 through September 1978) were not statistically different between the areas ($p \leq .05$), suggesting that orientation of the catchment slopes had little effect on amount of precipitation received. Most of the rain came in the winter when temperatures were too low for plant growth, although there were several rain events in July which came too late to be of value to the wheat.

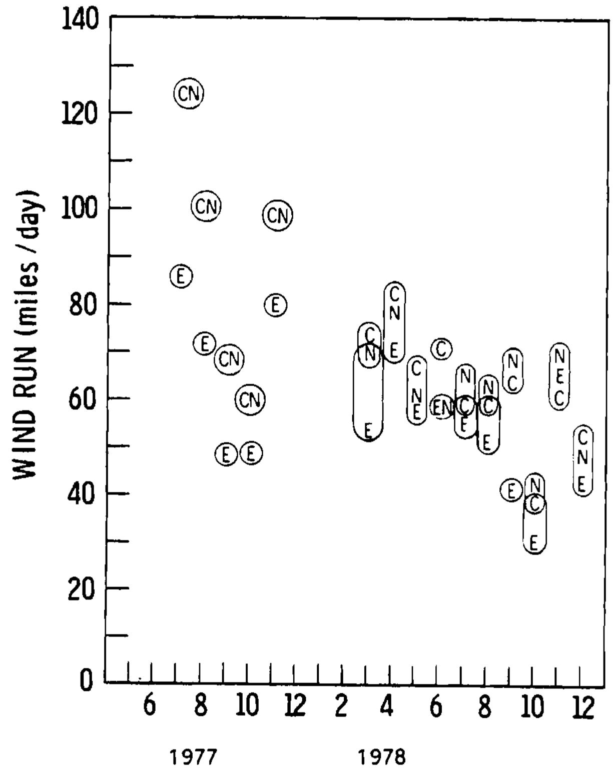


FIGURE 4. Monthly means of wind run (miles/day) at the Hanford site. Means within circles are not different (p<.05). C = flat control, E = east west valleys, and N = north south valleys.

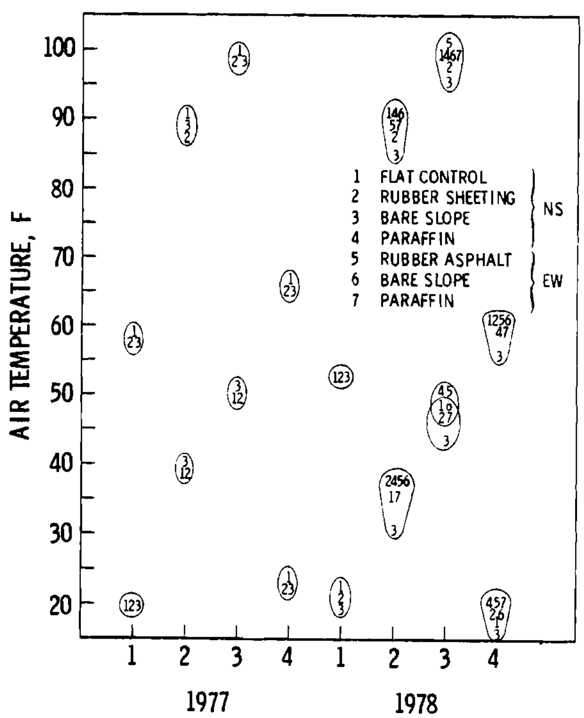


FIGURE 5. Quarterly (3 month) means of air maximum and minimum temperature at 30 cm height at Hanford site. Values in same circle are not different (p<.05).

Soil water content through the growing season was studied to determine the effects of the slope treatments. The water available to the wheat for the growing season (October 15, 1977 to June 20, 1978) calculated with eq. 1 is shown in Table 2. As expected, the rubber sheeting treatment had the highest value and was 85% of a maximum value of 382,788 bar·cm·days (14.7 bars·105 cm·248 days). A surprise, though, was the difference between the flat control with no adjacent slopes and the bare slope controls. The lesser water content of the flat control suggests that, even though the porous bare slope controls produce little if any runoff, the physical presence of the slopes apparently gave a sheltering effect that reduced evaporative losses. (The bare slopes never showed any indication of runoff such as erosion or ponding).

The coefficient of variability between the four moisture sensor stations (Table 2) is a measure of the homogeneity within a valley with respect to the distribution of the runoff between stations. The least

TABLE 1. Monthly totals of precipitation (inches) at the flat control, EW valley and NS valley for the 1978 growing season at the Hanford site. (Rain gauge not in place in EW valley until May 1978.)

Month	Flat Control	EW Valley	NS Valley
October 1977	0.01	--	0.01
November 1977	0.66	--	0.66
December 1977	1.95	--	1.90
January 1978	1.50	--	1.40
February 1978	1.10	--	0.97
March 1978	0.74	--	0.70
April 1978	0.44	--	0.42
May 1978	0.83	0.86	0.84
June 1978	0.40	0.47	0.42
July 1978	1.02	0.96	1.00
August 1978	0.75	0.74	0.84
September 1978	0.18	0.20	0.18
Total	9.58	--	9.34

homogeneous was the paraffin treatment on cobbles, and the most homogeneous was the rubber sheeting treatment. The paraffin apparently sealed the soil surface better in some areas than others, and there was evidently enough runoff in the rubber sheeting treatment to moisten the entire width equally.

Paraffin on rocky (NS) or smooth (EW) surfaces compares better to the rubber sheeting than the rubber asphalt (Table 2) even though the amount of paraffin applied was inadequate to seal around the cobbles. While a precise estimate of the cost of the three treatments is not possible, the ranking from the most to least expensive is rubber sheeting, rubber asphalt, and paraffin. Thus, paraffin appears to be worthy of further evaluation as a slope treatment.

TABLE 2. Available soil water (bar·cm·days)[1]

Valley	Soil Water available During growing season (bar·cm·days)	Coefficient of variation % within valley	Available Soil Water as a % of Rubber Sheeting Treatment
North South			
Flat Control	189,241	8.6	58
Rubber Sheeting	325,460	1.5	100
Bare Slope Controls	221,431	6.4	68
Paraffin on Cobbles	267,443	16.4	82
East West			
Paraffin on Soil	290,038	4.9	89
Bare Slope Control	223,226	2.8	69
Rubberized Asphalt	219,401	2.9	67

[1]The coefficient of variation (standard deviation/mean) indicates valley variability between the four (two in Flat Control) stations.

Test Crops

The wheat yield in each valley is shown in Table 3. The production in the flat control, 5.0 bu/ac, is the yield expected from a totally planted flat area. The production in the rubber sheeting valley, at 22.7 bu/ac, is an annual yield. Dryland wheat production typically is on a summer fallow rotation in which wheat is planted in alternate years. The intervening year is used to accumulate soil water. Since the 22.7 bu/ac is an annual rate of production, it compares very well with the rate of alternate year production of 27 bu/ac for Washington in 1973 (21).

The low wheat productivity in the EW valleys, compared to the NS valleys, appears to be related less to availability of water than soil erosion shortly after germination. During November 1977, high winds removed up to an estimated 5 cm of soil from the EW valleys. Soil erosion in the NS valleys at the same time was negligible. As a result of the death of many wheat seedlings, weeds (*Salsola kali*) became established in the sparse wheat and probably further reduced the wheat yield via competition.

The coefficients of variation for wheat production (Table 3), which indicate within-valley variation, suggest that production was more uniform in the wettest valleys (e.g. rubber sheeting). Perhaps distribution of water over the surface of the cultivated area was inadequate in the drier valleys. For example, only the wheat plants on the edge of the flat control where competition for water was less produced plump kernels.

Seasonal soil water values were correlated with wheat production for the NS and EW valleys. The correlation in the NS valleys ($y = -21.48 + 1.37 \times 10^4 X$, $r^2 = .98$) is highly significant ($P \leq .01$) and

TABLE 3. Wheat production at Hanford site (1977)

Valley	Bushels/acre	Coefficient of Variation (%)	Percent of Rubber Sheeting
North South			
Flat Control	5.0	127	22
Rubber Sheeting	22.7	32	100
Bare Slopes	7.5	62	33
Paraffin	16.5	44	73
East West			
Paraffin	4.5	46	20
Bare Slopes	4.5	55	20
Rubberized Asphalt	4.2	53	19

greater than the correlation in the EW valleys ($y = 1.09 + 1.26 \times 10^5 X$, $r^2 = .29$, NS). Thus, the wheat production in the NS valleys was strongly influenced by slope treatment and resultant water availability. In contrast, slope treatment in the EW valleys had little effect on wheat yield, due in large part to the wind soil erosion and death of wheat seedlings.

Apple trees were planted in 1981, but the production of apples cannot be evaluated due to termination of the program. The survival of the trees in the first year was 100%, due in large part to the addition of supplemental water to establish the trees in their first year.

The grapes at Hanford grew as well as commercial vineyards their second year when they were irrigated only with water harvesting. However, in 1978 the unusual winter cold and a very severe defoliation by grasshoppers in the spring killed most plants. In 1979 the dead plants were replaced. Grape production begins the third year after planting the rooted cuttings; the first production from these new plants will be in 1982, but cannot be evaluated due to termination of the program. Survival of the grapes, watered in the first year only, appeared to be nearly 100%, showing promise of at least survival even in the untreated slope areas. A few deaths occurred on the Flat Control area where wind probably dessicated the plants more than in the valleys. It should be noted that survival is not a dependable indicator of production, as grapes will survive extreme stress without significant fruit production. Production and market quality of grapes are presently unknown for water harvesting systems.

Alfalfa was harvested in August, 1981 by cutting a 1 m swath down the middle of the planted area (30 m length). The cut material of the four varieties was combined (no evident visual differences), and weighed in the field. The results (Table 4) must be interpreted in terms of the supplemental water given to establish the stands. If the study were continued, results would be available for water from the catchment areas only, yielding a more realistic test of the water harvesting environment on alfalfa production. The EW valleys produced the most alfalfa, but had poor wheat production; the reasons for this are not clear. It is significant that the valley with no wind protection, the flat control, had too little to harvest, illustrating the value of the catchment slopes in providing shelter from the wind.

Findings at the Hanford site include the following:

- Insolation, wind run, canopy air temperature and precipitation were not different between valleys.
- Slope treatments were different and effective in increasing runoff to irrigate the valley floors.
- Paraffin was the most cost-effective catchment area treatment.
- The slopes provided shelter to reduce water loss.
- Wheat yield, as increased by waterharvesting was at a commercially acceptable level.
- Grape vegetative growth was comparable to commercial vineyards.

TABLE 4. 1981 alfalfa production at Hanford[1]

	Pounds/Acre	Kg/ha
North South Valleys		
Flat Control	--	(Too thin to harvest)
Rubber Sheeting	2744	3049
Bare Slopes	600	666
Paraffin	872	969
East West Valleys		
Paraffin	4029	4477
Bare Slopes	1095	1216
Rubber Asphalt	1260	1400

[1]Values are wet weight for four varieties combined as no intervarietal differences were observed.

BLACK MESA SITE

Site construction was complicated by the requirement to obtain two mound and valley systems with approximately the same slope lengths and inclinations. Because of differences in the height of the original spoil rows, more material had to be moved than would be necessary if the method were to be used on an operational basis where uniformity would not be important. Complications also arose because the equipment operators were unfamiliar with the type of grading required. Considerable time was lost due to machinery breakdowns, difficulties in obtaining equipment at times when needed to complete a sequence of operations, and communication problems with operators through the union hierarchy. Solutions to these problems could reduce construction time and costs by 10 to 20 percent.

Physical Environment

Soil analyses indicated some differences between the topsoil and spoil. Both soils were between pH 7.7 and 7.4 with an electrical conductivity that varied between 3.17 and 1.46 mmohs. Macronutrients were generally low. The spoil consisted of 57% sand, 25% silt, and 18% clay, while the top-soil consisted of 37% sand, 41% silt, and 22% clay. Field capacity in the spoil was 23% water, and in the topsoil 15% water. At -15 bars (-1.5 mPa), the water content in the spoil was 12%, and in the topsoil, 7%.

Soil moisture (Table 5) was measured during 1979 and 1980 to determine differences in the runoff efficiencies of catchment slope treatments. No consistent differences in soil moisture in the valleys due to slope treatment were detected. In the spring and early summer when differences in runoff efficiencies would be most pronounced, the moisture content of soils in the valleys receiving runoff from the salt-compacted slopes (believed to be the most effective treatment) did not differ significantly from that in valleys receiving runoff from other slopes. In contrast, moisture content of soils in valleys of untreated slopes appeared to be higher (but not significantly so).

Soil moisture in August of 1979 and 1980 and in September 1980 was significantly higher for the salt-compacted treatment. The action of the sodium in dispersing colloids no doubt helped to seal the soil and create the ponding observed in the valleys during wet periods. Salt also helped create soil crusts and otherwise inhibited plant growth, reducing evapotranspiration. The slightly higher moisture content of valley soil during August 1980 may have been due to the presence of salt rather than to runoff efficiency of the catchment slope.

In 1981 a greater emphasis was placed on soil moisture measurements; sampling frequency was increased and an additional soil depth was sampled. The moisture content of the soils in the valleys at both depths sampled (Table 6) was about midway between field capacity and the wilting point at the beginning of the season in May. It was at or below the wilting point on the ridges and side slopes of the catchment areas, indicating that the water harvesting was effective at the critical time of plant germination and initial establishment. This could be significant since slopes of the catchment are representative of normal regrading. If the slopes were topsoiled as done in conventional reclamation, however, runoff to the valleys could be decreased.

Soils at all locations and depths dried out considerably during the summer. Though ridge tops appeared to be consistently drier than the side slopes, differences were not significant due to a large variance. The catchment slopes appeared drier than the valleys (not significant), not surprising since the evapotranspiration on the bare slopes would be less than in the vegetated valleys. Soil moisture in unplowed valleys was not significantly different from that of the catchment slopes. During the three years of study, fine material washed from the catchment slopes into the valleys, inhibiting infiltration. Soil crusting and rill erosion created by runoff are indications that occasional tillage would be important in operational programs.

TABLE 5. Effect of slope treatment on valley soil moisture on Black Mesa. Values are mean ± 95% confidence limit. N is 12 in all cases. Treatments: AB = seeded, CD = untreated, EF = compacted, GH = compacted and salted.

Date	AB	CD	EF	GH
			1979	
7-13	3.21 ± 1.00	8.50 ± 2.30	5.72 ± 1.22	8.82 ± 2.00
8-17	9.47 ± 3.12	8.81 ± 2.27	7.96 ± 1.17	12.85 ± 3.01
			1980	
5-10	16.72 ± .98	19.79 ± 2.02	14.27 ± 2.19	15.89 ± 2.65
6-18	4.77 ± .81	4.77 ± .69	3.89 ± 1.25	3.10 ± .62
7-16	4.06 ± .70	4.35 ± .57	5.07 ± 1.05	5.93 ± 1.22
8-11	2.05 ± .37	2.22 ± .30	2.03 ± .33	3.03 ± .71
9-11	13.69 ± 1.07	15,11 ± 3.78	13.26 ± 2.32±	17.76 ± 4.46

During the dry period of May and June, no differences were observed in soil moisture between plowed and unplowed valleys. However, after rainy periods in July and August, the moisture content of plowed valleys was about twice as great as that of the unplowed valleys (significant). Soil water content in the unplowed valleys never rose above the wilting point at either soil depth. In contrast the plowed valleys were consistently well above the wilting point during the rainy periods. The effect of ponding on soil moisture measurements was demonstrated by the August sampling. Ponding occurred in both unplowed valleys, but rarely in the plowed valleys.

TABLE 6. Black Mesa soil moisture - 1981. Mean % moisture by weight ± 95% confidence intervals.

	n	May	June	July	August
			3-6 cm		
Ridge tops	4	9.61 ± 2.66	4.73 ± 1.98	5.88 ± 1.29	-
Slopes	16	10.09 ± 1.61	4.64 ± .59	5.35 ± .62	4.46 ± .52
Plowed Valleys	16	14.22 ± 2.68	3.91 ± 1.27	13.57 ± 2.34	8.14 ± 2.18
Unplowed Valleys	16	13.69 ± 2.15	3.72 ± 1.48	6.39 ± 2.58	6.66 ± 3.56
			15-20 cm		
Ridge tops	2	6.18	3.69	7.41 ± .96	-
Slopes	16	12.01 ± 2.93	6.26 ± 1.25	8.39 ± 1.55	5.81 ± .56
Plowed Valleys	16	15.47 ± 3.60	7.73 ± 2.35	15.99 ± 1.86	10.59 ± 2.56
Unplowed Valleys	16	12.88 ± 2.49	5.33 ± 1.42	7.25 ± 2.57	9.23 ± 7.73
Precipitation (mm)		1	15	75	8

The north and south orientation of the valleys may be an important factor, as prevailing winds in summer are out of the southeast. These mounds and valleys thus provided little protection from dessicating winds; in fact, they may funnel summer winds. Favorable moisture conditions in the valleys persisted in spite of this extra stress, implying greater moisture availability from water harvesting.

Data from the nail and washer transects (Table 7) for 4/79 - 12/80 and 12/8 - 8/81 were separated because December 1981 seeding of the slopes destroyed existing transects as well as loosened the upper soil layer. Assuming a bulk density of 1.30 g/cc, average soil loss on the catchment slopes for the 1979-1980 period was calculated as 19,200 Kg/ha/yr, higher than that allowed by the Surface Mine Control and Reclamation Act of 1977. The catchment slopes were seeded in December 1980 to control erosion, and the drill seeding actually increased erosion (52,000 Kg/ha for the period after seeding). This rate is expected to decrease with time, especially with vegetation establishment.

The standard errors associated with the erosion measurements were larger than the means in all cases. This was due to localized deposition (measured as a negative loss) and to the presence of rills on the slopes. With this large sampling error it was difficult to determine differences in soil loss due to slope treatment.

TABLE 7. Black Mesa erosion summary. Values represent changes in soil level (loss) on nail and washer sets expressed in mm.

Slope Treatment	1979 - 12/80			12/80 - 8/81		
	n	mean	standard deviation	n	mean	standard deviation
A seeded	26	2.26	5.98	27	8.87	18.73
B seeded	18	3.17	5.60	18	2.89	11.10
C untreated	23	2.83	6.07	25	2.24	13.00
D untreated	14	3.71	5.35	19	2.53	17.06
E compacted	20	3.65	7.15	24	3.67	19.33
F compacted	24	3.02	8.52	26	7.35	14.60
G compacted-salted	16	1.62	7.05	21	6.24	13.62
H compacted-salted	20	2.95	9.18	20	2.90	12.31
cumulative $\bar{x}$		2.90			4.59	

Test Crops

With the exception of the salt-treated catchment where yellow clover and western wheatgrass did not do well, no consistent differences in the performance of vegetation between the other catchment treatments were observed. The poor performance in the salt treatment area is attributed to heavy crusting and possibly increased salinity in the planted areas.

Plant densities within the vegetation treatments were not high the first season. However, seeded plants became established in all but three transects, (Table 8) where persistent ponding was evident. Some Russian thistle and yellow mustard established naturally on some of the plots. Yellow clover and crested wheatgrass had the highest densities and did not differ greatly in their performance, though western wheatgrass and four-winged saltbush did not become well established. A number of factors, including seed source, viability, and temperature and moisture requirements, could have been responsible for poor germination of the latter two species. A slight decrease in plant density was observed between sample dates and can be attributed to an absence of rain between samplings.

Despite poor initial establishment, both western wheatgrass and four-winged saltbush withstood the extended dry period without significant losses. Saltbush appears to be hardy enough to withstand the adverse effects of ponding in the salt treatment, but yellow clover and crested wheatgrass declined between samplings.

TABLE 8. Density of planted species at Black Mesa[1]

Catchment Treatment	Density Plants/m^2			
1979	7/13	8/18		
AB	36.16 ± 24.64	9.2 ± 3.76		
CD	52.67 ± 42.38	5.42 ± 2.33		
EF	52.58 ± 30.91	6.32 ± 1.14		
GH	16.04 ± 27.07	5.43 ± 5.08		
1980	6/19	7/26	8/11	9/12
AB	20.25 ± 13.84	22.60 ± 10.51	19.00 ± 10.73	15.25 ± 10.75
CD	43.31 ± 29.07	37.45 ± 24.55	29.06 ± 23.69	21.75 ± 20.00
EF	32.94 ± 22.06	27.19 ± 12.37	24.19 ± 12.19	18.45 ± 11.52
GH	21.62 ± 21.32	31.06 ± 19.27	29.44 ± 16.84	28.12 ± 18.01
Precip. mm	0	15	2	49
1981	5/26	6/28	7/30	8/19
AB	34.37 ± 16.49	21.75 ± 2.81	11.62 ± 2.85	14.62 ± 5.32
CD	18.06 ± 7.4	15.62 ± 4.62	14.50 ± 6.35	10.75 ± 7.85
EF	14.00 ± 8.28	10.00 ± 3.95	11.37 ± 4.82	9.62 ± 4.90
GH	11.53 ± 5.34	10.37 ± 7.62	10.50 ± 6.62	11.12 ± 11.31
Precip. mm	1	15	75	8

[1]Values are means ± 95% confidence intervals. 1981 values are from unchanged plots. Treatments: AB = seeded and fertilized; CD = untreated; EF = compacted; GH = compacted and salted.

Density was not uniform over the plots as indicated by differences between transects within the vegetation treatments (Table 8). Total dried biomass (Table 9) for 1980 uniform seeding of the valleys yielded 147.25 g/m^2 as compared to 15.0 g/m^2 for the non-topsoiled catchment slopes and 103.3 g/m^2 for Peabody's topsoiled area (measured on an adjacent area in the same manner employed on the study site). Plant density decreased as the growing season progressed for each year of study; moreover, the sampling error was large for all years. Because a variety of life forms was planted (i.e. sod formers, shrubs, forbs and clump grasses), one transect might intercept mostly shrubs, while another transect might encounter mostly grasses.

Plant densities measured near the end of the growing season were higher in 1980 and 1981 than in 1979, possibly because it was easy to mistake goosefoot (Chenopodium sp) for very young saltbush. Nevertheless, comparison of the 1980 data with the more exact data of 1981 indicates the maximum density (12 plants per square meter) that might be expected in the area had been obtained. This is three times the density Peabody uses as a criterion for successful revegetation.

In 1981 attention was given to annual weed species (Table 10). Tumbleweed (Salsola kali) was the most dominant species on both the catchment slope and valleys, though large numbers of tumbleweed plants may be misleading. Nearly all of the tumbleweed plants were only a few cm in height.

Crested and western wheatgrass were the only plants encountered in the transects on slopes. Although side oats grama (Bouteloua curtipendula) and buffalo grass (Buchloe dactyloides) were used by Peabody, they failed to become established on the catchment slopes. Side slopes had much lower plant densities than did the valleys, less than one plant per square meter. However, these are the results of only one growing season.

TABLE 9. Comparison of total dried plant biomass (g/m^2 collected from each collection area for the four plant species grown during the 1980 season).

Dried Plant Biomass (g/m^2)
Collection Areas

Plant Species	AB	CD	EF	GH	Valley I	Valley II	mean
Yellow Clover	162.5	106.0	125.0	Flooded	134.2	125.0	131.2
Crested Wheat-grass	75.5	108.5	192.0	140.0	92.0	166.0	129.0
Four-Winged Saltbush	312.0	127.5	58.0	402.0	220.8	230.0	225.4
Western Wheat-grass	123.0	99.5	36.5	156.0	111.2	96.2	103.8

TABLE 10. Summary of 1981 Black Mesa vegetation expressed as average plant densities (plants/m^2) and 95% confidence level.

Area/Catchment	May	June	July	August
Catchment slopes				
planted species (1981 seeding)	2.3	2.5	1.06 ± .34	.43 ± .52
goosefoot ssp	6.7	3.4	3.44 ± 4.19	3.41 ± 3.06
tumbleweed	1224	283	371 ± 106	200 ± 57
Valley bottoms				
planted species (1979 and 1980 seeding)	14.4	9.2	11.18 ± 2.97	11.65 ± 3.68
goosefoot ssp	39.8	47.4	17.52 ± 9.50	12.72 ± 6.57
tumbleweed	448	312	317 ± 109	200 ± 80

Survival counts of pinyon pine were taken on August 17. The survival rate was 60 percent in the valleys, while pines planted on an adjacent area which had been topsoiled and reseeded had a survival of only 41 percent. Researchers at the Rocky Mountain Forest and Range Experiment Station in Flagstaff, Arizona believe that five years are necessary for Pinyon establishment. Grasses, forbs and shrubs were prolific in the pine plots, probably the result of plowing and mulching. Despite this competition, the pines have done extremely well. Some mortality may be a result of water excess rather than water stress.

Establishment of sorghum was excellent. A total of 384 hills were counted in August. Rains in July resulted in germination of dormant seeds and rapid growth of existing seedlings. Range in height of the plants in August was from 15 to 180 cm and some were already tasselling. In September the individual plants ranged from 1 to 2 m in height, with the majority of plants in the range of 1.6 m. The bright green appearance of plants indicated a high vigor. Biomass in September averaged 1.51 metric tons per ha. The overall world average is 1.04 metric tons/ha (22); under intensive cultivation and irrigation in areas with long growing seasons in the U.S., production is about 6.25 metric tons/ha (23). Thus, water harvesting is obviously well suited to growing this crop. The carrying capacity of the better surrounding range is 5 AMU (animal month unit). This implies a production of 273 kg of edible dry plant material per month. Only one ha of sorghum would be required with the water harvesting system to carry one AU (animal unit) through five months of winter, as compared with 260 ha required of the better range lands in the Black Mesa area.

Corn establishment was satisfactory. Because 2 m x 3 m spacing was used, density measurements were inappropriate. Overall germination rates of 41% in June increased to 65% in August as a result of July rains. Production based on the limited sample was estimated at .21

metric tons per ha of dried material. Corn ears were estimated at 6,578/ha. Flooding of the plots occurred several times during the growing season. With drainage, production could probably be increased significantly.

Alfalfa performance improved greatly as a result of July rains. In June, alfalfa density was less than 1 plant per m^2. In August, measurements on the same transects averaged 56 plants per m^2, a higher than usual value for field alfalfa. These plants were not evenly distributed and often crowded in some spots as a result of hand seeding techniques. Since alfalfa is perennial, density will probably decrease, and the remaining plants will be larger next season. Estimates of production were .31 metric tons per ha.

Findings at the Black Mesa Site include the following:

- Difficulty and cost in constructing the test area could be reduced if construction were done on a routine basis.
- Slope treatments did not differ in effect on valley soil water content.
- Sodium from the salt-treated slopes caused crusting and ponding in some areas.
- Except in areas of ponded water, vegetation was established in 1979.
- No differences in vegetative establishment between slope treatments were observed.
- Vegetation was more abundant in the water harvesting area than in conventionally reclaimed areas of the same age.
- Sorghum production was above world average yield.
- Soil erosion from the catchment areas was higher than allowed by the Surface Mine Act, but the data are too variable for firm conclusions.

NUCLA SITE

Physical Environment

The analysis of the Nucla soils showed little difference between the topsoil and spoils. The spoil material had a pH of 4.7, electrical conductivity of 3040 mmhos, and consisted of 33% sand, 40% silt, and 27% clay. Water content of the soil at field capacity was 14%, and at -15 bars was 8%. The topsoil had a pH of 7.3, electrical conductivity of 1980 mmhos, and was 45% sand, 27% silt and 28% clay. Water content at field capacity was 16%, and at -15 bars, 9%.

TABLE 11. Nucla spoils erosion summary - 1/81 - 8/81

Site	n	mean Loss (cm)	standard deviation	soil loss tons/acre
Slopes	51	4.46	7.07	25.0
Valleys	9	10.00	34.25	57.8

In 1981 soil moisture was measured on slopes and valleys to determine if the valleys had significantly higher soil moisture content. On the spoils site, no significant difference in soil moisture between slopes and valleys was found on any sampling date at either depth, except for August 17, when the valley had significantly higher soil moisture at the deeper depth (Table 12). No runoff-producing rains occurred prior to August that year. A greater average soil moisture was recorded at the deeper depth on the spoils site for all sampling dates.

1981 was a wet year at Nucla, with 138 mm of rain occurring during the growing season. Soil moisture was generally above the wilting point on all sampling dates at both depths except on June 29, and on July 27 at 3-6 cm (slopes). The topsoiled site was higher in soil moisture in the valleys than the catchment slopes in July, but not in August. Unlike on the mine spoils, the water harvesting may be effective on topsoiled sites during dry periods.

Soil erosion was measured at Nucla on the mine spoil site via the nail and washer method (Table 11). Nearly all erosion on the site was the result of a single intense storm system which persisted for about a week in mid-July and caused considerable erosion on the catchment slopes (about 56,000 Kg/ha) with resulting deposition and occasional rill erosion in the valleys.

Test Crops

The site was seeded in February after a dry winter of very light snowfall. Water harvesting may favor snow accumulation. Though we hoped to demonstrate this in the windy environment of Nucla, the period following seeding was dry well after the last date for successful seed germination and plant establishment.

Quadrats of .5 m^2 were monitored monthly on the mine spoils site and in July and August for the topsoiled site. On the spoils site, no significant differences in plant densities between the slopes and valley bottom for any of the species present were observed, no doubt due to the lack of runoff (Table 13). On the topsoiled site, which represents natural seeding, a greater number of forbs were observed in the valleys than on the slopes on both sampling dates, but sampling error was high. One value which may seem anomolous is the count of 14.5 forbs in August for the spoils valley. Many geranium seedlings located under protective tumbleweeds were counted after cutting the tumbleweed for biomass measurements.

TABLE 12. Nucla soil moisture in 1981. Values are means ± 95% confidence interval.

Site		5/21	6/29	7/27	8/17
Spoils					
Sideslopes	3-6 cm	8.59 ± .66	5.02 ± .51	7.36 ± 1.57	13.71 ± 2.69
	15-20 cm	10.01 ± 1.69	7.69 ± 1.60	10.00 ± 1.84	8.83 ± 1.59
Valleys	3-6 cm	8.66 ± .75	5.69 ± 1.77	8.37 ± 1.32	13.38 ± 1.84
	15-20 cm	10.06 ± 1.45	8.13 ± 1.21	11.31 ± 1.09	11.45 ± .88
Topsoil					
Sideslopes	3-6 cm			4.30 ± .98	12.08 ± 1.28
	15-20 cm			6.31 ± .71	11.28 ± 1.37
Valleys	3-6 cm			6.96 ± 1.88	13.28 ± .75
	15-20 cm			9.58 ± 1.71	14.05 ± .90
Precipitation (mm)		11	12	65	50

Precipitation values are obtained from the Rimrock Report of Nucla, Colorado, collected about 3 miles from Nucla.

Grass density increased in August because of summer rains, though sampling error here was large due to the patchy spatial distribution of seedlings.

Tumbleweed, with the fewest individual plants produced the most biomass. Tumbleweed density remained consistent through time and did not vary from topsoil to spoils site.

The density of all other species varied somewhat. Cheatgrass (*Bromus tectorum* L.), an annual, was dominant in May and June on the spoils area. The forb species, including *Geranium* sp, morning glory (*convovulus* sp), yarrow (*Achillea millifolium*), and young rabbitbrush (*Chrysothammus* sp), were more abundant in August than May on both sites for slopes and valleys. New seedlings were found following summer rains.

Of the planted species on the spoils site (galleta grass, Indian rice grass, crested wheat grass, side oats grama, alfalfa), alfalfa was the most abundant. None of the planted grass species reached maturity; most were less than 8 cm high and consisted of only two or three blades when counted. Mortality of these young seedlings was high. The late seeding in February may be responsible in part for the low establishment rate of the planted species. Considering the winter moisture regime at Nucla, fall planting may be preferred. In July, soil moisture was above the wilting point only in the valley at the deeper depth. This could be an important factor in vegetation establishment on topsoiled areas.

TABLE 13. Summary of vegetation densities at Nucla. Plants/0.5 m^2

Site/Type	5/21	6/29	7/27	8/17
Spoils				
Slopes n=32				
Cheatgrass	4.43 ± 1.59	4.75 ± 1.34	0	.62 ± 09
Tumbleweed	.34 ± .31	.94 ± .52	1.06 ± .53	.81 ± .41
Forbs	.84 ± .68	.97 ± .72	2.12 ± 1.83	1.81 ± 1.63
Planted spp	.62 ± .66	.41 ± .28	.28 ± .24	1.94 ± 1.85
Valley bottom n=16				
Cheatgrass	4.44 ± 1.41	5.12 ± 3.05	.06 ± .12	0
Tumbleweed	.62 ± .76	.31 ± .29	.75 ± .42	.37 ± .5
Forbs	.75 ± .75	1.06 ± .79	1.25 ± .83	14.5 ± 33.2
Planted spp	.87 ± .71	.94 ± .75	2.06 ± 1.82	1.62 ± 1.65
Topsoil				
Slopes n=8				
Grasses			1.87 ± 3.43	13.12 ± 18.09
Forbs			10.87 ± 15.83	13.87 ± 15.55
Tumbleweed			1.37 ± .64	1.37 ± .36
Valley bottom n=8				
Grasses			1.25 ± 2.18	14.75 ± 18.51
Forbs			26.87 ± 30.93	75.25 ± 85.94
Tumbleweed			3.50 ± 1.85	2.5 ± 1.39

Plant production (Table 14) was measured on both the topsoiled and the spoils site in August 1981. Tumbleweed had the greatest effect on biomass measurements. Single tumbleweed plants ranged in weight from 0.01 to 183.6 g; alfalfa ranged from 0.01 to 1.5 g per plant. Cheatgrass, which was more abundant than any other grass on the site, ranged from 1.0 to 3.4 g per m^2. The planted grasses weighed less than 0.1 g per plant.

Because of large variances in sample weights, no difference between slope and valley production could be identified. It was likewise difficult to discern any real differences between the topsoil and spoil areas. Natural reseeding was the major source of successful plants. The great variability on all sites reflected the patchiness of vegetative cover. Cover is sparse, and the weights measured may reflect only one plant or up to 334 plants. On one plot, one large tumbleweed weighed 184 g; however, on other plots, desirable young grasses and alfalfa showed combined weights of less than 5 g. Individual plot weights ranged from 0 to 184 g.

Production was similar to values estimated by the Soil Conservation Service for nearby natural areas: 600 Kg/ha of dry matter in the understory of Pinyon-juniper for areas in good condition and 200 Kg/ha in the understory for a deteriorated range. The water harvesting sites averaged more than 200 Kg/ha.

TABLE 14. Nucla plant production - August 1981

Site	n	(g/0.5 m^2)	Kg/ha
Mine spoils			
Slopes	32	10.54 ± 5.96	229
Valley	16	13.11 ± 9.81	284
Topsoiled			
Slopes	8	47.53 ±44.72	1020
Valley	8	11.95 ± 7.94	259

Findings at the Nucla Site include the following:

- Preliminary results indicate few differences in soil water content between catchment areas and valley floors, as the catchment areas were not treated.
- Absence of precipitation at planting time resulted in poor vegetation establishment until August rains.
- Erosion from the catchment areas was substantial, but again, as at Black Mesa, the data were too variable to allow firm conclusions.

ECONOMIC ANALYSIS

The present value of direct net benefits (income from subsequent land use minus production and reclamation costs) was calculated for grazing (conventional reclamation) and for cropping (water harvesting reclamation). All calculations were specific to the Kayenta mine site. Only private costs and income potential were considered. Non-market costs and benefits, though possibly important, were beyond the scope of this study. This analysis is fully documented elsewhere (24) so only a summary of findings is presented here.

The operations involved in conventional reclamation are: grading/leveling, topsoiling, contour discing, seeding, fertilizing, straw mulching, and reworking. Grading/leveling costs for recontouring the spoil piles are the largest component of total reclamation costs and are a function of the amount of overburden moved. Because water harvesting reclamation requires less overburden handling but may incur additional costs for slope treatments, differences in total reclamation costs of the two alternative reclamation systems are principally due to the trade offs between grading/leveling and slope treatment costs.

For conventional reclamation, grading/leveling costs were calculated as $7,840/acre. Topsoiling costs were $3,000 and other operations (discing, seeding, fertilizing, straw mulching, and reworking) were $420/acre. These costs total $11,260/acre, and are within the range of $9,000-$12,000 reported by Dawson (25).

Reclamation with the PNL water harvesting system can be accomplished in two ways so two basic cost levels are considered. One way to reclaim the land is by treating the slopes to enhance water collection and growing crops only in the valleys. This approach has a grading/leveling cost of $5,190/acre plus $2,000/acre for topsoiling, plus initial slope treatment costs that vary from $0.00/acre to $5,600/acre. When maintenance costs are included, the present values of total slope treatment costs range from $7,365 to $15,060 per acre. The other way to reclaim the land involves planting crops on the slopes, so there are no slope treatment costs as such. However, more grading/leveling and spreading of topsoil is required, resulting in a cost present value of $8,950/acre.

Table 15 summarizes all of the land reclamation costs associated with the two systems. It also shows the net present value of the income streams, assuming conventional reclamation is followed by grazing use and that water harvesting is characterized by cropping in alfalfa, barley, corn, beans, or wheat.

Three water harvesting slope treatments have lower estimated costs than conventional reclamation due to reduced earth moving costs. The difference is $3,895/acre for compacted slope, $3,025/acre for salt-compacted slope and $2,310/acre for crop-on-slope. These differences constitute a substantial cost advantage for water harvesting on the basis of the present value of land reclamation and maintenance costs.

Water harvesting also has advantages based on the estimated value of agricultural production capacity. Even the lowest yield levels considered for alfalfa, corn and pinto beans had higher net present values than grazing. Both conventional and water harvesting reclamation

TABLE 15. Present value of costs and benefits of reclamation alternatives (1979 $)

Alternatives	Reclamation Costs/Acre	Net Income/Acre Grazing	Alfalfa	Barley	Corn	Beans	Wheat
Conventional	$11,260	$ 0					
Water harvesting							
Crop-on-slope	$ 8,950		$448	$-75	N.A.	N.A.	$-462
Compacted[a]	7,365	H[b]	255	38	$164	$147	30
Salt[a]	8,235	M	190	-10	86	82	19
Paraffin[a]	13,170	L	136	-46	21	43	-52
Asphalt[a]	15,060						

(a) For water harvesting, 18% of the reclaimed land area is usable. Net income per acre of reclaimed land is 18% of income per acre of cropland.

(b) The income present value estimates are for high, H; medium, M; and Low, L, yields and apply to all four slope treatments.

may have nonmarket benefits that are not included in the benefit estimation. In order for the total net present value of conventional land reclamation to equal the private benefits of the three cost-effective PNL options (crop-on-slope, compacted and salt-compacted slope), the present value of the nonmarket benefits from restoring land to original contour and use would have to be at least $2,760/acre ($11,260 = $8,950 - $448 + $2,758). The value per square mile of land used for hunting in northeastern Arizona, based on data for 1970, is less than $1/acre (26). Given this level of estimated benefits from use of the study area for hunting, it is unlikely that the total nonmarket benefits equal $2,760/acre.

Climatic and soil conditions at Black Mesa render this area poorly suited to agricultural production. As a result, the findings of this analysis may understate the potential of water harvesting on other more favorable semi-arid or arid sites.

During the course of this economic analysis, several potentially important institutional-social issues emerged that may impact the feasibility of the water harvesting system. Though analysis of these issues is beyond the scope of the this project, they are worthy of note. Perhaps the most important issue is the question of what is successful reclamation under the law. In most states, when the land has been restored to its original contours and vegetation is well established, the mining company would be in compliance with the laws. Water harvesting reclamation, however, might require a waiver of requirements since the water harvesting options do not restore the land to original contours.

The question of the mining company's liability is another issue which affects the viability of the water harvesting. If a farmer using land reclaimed by water harvesting experienced financial difficulties, he might cut the costs of production to keep farming. The most likely candidate for cost cutting would be annual slope maintenance costs. The maintenance operations would have less effect on yield than production costs, but could cut costs significantly. If the annual maintenance of the slopes were discontinued, however, the system might no longer be in compliance with reclamation law because of erosion or because of substandard crop productivity. This would also be the case if the farmer went out of business or chose to stop farming the land altogether. In either event, would the mining company be required to carry out conventional reclamation?

Physical characteristics of the mining operation as well as the reclaimed land are issues affecting the viability of water harvesting. The quantity of land required to constitute a viable farming operation on reclaimed land is unknown. At the Kayenta mine, the Peabody Coal Company plans to mine and reclaim 500 acres per year. If 18% of this land is made productive (valley area), 90 acres of cropland area would be added each year. The resulting acreage might not reach a viable farm size until several years had passed.

The issue of cropland demand on the Navajo Reservation, where sheepherding is the major productive activity, is a final consideration that must be made with water harvesting. Possible conflicts might result from contrasting land uses, and though this issue may be unique to the Kayenta mine, similar problems might arise at other sites.

Economic Analysis Findings include the following:

- Total reclamation costs for three water harvesting slope treatments were calculated to be less than costs of conventional reclamation.

- Several crop and slope treatments under water harvesting did show positive net incomes.

- Grazing, as in conventional reclamation showed no net income.

- Unresolved institutional issues related to liability, legal compliance, and cultural practices may impact the viability of water harvesting and should be explored in depth.

- The results of this preliminary economic analysis need to be verified in an actual water harvesting cropping operation.

REMAINING PROBLEMS

To date, this research has demonstrated that water harvesting reclamation is technically and economically feasible. To make it available to industrial users, though, techniques for application must be developed. Needs and options to be addressed before water harvesting reclamation can be widely used are discussed in this section.

Slope Treatments

The key to effective water harvesting is a slope treatment that will provide maximum runoff and remain stable for many years. Inexpensive materials that can increase runoff under a variety of environmental conditions will need to be identified, if water harvesting reclamation is to be generally applicable. For a high benefit to cost ratio, it will be necessary to maintain high and known efficiencies of runoff.

Crops

Not all crops appear to be suitable for use in water harvesting reclamation. Information needs to be gathered on the costs of producing crops under less than optimal irrigation regimes. At any given potential reclamation site, crop choice will depend on characteristics of the local climate and potential yield.

Topography

The optimum ratio of catchment area to cultivated area depends upon crop water requirements, runoff efficiency, seasonal distribution of rainfall, storm sizes, and water holding capacity of the soil. These parameters need to be related to each other quantitatively, with data from other sites (perhaps using a model) to effectively engineer water harvesting reclamation at a given site.

Rainfall Maps

The success of water harvesting reclamation depends in part on the seasonal distribution and size of precipitation events. Maps should be located or prepared for the arid and semi-arid regions. With such maps available, time would not be wasted in considering water harvesting as an option in areas with unsuitable climates, such as those with very large or very infrequent rain events.

Cistern Storage

A modification of water harvesting reclamation is to store excess water in a cistern for use during periods of drought. A water impermeable layer placed at the lower limit of root growth would be added to the normal slope and crop area. Water percolation below this depth which would normally be lost to the crop would be carried to drain tile along the top of the impermeable layer to the end of the valley where it would drain into a cistern for storage. During drought, this water would be applied to the surface of the topsoil with a wind-powered pump. Such a system would use water and fertilizer efficiently and wouldn't have a salt build-up characteristic of areas irrigated with western river or well water. The effectiveness and costs of cistern storage are currently unknown and deserve further study.

Solar Energy

If catchment areas are not used for vegetation, the incident sunlight is wasted. It may be feasible to collect runoff water and solar energy from catchment areas by using the surfaces of solar thermal collectors or arrays of photovoltaic cells to cover the surface of the slope. The key here is that the land would be used for two purposes, water harvesting and energy collection.

Federal Regulations

At present, water harvesting reclamation is not allowed on post-law spoils, principally because it does not satisfy grading requirements (original contours) and vegetation requirements (complete vegetative cover). For the value of water harvesting to be realized and for mining companies to obtain bond releases, the laws need to be modified to take advantage of the inherent values of using runoff to irrigate desirable vegetation.

SUMMARY AND CONCLUSIONS

The goal of conventional vegetation restoration procedures is to cover the total land area with a vegetative cover after the spoil material has been regraded to a nearly level configuration. Water and good soil are spread over the total land surface. In arid regions where water and good soil are scarce, these commodities may be spread too thinly to produce a useful vegetative cover. Without adequate water and soil, low value plants grow and the useful productivity of the land is minimal.

Restoration with water harvesting concentrates resources in short supply into a portion of the total area. Part of the land becomes rainfall catchment area, which supplies irrigation water to the cultivated portion. With more soil and water, species of greater value can be cultivated and harvested.

Central to the success of water harvesting for reclamation is the identification of an effective and durable surface treatment to maximize the quantity of runoff. A number of materials have been reported. Paraffin shows promise because it is inexpensive and nontoxic. However, paraffin appears to be easily damaged, particularly by unstable soil beneath it (15, 27, 28, 29, 16, 30, 31). Silicon has been tested and found to be effective, but is more prone to damage than paraffin (15). Paraffin-treated plots yielded an average of 90% runoffs, compared to 100% for butyl rubber (16). A comparison of light fuel oil with emulsions of latex, asphalt and wax showed that light fuel oil was the most efficient for increasing runoff (30). The addition of salt to a clay soil has been proven successful in increasing runoff (32). Frasier has summarized the characteristics of the more common catchment area treatments (13).

Butyl rubber sheeting appears to be a good control treatment because it produces runoff from very small rain events, but the expense and ease with which it is damaged by wind precludes its desirability as a large-scale treatment. The paraffin treatment has persisted with no apparent change to date and would appear durable, particularly if applied liberally and if traffic could be eliminated or the base soil firmly packed. Asphalt-rubber, if applied liberally, would perform well and for a long time, as it is durable even under animal and human traffic. The relative costs of these three treatments at the Hanford site (rubbersheet, asphalt-rubber, paraffin) and the estimated 70% efficiency (based on wheat production) of the paraffin catchment compared to rubber sheeting suggests paraffin is the most cost effective treatment. The 70% value does not, however, include water that may have percolated down past the deepest water sensors; 70% may be high. The efficiency of the paraffin treatment could be raised by preparing a smooth surface for the wax and eliminating surface traffic. If traffic cannot be controlled, the more expensive asphalt rubber, applied on a smooth surface, would be a better choice. These hypotheses should be tested. At Hanford, Black Mesa and Nucla, the untreated slopes produced very little runoff; it is important that effective surface treatments be identified.

The wind factor in the valleys may be important. If the strongest winds come from a predictable and constant direction, as they do at Hanford and Kayenta, it might be advisable for the mining plan to be organized so that the spoil bank is placed perpendicular to these winds. Such a precaution would minimize wind erosion and minimize evapotranspiration in the valleys.

The crop species cultivated in water harvesting reclamation should be relatively valuable, deep-rooted and drought-hardy. Since some fraction of the land is used for water harvesting, the cultivated area must be as economically productive as the total area would have been. At Hanford, wheat could be cultivated successfully using this first version of water harvesting reclamation. That other areas can produce much more wheat is not important, as this demonstration is aimed at arid regions only. If nothing could be grown in an arid mined region and wheat prices were high, water harvesting reclamation could be an option. With more water available to the wheat using efficient slope treatments, wheat production would be increased (33,34). Grapes would be a higher value crop, as well as offering the capacity of deep rooting and drought resistance. Water percolating down through the soil past the rooting zones does not add to the efficiency of the catchment area, so deeply rooted plants such as grapes, alfalfa, and fruit trees have an advantage, particularly in areas that receive large rain events. Though water harvesting effectively increases storm sizes, it doesn't decrease time between storms. The greater content of soil water will compensate to some degree for infrequent storms, but there will be periods of no rain when the crops will have to be drought-tolerant to survive. This survival is important. Water harvesting reclamation is a form of intensive cultivation and a return is to be expected each year for the system to be realistic; the loss due to drought should be avoided. A final consideration is the utility of the crop plants in the immediate area. Crops must fit into the local economy to be useful. Thus, forage species and corn are the choice at the Kayenta site. Wildlife may be the most desirable crop, and could readily be supported in the relatively abundant vegetation of the valleys without cultivation or harvesting the vegetation.

The spoil at the Black Mesa site has potential for developing into a good agricultural soil, particularly with the addition of organic matter from established vegetation (35). Soil improvement could be expedited by the addition of organic matter from common weeds that will raise the humic and flora level of the soil on decomposition (36). Thus, with continual cultivation and runoff input, the valley soils will become more fertile and productive.

Water harvesting may well be economically attractive and certainly merits serious investigation. However, this evaluation rests on several assumptions that will require field tests. One of these is the assumption that 50% of the precipitation will run off the slopes and be relatively evenly delivered to crops in the valleys. A second is the assumption of crop yield levels resulting from precipitation alone that are greater than 50% of normal yields with flood irrigation. Another is that typical crop production methods and average costs will apply to a "strip farm." These factors and others such as soil type, climate, and precipitation will determine the relative advantages of water harvesting versus conventional reclamation.

While these uncertainties regarding feasibility of water harvesting for use on various sites remain, it appears that the system is economically viable on sites that have as little as 25 to 30% of the precipitation normally required for crop production. This is due to the ratio of water collection area to growing area. Any future improvements made in the cost-effectiveness of the slope treatments would increase the profitability of the system by making it possible to raise various types of crops and increasing potential yields above those assumed in this study.

This demonstration has shown at Hanford, Black Mesa and Nucla that irrigation by water harvesting will produce a greater yield or establishment than totally planted areas. Refinement of this technique will involve consideration of the advantages of combinations of different slope angles, catchment to cultivated area ratios, plant species/varieties with the most return, and durable, cost effective catchment area treatments. To return to the choice presented in the introduction, man can have a restored vegetative production on mined lands with relatively little cost, but it will require an appreciation of the tremendous possibilities offered by water harvesting.

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