New Mexico Bureau of Mines and Mineral Resources

Open-File Report 282

PHASE-III RECHARGE STUDY

AT THE NAVAJO MINE--

IMPACT OF MINING ON RECHARGE

by

William J. Stone
Senior Hydrogeologist

November 1987

CONTENTS

INTRODUCTION

Surface mining regulations call for protection of the hydrologic balance of a mine area. More specifically, they require restoration of ground-water recharge through reclamation. This is a tall order as it assumes several things: 1) that recharge can indeed be measured, 2) that mines will have both pre- and post-mining recharge data, and 3) that a desired recharge rate can be achieved by customizing reclamation practices. Nonetheless, efforts have been made over the past three years to learn as much as possible of recharge in undisturbed and reclaimed areas at BHP-Utah's Navajo Mine, San Juan County, New Mexico (Figure 1). This is the third and final report on those recharge studies conducted by the Bureau.

OVERVIEW OF RECHARGE

Recharge is an important but elusive part of the hydrologic cycle. Water that infiltrates into arid-land soils is subject to rapid evaporation and transpiration back to the atmosphere. Most water escaping the root zone eventually reaches the water table, where it is added to (recharges) the saturated zone. This assumes vertical movement under piston-flow conditions. That is, for every slug of water that enters the top of the soil-water column, an equal slug moves downward. However, low permeability horizons (silty or clayey beds) may become temporarily saturated or cause overlying material to become saturated, resulting in lateral flow. Such flow may also occur without impeding layers in response to topography (McCord and Stephens, 1987).

Recharge has been shown to vary with landscape setting

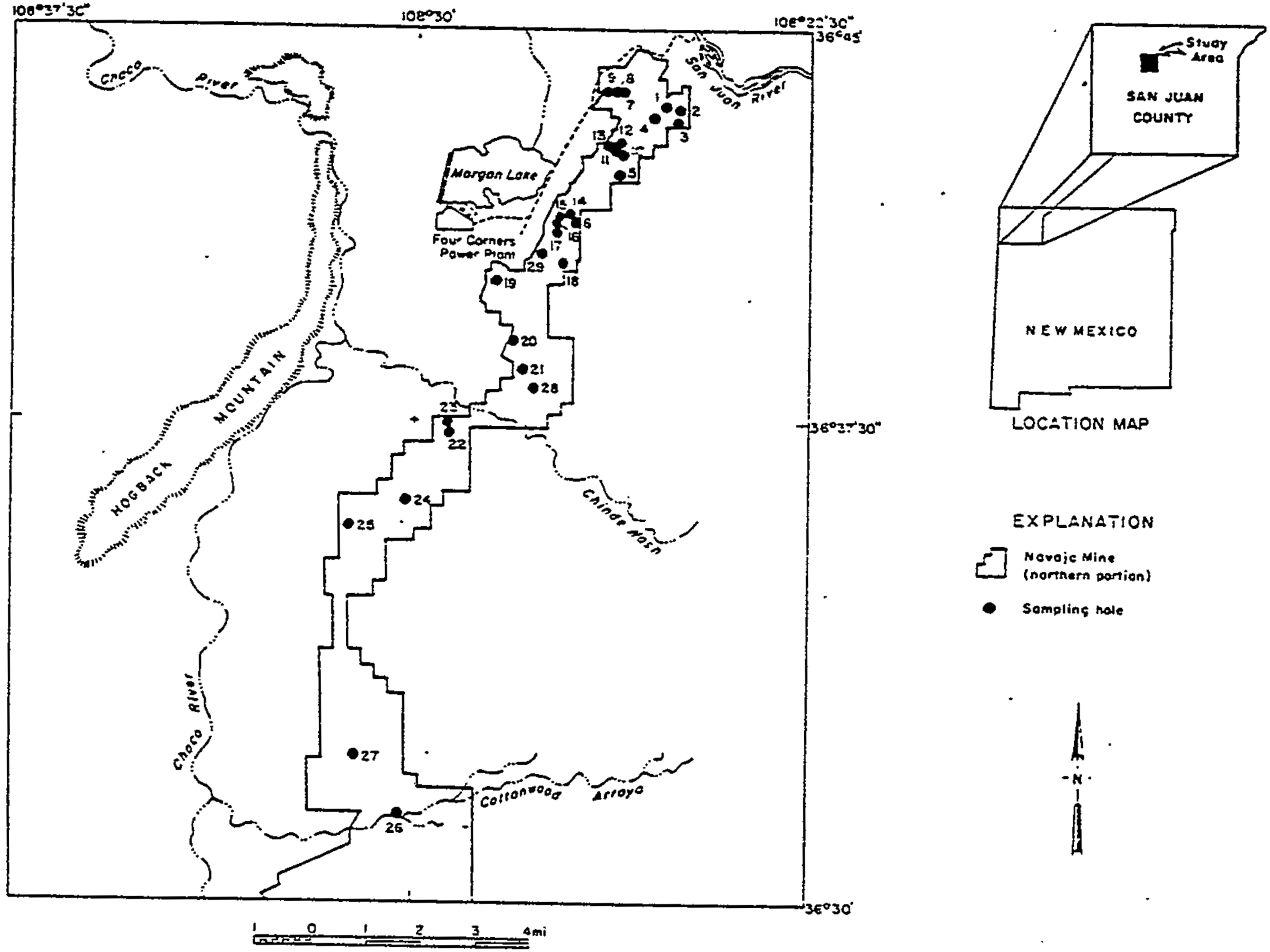

Figure 1. Location of Navajo Mine and sampling holes

(Allison and others, 1985; Stone, 1986c). Each setting is a unique combination of geology, landuse, soils, topography, and vegetation. Premining (undisturbed) settings differ from post-mining (reclaimed) settings (Figures 2, 3, 4). In order to evaluate impact of mining, recharge under both conditions must be compared.

Recharge may be addressed in different ways. For example, it may be expressed in terms of a velocity-style value or rate, associated with a point in a given setting, or as a volumetric flux, associated with the area covered by one or more settings. Also, recharge may be viewed at three different scales: local, areal, and regional. Local recharge is the rate of deep percolation for a given setting as measured or estimated at a point. It may be a single observation or the average of several such measurements. Areal recharge is the volumetric flux for the entire extent in the study region of a given setting (local recharge times area). Regional recharge is merely the sum of all of the areal recharge fluxes in the study region. Average recharge is a velocity-style value obtained by dividing regional recharge by the total area of the study region.

In these studies, local recharge has been determined by the chloride mass-balance method. Chloride is useful because it is a conservative natural tracer. Details of the method are given in the Phase-I and -II reports (Stone, 1984 and 1986). Briefly, however, it is based on the premise advanced by Allison and Hughes (1978) and others, that average annual precipitation (P) times the total annual chloride content of precipitation (Clp) should equal the annual recharge rate (R) times the average

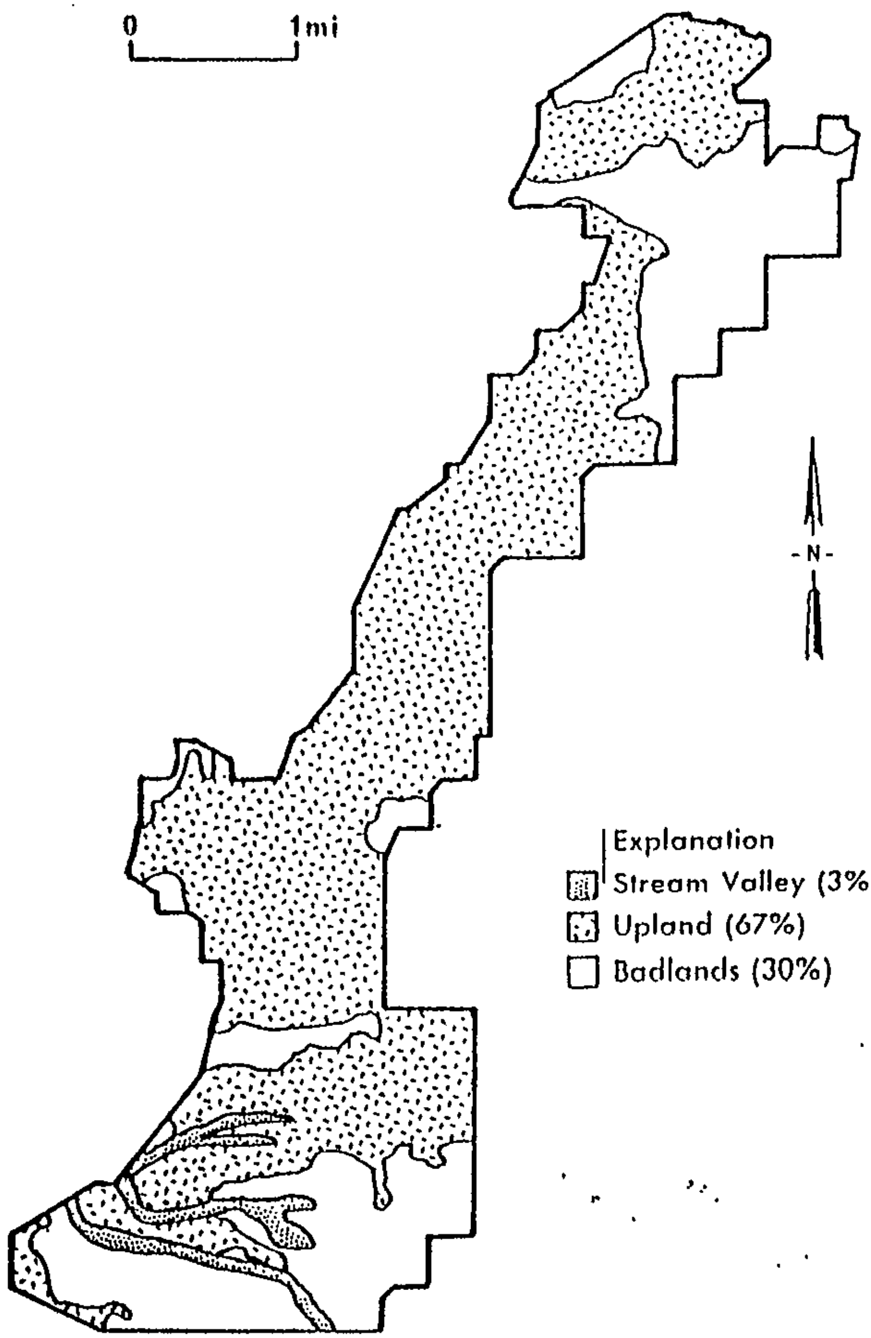

Figure 2- Premining landscape settings, mine area 1.

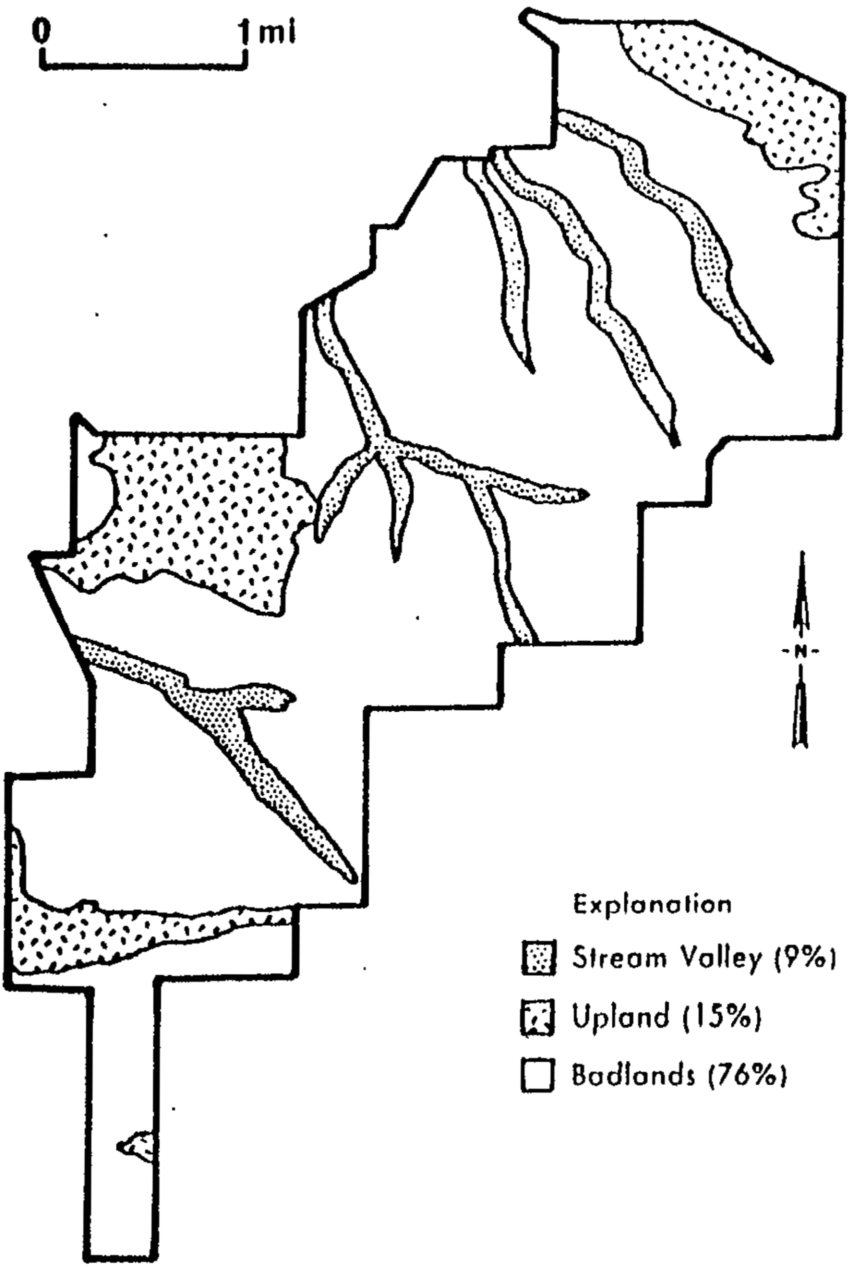

Figure 3 - Premining landscape settings, mine area 2.

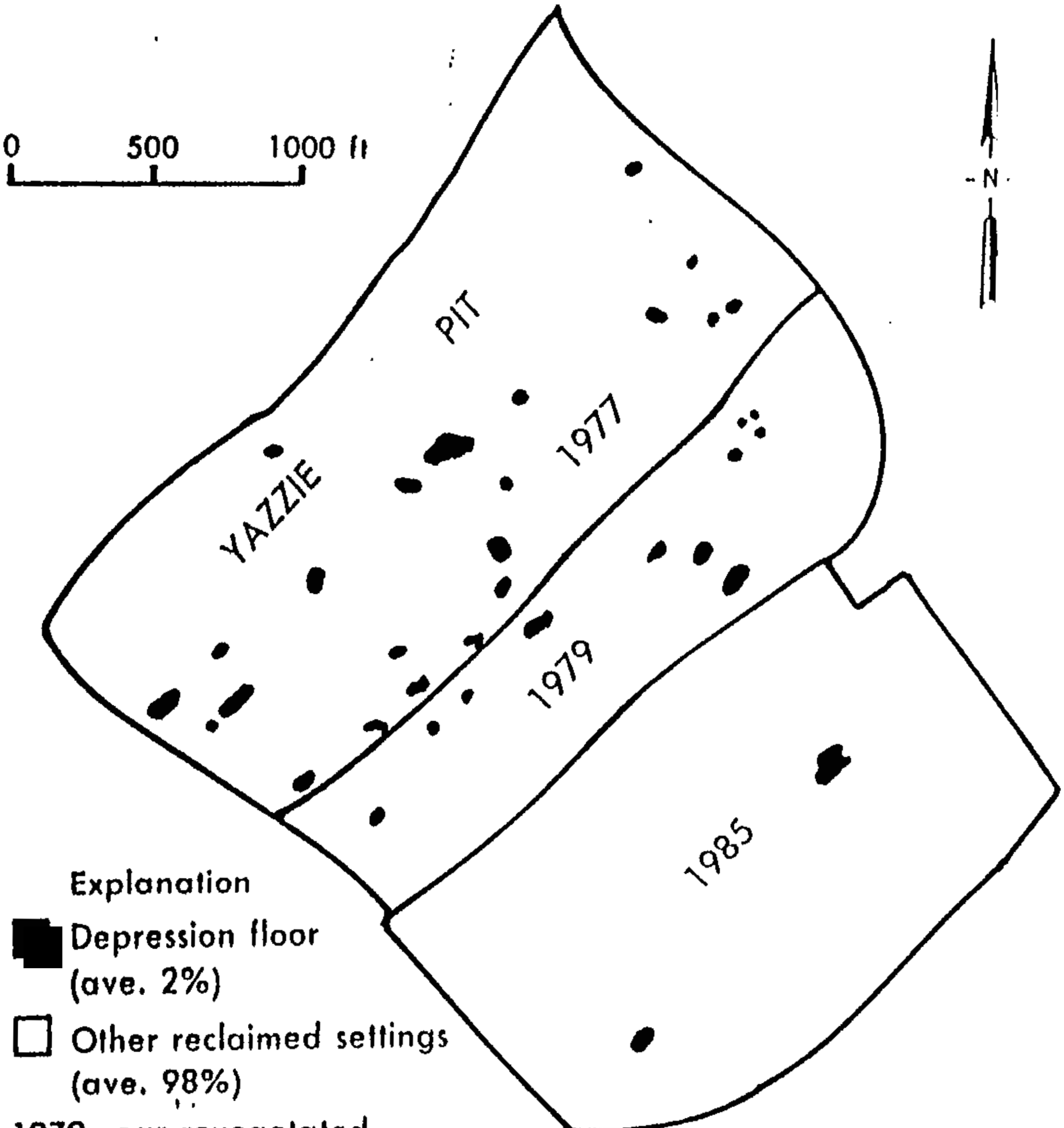

Figure 4 - Example of post-mining landscape settings.

chloride content of soil water (Clsw). Shown mathematically, this is PClp = RClsw. Rewritten for recharge it becomes $R = (Clp/Clsw) \cdot P$.

BACKGROUND OF STUDY

The evaluation of recharge at the Navajo Mine was accomplished in three phases. Phase I was conducted to test the applicability of the chloride mass-balance method of determining recharge to conditions in northwest New Mexico and to obtain preliminary estimates of local recharge for major landscape settings (three undisturbed and two reclaimed) recognized at the mine. Phase II was an expanded study of local recharge in reclaimed settings. Phase III, that reported on here, focused on areal and regional recharge volumes and the net impact of mining on recharge.

PROBLEMS AND PURPOSE

The chloride mass-balance method gives reasonable recharge estimates in undisturbed settings (Allison and Hughes, 1978), but to my knowledge, it had not been applied to reclaimed settings prior to the Phase-I study. Even more chloride vs depth profiles for reclaimed ground were obtained in the Phase-II study (Stone, 1986a). Examination of these profiles reveals that all are one of three basic types. Some show large variation in chloride content, suggesting equilibrium had not yet been regained. Others have uniformly low chloride values, in some cases above a deep peak (flushing bulge?). Still others are characterized by a shallow peak above lower values at depth, as in profiles from undisturbed settings.

These observations raise two important questions. Which profile type represents equilibrium conditions and is thus a good source of local recharge values? How can this equilibrium be tested? The Phase-II study suggested natural isotopes may be a useful means of testing these profiles.

In order to get at impact of mining on recharge, pre- and post-mining regional recharge fluxes must be compared. This requires local recharge rates, as discussed above, and areal-extent values. Several questions arise as to areal extent. What was the distribution of premining landscape settings? What will be the distribution of post-mining settings? How can their areas be approximated without exhaustive surveys?

The purposes of this study were, therefore, 1) to further evaluate chloride mass-balance results for reclaimed ground by means of natural isotopes, 2) to determine areal extents for the major landscape settings, 3) to calculate volumetric recharge fluxes for each of these settings, and 4) to assess impact of mining on recharge at the Navajo Mine.

REGIONAL SETTING

The Navajo Mine lies in the northwestern part of the structural feature known as the San Juan Basin, a Laramide (Late Cretaceous-Early Tertiary) depression at the eastern edge of the Colorado Plateau. More specifically, it is situated just east of the Hogback Mountain Monocline which separates the Four Corners Platform from the central San Juan Basin in northwestern New Mexico.

Coal is strip-mined from the Fruitland Formation

(Cretaceous) which lies at the surface in this area. The Fruitland is generally 200-300 ft thick and consists of interbedded sandy shale, carbonaceous shale, clayey sandstone, coal, and sandstone (Stone and others, 1983).

Data collected at the mine (Utah International Inc., 1981) indicate the climate is arid with an average annual rainfall of 5.7 inches, based on the period 1962-1980. Greatest precipitation occurs in the period August through October. Average annual class-A pan-evaporation rate is 55.9 inches or nearly 10 times the rainfall.

The reclaimed areas studied in Phase III were regraded or revegetated during the period 1975 to 1979. Water added during irrigation generally did not exceed 6 inches/year. The seed mix most commonly applied for revegetation includes alkali sacaton, galleta, globe mallow, Indian rice grass, saltbush, and sand dropseed. The average rooting depth is probably <2 ft.

The mine area is drained by the San Juan River and its tributaries (Figure 1). The San Juan is perennial, but the tributaries are ephemeral.

ISOTOPE STUDY

Chloride recharge values from one undisturbed upland flat site and one reclaimed depression were checked by the stable isotopes oxygen-18 (O-18) and deuterium (D), as well as tritium (T), in the Phase-II study. Stable isotopes confirmed the chloride recharge rate in the undisturbed site, but suggested the reclaimed site was not yet in equilibrium, 6 yrs after revegetation. A major task of the Phase-III study was to resample three of the Phase-II sites, each characterized by one of the three basic chloride profile types.

METHODS

Sample preparation and analysis methods for isotopes were the same as in the Phase-II study (Stone, 1986). Samples were taken by coring with a hollow-stem auger rig, as in the case of chloride. No water, mud, or air were introduced during drilling. Samples were placed in covered 500 ml widemouth plastic bottles. The caps were sealed with plastic tape, bottles were placed in large zip-top plastic bags, and bags were stored out of direct sunlight to minimize evaporation.

Soil water was extracted by solvent distillation using toluene, as described by Snell and Biffen (1964). Samples were analyzed commercially (Environmental Isotope Laboratory, University of Waterloo, Waterloo, Ontario, Canada). Data are given in Appendix A. Concentration vs depth profiles and O-18 vs deuterium plots were made by hand. Regressions and correlation coefficients were determined on a hand-held calculator.

O-18/D values for precipitation plot along a line having a slope of 8. This is called the meteoric water line (Craig, 1961). In arid settings, O18/D data plot on a line below and diagonal to the meteoric line (slopes of 5 or less). The decrease in slope results from less negative values in the shallow part of the profile because of enrichment (evaporation). Displacement of deuterium from the meteoric line (D) provides recharge (R) using a proportionality constant (k): $R=(k/D)^{1/2}$ (Allison and others, 1983).

HOLE 1: CUSTER DEPRESSION

This site was chosen to test an erratic chloride profile. Hole 1 was drilled approximately 10 ft due east of Hole 16 in the Phase-II study. More specifically, it lies in a depression just south of Ramp 6 in the Custer area. It was located southwest of a large rock pile and southwest of a Forest Service experimental plot sign.

Although the area was reclaimed in 1975, the chloride profile is quite variable, suggesting equilibrium has not yet been regained (Figure 5). Total depth was 56 ft. A brief field log of the hole is given in Appendix B.

Oxygen-18 and deuterium profiles parallel each other quite well, except for the deepest point (Figure 6). The hard drilling that caused sampling to be halted at 56 ft may have resulted in heating the water in the sample and altering its isotopic makeup.

Stable-isotope points plot on an evaporation line below and diagonal to the meteoric line having a slope of approximately 6 (Figure 7). Regression analysis gives a good correlation coefficient (r = 0.88). Deuterium displacement gives a recharge rate of 0.04 in/yr; chloride gave 0.03 in/yr for the same site (Hole 16, Phase II). Although results of the two methods agree quite well, the deuterium displacement method may not be appropriate for this profile.

Tritium results look quite erratic (Figure 6). This may be due to inequilibrium or movement of water (and T) in the vapor as well as liquid phase in these arid conditions.

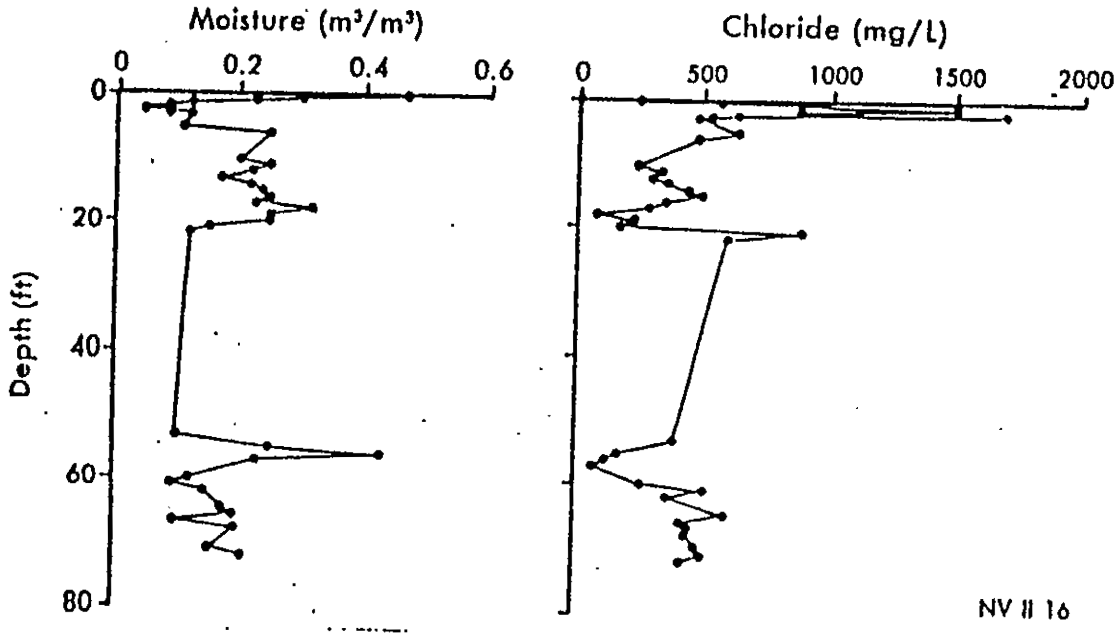

Figure 5 - Chloride profile, Custer depression (hole NV II 16).

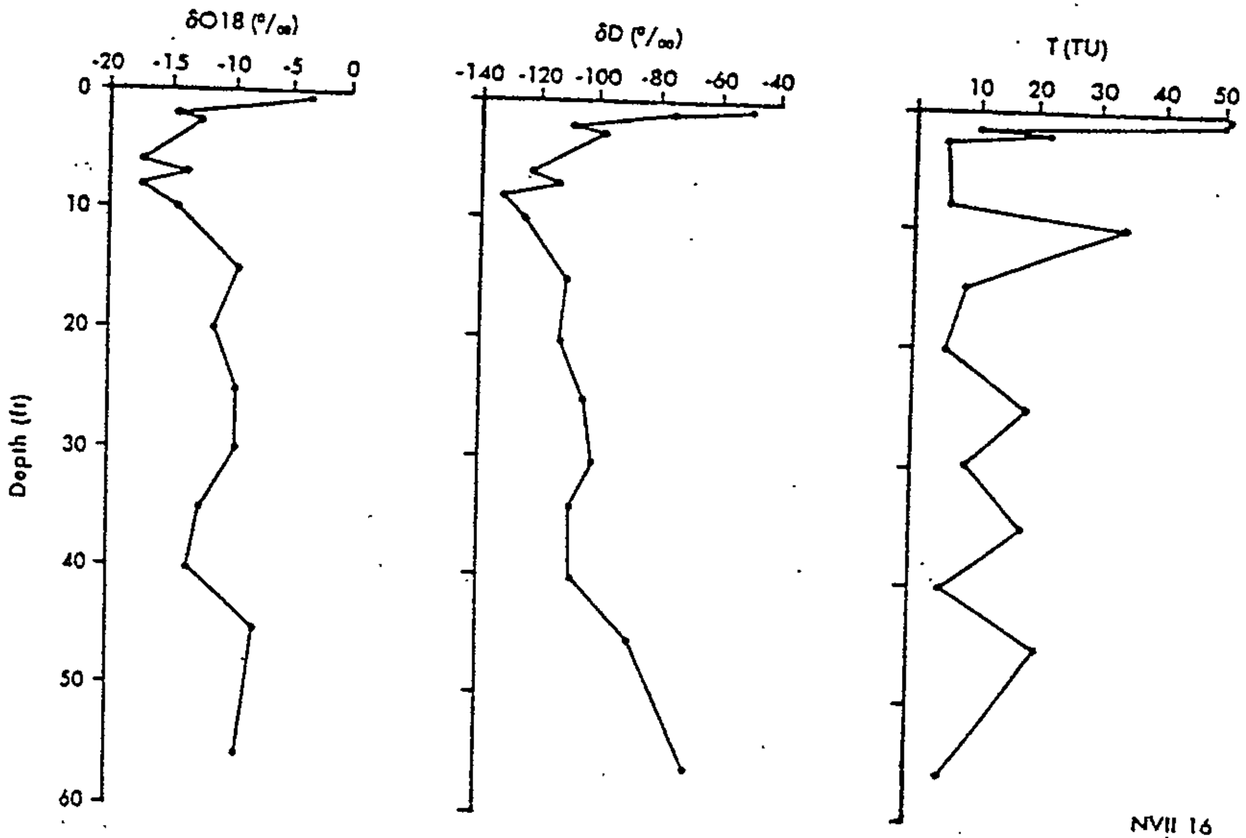

Figure 6 - Stable-isotope and tritium profiles, Custer depression (hole NV II 16).

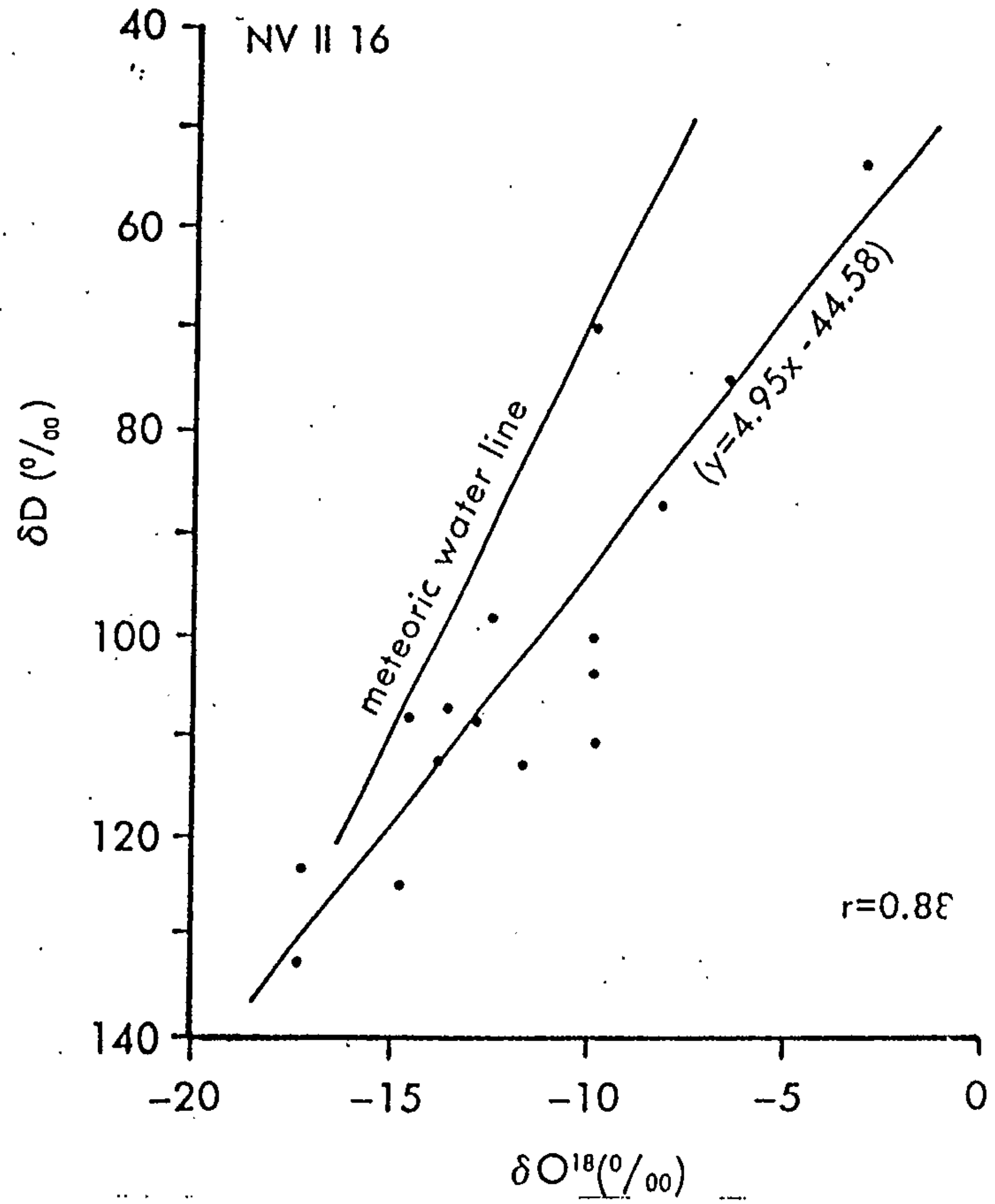

Figure 7 - Oxygen-18/deuterium plot, Custer depression (hole NV II 16).

HOLE 2: PINTO DEPRESSION

This site was chosen as an example of the undisturbed-type chloride profile. Hole 2 was drilled approximately 20 ft northeast of Hole 19 of the Phase-II study. More specifically, it lies in a depression north of the road above a deep open cut and east of a radio tower.

Like Hole 1, it was reclaimed in 1975/1976. By contrast, however, the chloride profile looks like those of undisturbed areas (Figure 8). Total depth was 25 ft; a log appears in Appendix B.

At first glance O-18 and D profiles don't seem to parallel each other very well (Figure 9). However, closer examination reveals that only two points are not in agreement (those at 10 and 54 ft, respectively).

Points plot on an evaporation line with a slope of approximately 4 (Figure 10). Regression analysis shows a high degree of correlation (r = 0.94). Deuterium displacement gives a recharge rate of 0.06 in/yr. Chloride gives a value of 0.04 in/yr.

Interestingly, the tritium vs depth plot resembles the chloride profile (Figures 8 and 9) and may be reasonable. The implication is that this profile is in equilibrium, 10 yrs after reclamation.

HOLE 3: NORTH BARBER DEPRESSION

This site was chosen to evaluate the flushed profile. Hole 3 was drilled approximately 25 ft southwest of Hole 24 of the Phase-II study. More specifically, it lies in a large depression

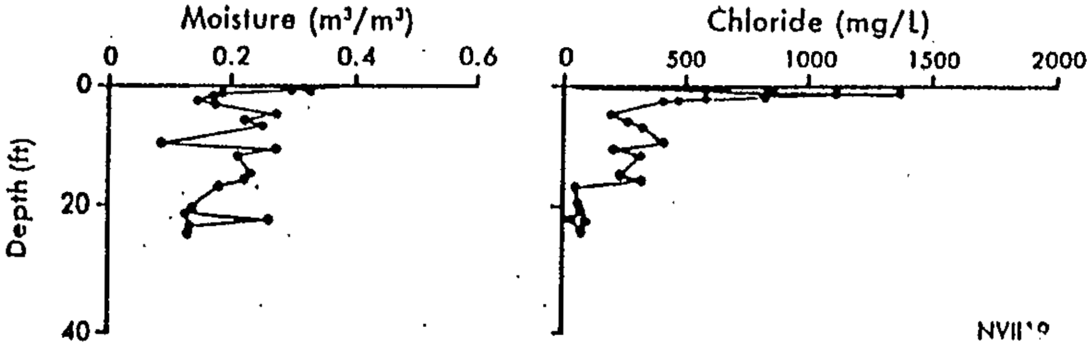

Figure 8 - Chloride profile, Pinto depression (hole NV II 19).

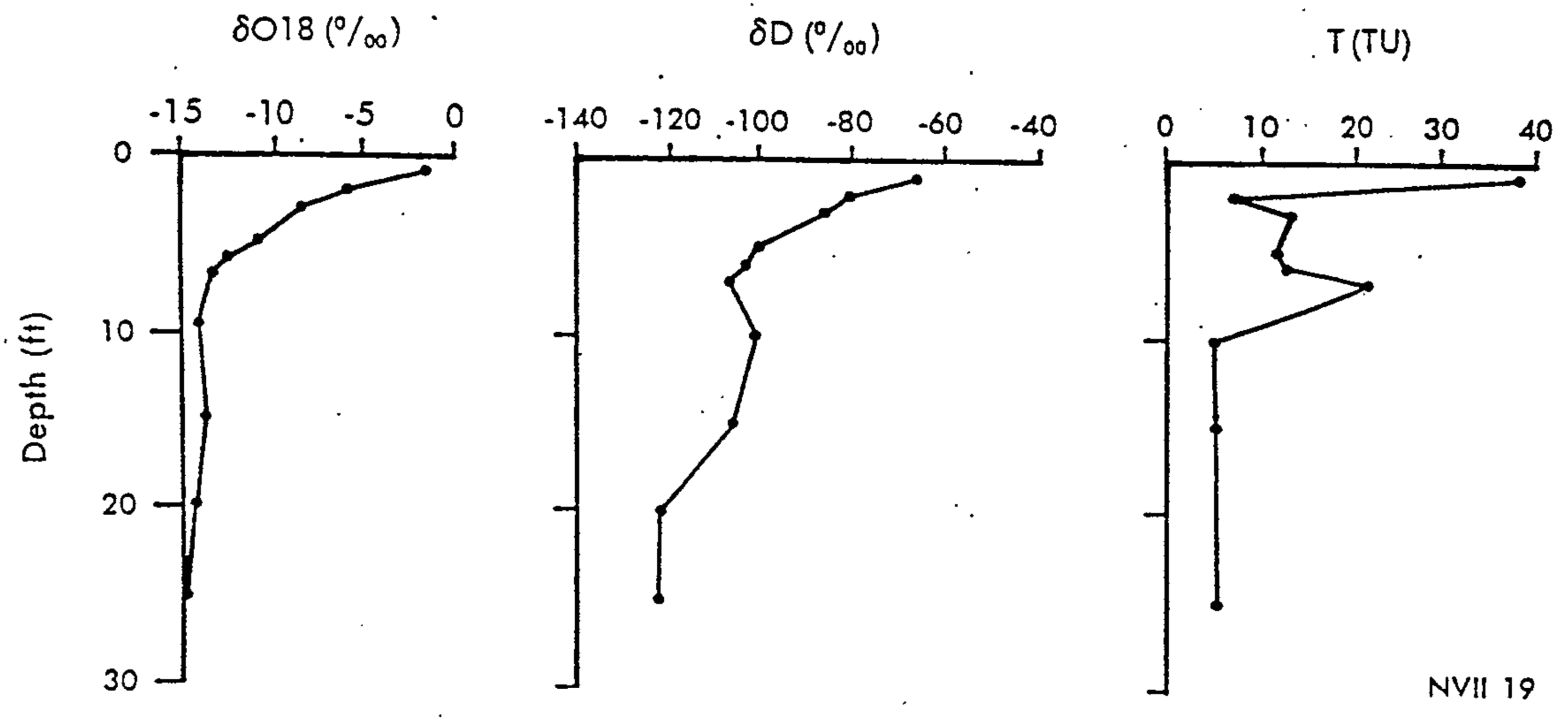

Figure 9 - Stable-isotope and tritium profiles, Pinto depression (hole NV II 19).

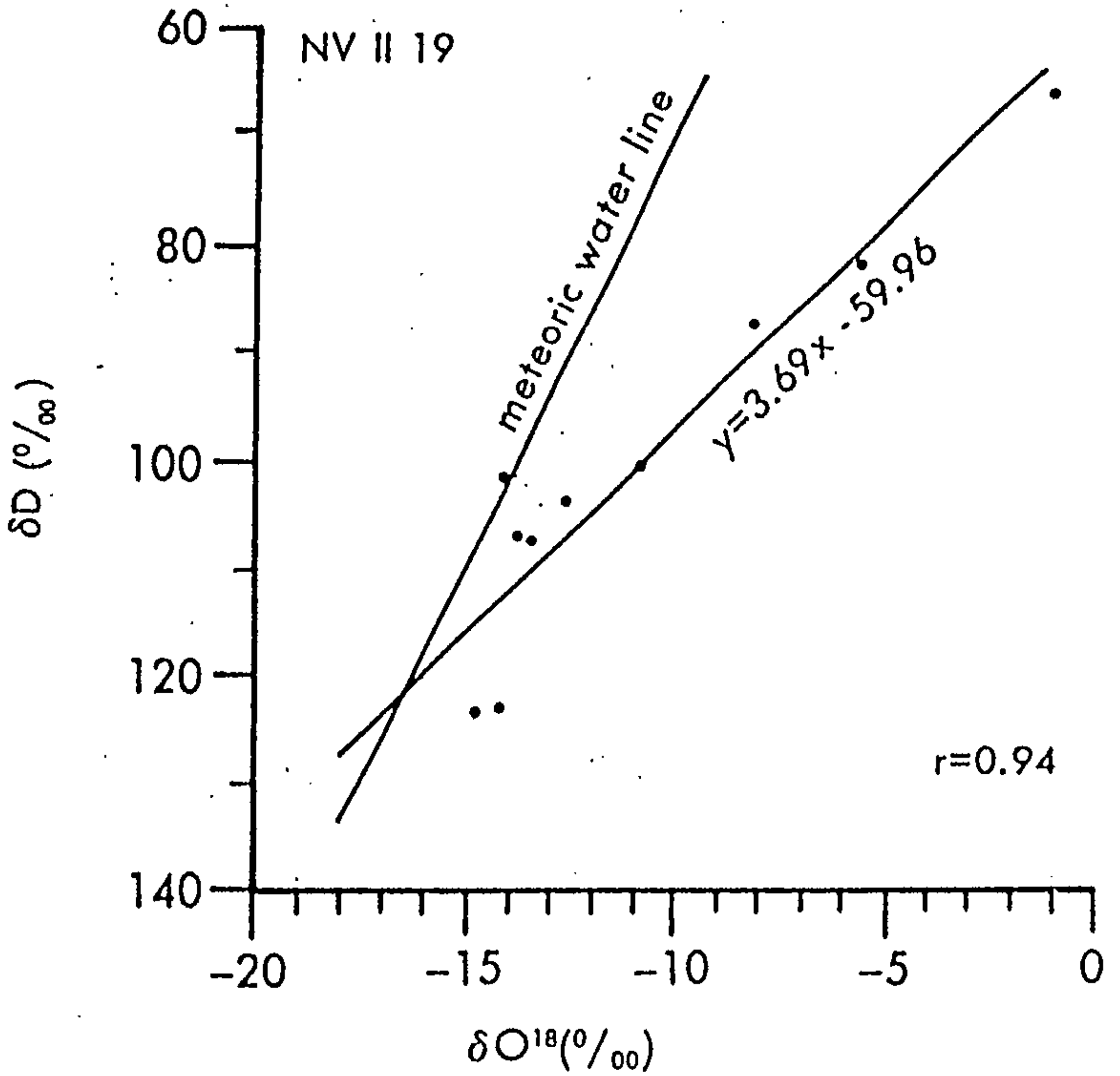

Figure 10 - Oxygen-18/deuterium plot, Pinto depression (hole NV II 19).

(the second one north of Ramp 2 in the North Barber area).

The area was reclaimed in 1979. The chloride profile shows a possible flushing bulge at a depth of approximately 35 ft (Figure 11). Total depth was 60 ft; a log is given in Appendix B.

The O-18/D profiles track each other very well and also show a bulge at depth (Figure 12). The stable-isotope bulge is curiously 10 ft deeper than the chloride bulge. It may be that sampling for isotopes missed the small upper peak seen in the chloride profile.

In the O-18/D plot (Figure 13) points describe a line below but nearly parallel to the meteoric line. The slope is approximately 6. Regression analysis gives a high correlation coefficient (r = 0.93). Recharge based on deuterium displacement is 0.05 in/yr. Chloride gave a recharge rate of 0.16 in/yr.

The tritium profile is erratic. Vapor-phase movement may be responsible.

RECOVERY OF RECLAIMED AREAS

The chloride and stable-isotope profiles suggest that all three sites restudied in Phase III are in equilibrium. The times of reclamation indicate that moisture and solute profiles are re-established between 6 and 10 yrs after revegetation. This is based on the equilibrium behavior of stable isotopes for all sites reclaimed 10 yrs previously (Holes 1 and 2) and 1 of 2 sites reclaimed 6 years previously (Hole 3). Another hole (28 of the Phase-II study), also reclaimed 6 yrs previously, was characterized by erratic stable-isotope/depth profiles (Figure

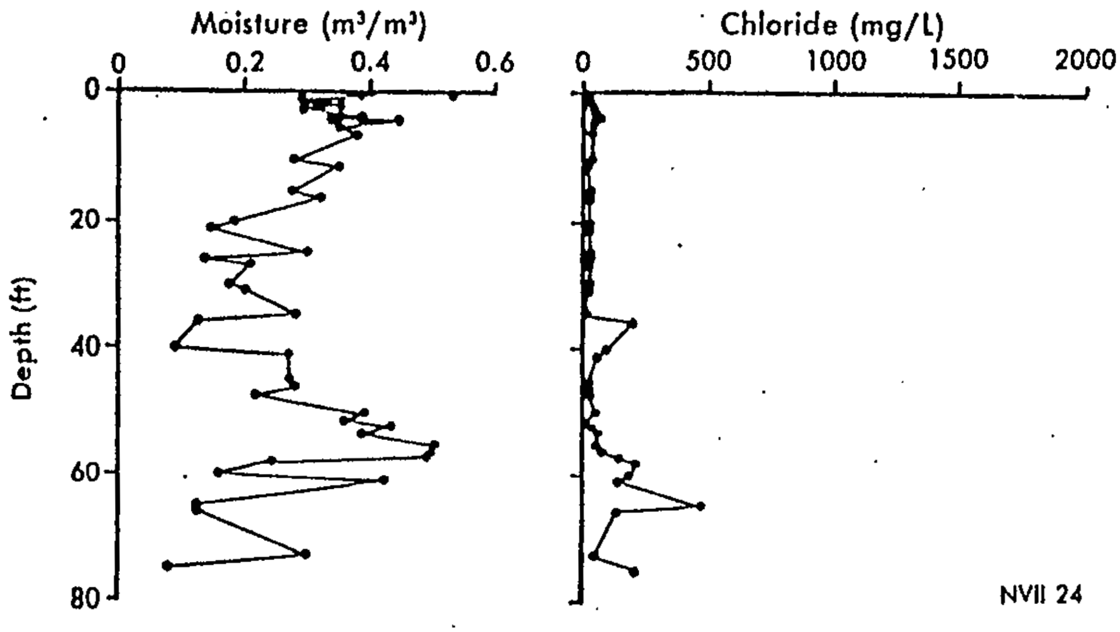

Figure 11 - Chloride profile, North Barber depression (Hole NV II 24).

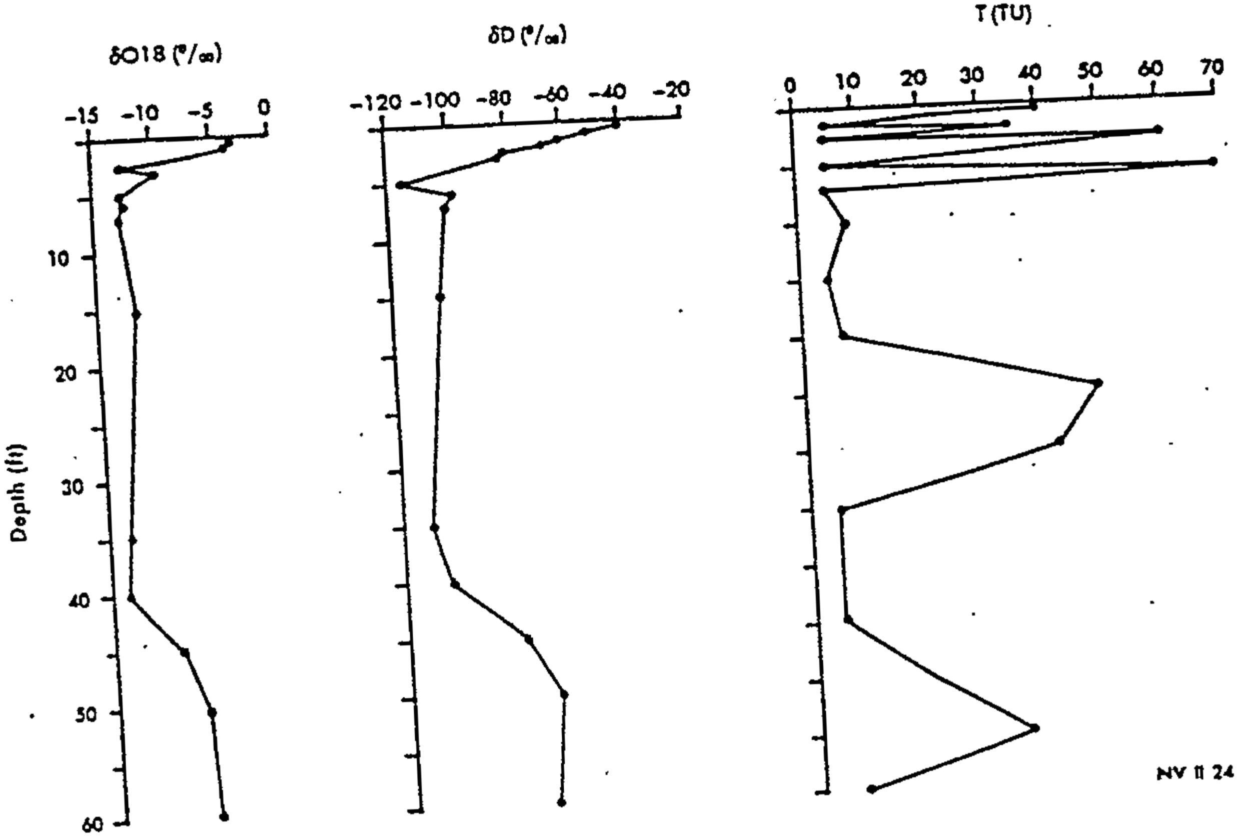

Figure 12 - Stable-isotope and tritium profiles, North Barber depression (NV II 24).

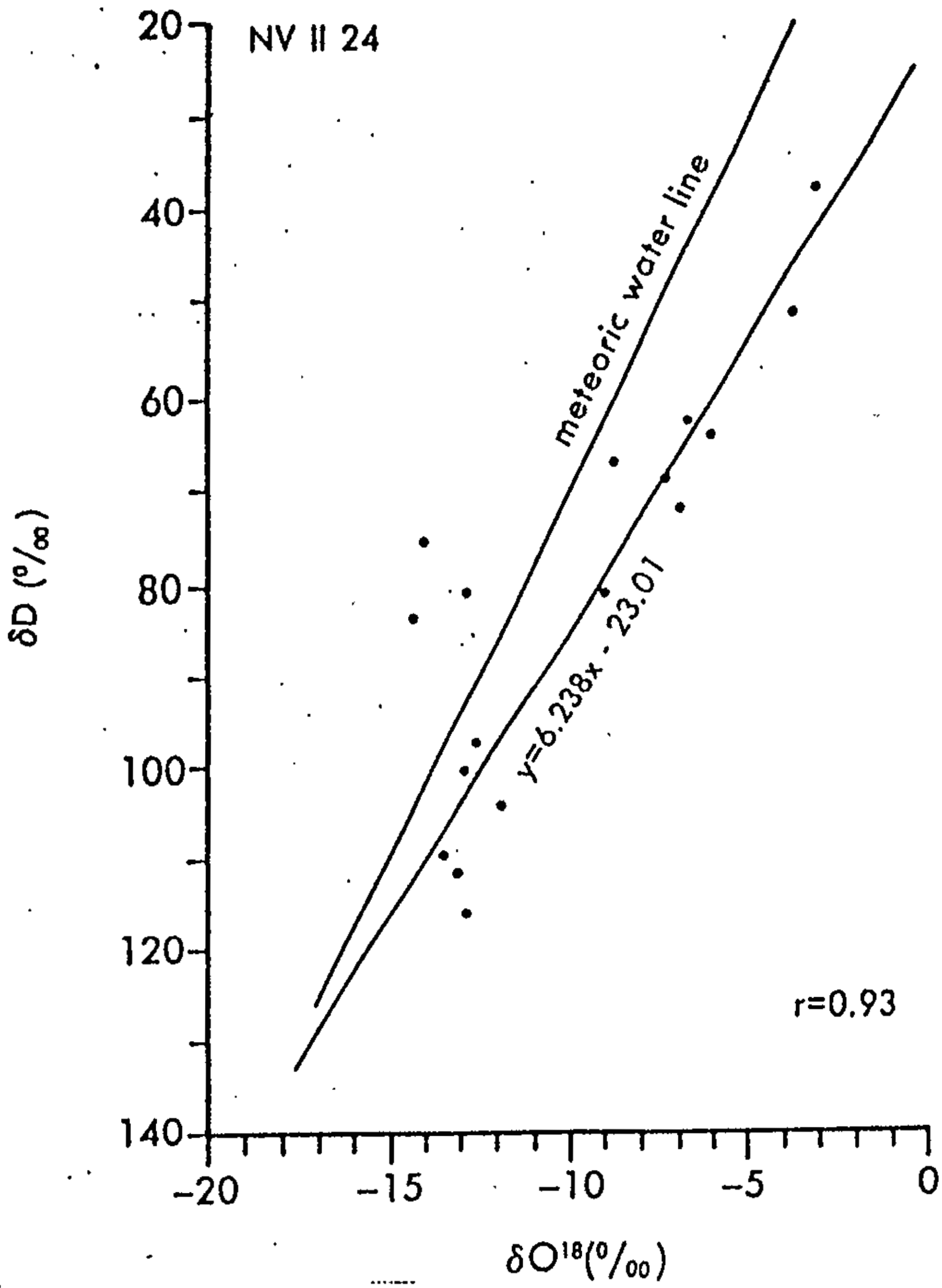

Figure 13 - Oxygen-18/deuterium plot, North Barber depression (hole NV II 24).

14). Slope of the evaporation line for these data is 3.3 and the correlation coefficient is only 0.54 (Figure 15).

The flushing bulge seen in Hole 3 and others is apparently more a matter of active recharge than nonequilibrium. Periodic flooding of such depressions by runon enhances recharge (Allison and others, 1985; Stone, 1984a, b). On the several occasions the North Barber depression was visited, the clayey bottom was soft. Great care had to be taken to not get the field vehicle and drilling rig stuck during sampling.

Local recharge values obtained for just the reclaimed depressions evaluated in Phase III are summarized in Table 1. Values (based on chloride) range from 0.03-0.16 in/yr. The median is 0.095 in/yr; the mean is 0.08 in/yr. For other reclaimed area rates see Table 2.

Table 1. Summary of local recharge values for reclaimed depressions studied in Phase III.

Hole No.	Depression	Year Reclaimed	Chloride Profile Type	R_{cl} (in/yr)[2]	R_{Dd} (in/yr)[3]
1 (II 16)[1]	Custer	1975	variable	0.03	0.04
2 (II 19)	Pinto	1975/76	equilibrium	0.04	0.06
3 (II 24)	North Barber	1979	flushing	0.16	0.05
II 28	Yazzie	1979	variable/flushing(?)	0.34	NA[4]

[1] numbers preceded by "II" are Phase-II hole numbers
[2] R_{cl} = recharge based on chloride mass-balance method
[3] R_{Dd} = recharge based on deuterium displacement; may not be applicable to these profiles
[4] NA = not applicable; stable isotopes do not track one another

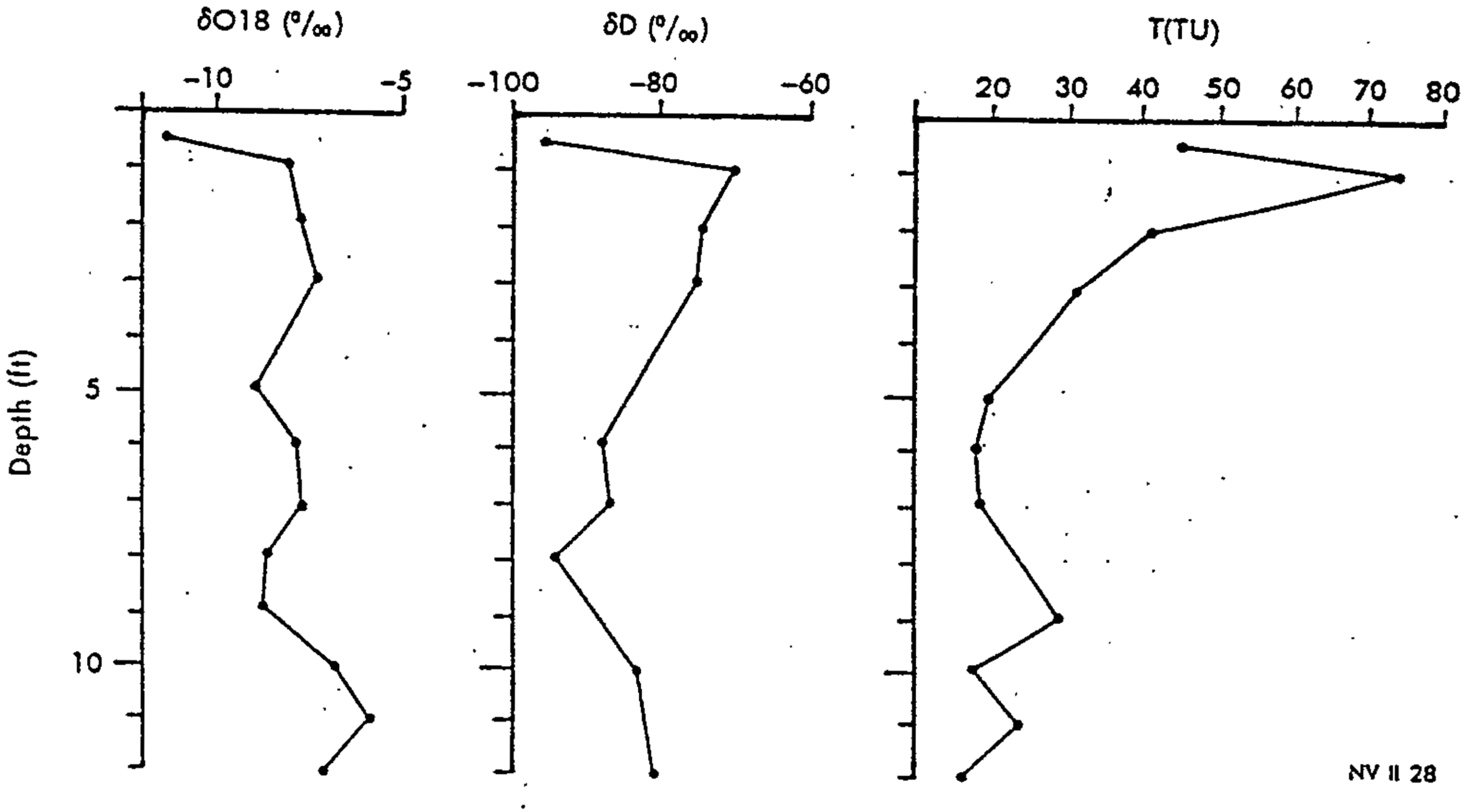

Figure 14 - Stable-isotope and tritium profiles, Yazzie depression (hole NV II 28).

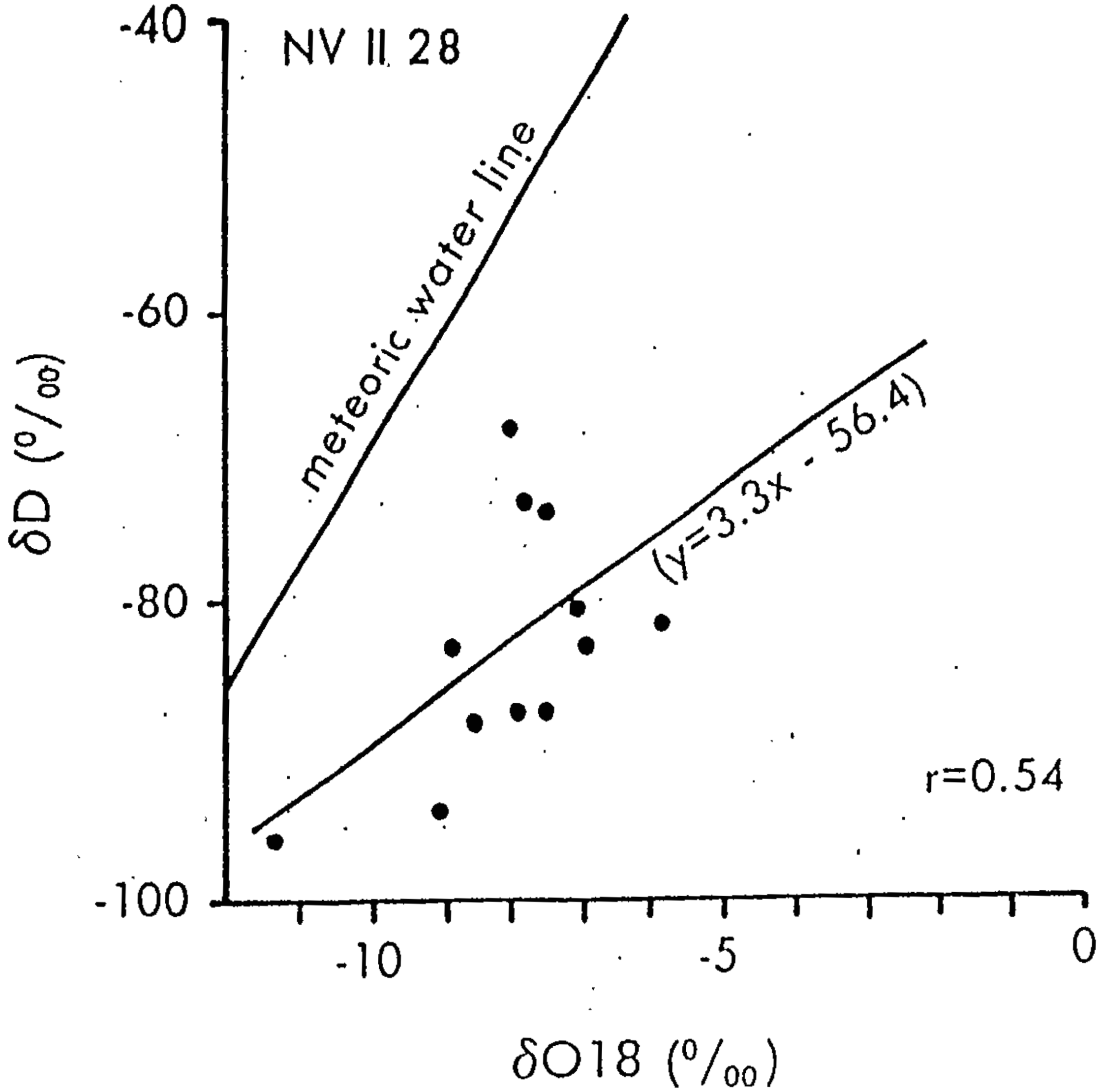

Figure 15 - Oxygen-18/deuterium plot, Yazzie depression (hole NV II 28).

Table 2. Local recharge rates for Navajo Mine landscape settings. See Stone (1984 and 1986) for specific values.

Setting	No. of sites	Range[2] (in/yr)	Median[3] (in/yr)	Mean[4] (in/yr)	Ranking[5] by recharge
UNDISTURBED	(7)	(0.002-0.09)	(0.046)	(0.03)	
badlands	3[1]	0.002-0.01	0.006	0.006	5
upland flat	3	0.02 -0.05	0.035	0.03	4
valley terrace	1	0.09	0.09	0.09	2
RECLAIMED	(22)	(0.01 -0.49)	(0.25)	(0.09)	
depression	9	0.03- 0.49	0.26	0.16	1
flat	13	0.01- 0.23	0.12	0.04	3

[1] includes valley bottom site of Phase-I study as in badlands
[2] recharge values based on mean (not median) Clsw
[3] median = (range/2) + low value
[4] mean = total/number of values
[5] 1 = highest; 5 = lowest

IMPACT OF MINING ON RECHARGE

The ultimate objective of the Bureau's recharge studies at the Navajo Mine was to determine the net change in recharge capacity due to mining, especially the impact of depressions in reclaimed areas. This change may be assessed by comparing premining and postmining recharge values. For example, local recharge rates may give an indication of change. Better yet, the total volume of water recharged before and after mining (reclamation) can be compared.

LOCAL RECHARGE

The first step in calculating volumetric recharge is to determine local recharge rates. Values were obtained in Phases I and II of this study (Stone, 1984b and 1986a) and the isotope work in Phase III shows that such values are usable. Local recharge rates for settings recognized at Navajo Mine are summarized in Table 2.

Local recharge ranges from 0.002 in/yr (Bitsui badlands valley) to 0.49 in/yr (Doby depression). The frequency of occurrence of local recharge values is shown in Figure 16. The vast majority of values fall below 0.10 in/yr. The most commonly obtained value is 0.02 in/yr (five sites). Three values share the next most common slot: 0.01, 0.03, and 0.05 in/yr (four sites each). Values of 0.04 and 0.10 in/yr occurred at three sites each. The values of <0.01, 0.07, 0.08, 0.09, 0.34, and 0.49 in/yr were obtained at one site each. Some values were not obtained at any site: 0.06, 0.12-0.34, and 0.35-0.49 in/yr.

Local recharge in undisturbed areas averages 0.03 in/yr, whereas, that in reclaimed areas averages three times that or 0.09 in/yr. Based on decreasing order of local recharge rate, settings would be ranked as reclaimed depression, valley terrace, reclaimed flat, undisturbed upland flat, and badlands (Table 2).

AREAL EXTENT OF SETTINGS

The next step in calculating volumetric recharge is the determination of the areal extent of various landscape settings in the study region. This may be accomplished through the use of field studies, aerial photographs, topographic maps, soils maps, geologic maps, or some combination of these tools. Different methods should give similar results. Stone (1985a) found that

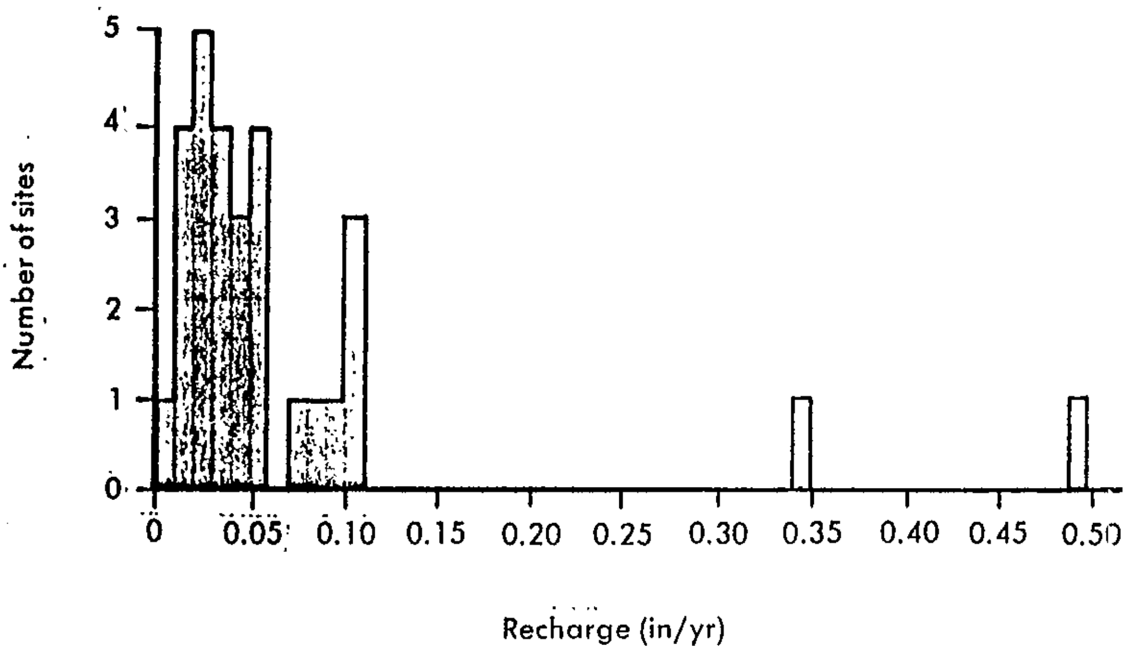

Figure 16 - Frequency of occurrence of local recharge values.

Table 3. Summary of pre- and postmining recharge rates and fluxes at Navajo Mine (Stone, 1987).

Setting (sites)	Recharge range (in/yr)	Median recharge (in/yr)	Mean recharge[1] (in/yr)	Area (ac)	Volumetric recharge (ac-ft/yr)
UNDISTURBED (7)	(0.002-0.09)	(0.046)	(0.03)	(8,821)	(16.05)
badlands (3)	0.002-0.01	0.006	0.006	4,240	2.12
upland flat (3)	0.02 -0.05	0.035	0.03	4,090	10.23
valley terrace (1)	NA	NA	0.09	491	3.7
			Mean regional recharge = 0.02 in/yr[2]		
UNDISTURBED AREA REDUCED TO MATCH RECLAIMED AREA	NA	NA	0.02[2]	2,881	4.9
RECLAIMED (22)	(0.01 -0.49)	(0.25)	(0.09)	(2,881)	(10.05)
depression (9)	0.03 -0.49	0.26	0.16	68	0.68
flat (13)	0.01 -0.23	0.12	0.04	2,813	9.37
			Mean regional recharge = 0.04 in/yr[2]		
RECLAIMED AREA EXPANDED TO MATCH UNDISTURBED AREA					(30.88)
depression	NA	NA	0.16	176	2.35
flat	NA	NA	0.04	8,645	28.53
			Mean regional recharge = 0.04 in/yr[2]		
WITHOUT DEPRESSIONS IN RECLAIMED AREA	NA	NA	0.04	8,821	29.40

[1] simple arithmetic average
[2] weighted by acreage (volumetric recharge divided by area)

areal extents, and thus volumetric recharge results, based on a geologic map were very comparable to those obtained from a soils map of the same area.

In this study, it was necessary to determine areal extent of premining and post-mining settings by different methods. Premining acreages were based on soils maps made between 1963 and 1977 (Keetch and others, 1980; see Appendix C). Boundaries between settings were determined and digitized (Figures 2 and 3). Areas were determined by a digital planimeter (Table 3). Areal extent of post-mining settings was based on the latest aerial photographs (1:6,000) and field checking. This covered only areas in which mining had occurred: 1 and 2. Depression floors were delineated on photos by means of a 10x mirror stereoscope. Depressions larger than 0.15 acres (6500 ft^2) were located in this way. Smaller ones escaped detection. Outlines of depression floors were transferred to 1 inch-to-500 ft mine maps and areal extents determined by means of a digital planimeter (Figure 4). The size and location of each depression was then verified in the field. Areal extents of postmining settings are given in Table 3.

AREAL AND REGIONAL RECHARGE

For a given setting, areal recharge is the product of its local recharge rate and its areal extent, in similar units. Local recharge is converted to ft/yr (divided by 12) and acreage is converted to ft^2 (multiplied by 43,560). Multiplying these gives a value of ft^3/yr; division by 43,560 gives acre-ft/yr. This calculation is made for both premining and post-mining settings.

As shown in Table 3, premining areal recharge in areas 1 and 2 ranges from 2 ac-ft/yr to 10 ac-ft/yr. Upland flats account for the greatest premining recharge volume (64%) and badlands contribute the least (13%). The valley/terrace setting is intermediate with 23% of the recharge.

Recharge volumes for reclaimed settings are also given in Table 3. However, the acreage is less than that of the undisturbed area. More specifically, 67% of the area is still taken up by open pits, ramps, roads, etc., features that would not be present at end of mining. Recharge volumes cannot be compared and impact of mining cannot be assessed unless pre- and postmining areas are identical.

Areas may be made equal in two ways: reducing undisturbed acreage to that of the reclaimed ground analyzed or increasing reclaimed acreage to that of the undisturbed ground. In the first case, recharge volume is calculated using the mean regional recharge rate and an area of 2,881 ac (Table 3). This gives a premining recharge volume of 4.9 ac-ft/yr as compared to a post-mining recharge volume of 10.05 ac/ft/yr. The difference is an increase of 5 ac-ft or 105%. In the second case, recharge volume is calculated using the respective recharge rates and acreages for the settings, based on the observation that depressions account for only 2% of the reclaimed ground. This gives a post-mining value of 30.88 ac-ft/yr (2.35 ac-ft/yr for depressions and 28.53 ac-ft/yr for other reclaimed settings). This represents an increase in recharge with mining and reclamation of 15 ac-ft or 108%. As recharge is higher in depressions and they are no longer being constructed, a more realistic impact of mining can be determined by calculating recharge volumes without depressions. This gives 29 ac-ft/yr, or an increase of only 83% (Table 3).

DISCUSSION AND CONCLUSIONS

In all cases, mining and reclamation appear to increase recharge. Those scenarios involving depressions suggest recharge is approximately doubled. With no depressions the indicated increase in recharge is 9-22% less. The increase in recharge with mining and reclamation is attributed to better infiltration capacity of the spoil as well as the blow sand used for top soil, improved vegetative cover, enhanced availability of water for recharge in depressions due to ponding of runoff, and addition of supplementary water during irrigation. Although the latter is short-lived, the other conditions prevail.

An increase in recharge at Navajo Mine should not be detrimental to the water resources of the region. As one parameter of the hydrologic budget changes, others also change to maintain the balance. In the case of an increase in recharge, the expected response would be a decrease in runoff. This is not unfavorable at Navajo Mine as the mine plan calls for zero runoff. A further consequence would be enhanced ground-water flow toward discharge areas. The amount of increase would be minimal, equaling the rate of increased recharge.

Results presented here are believed to be realistic and representative. Additionally, this is the first time, to my knowledge, that impact of mining on recharge has been addressed or documented to this extent. This study should serve as a model for such studies at other surface coal mines.

ACKNOWLEDGMENTS

Funding for sampling, isotope analyses, and recharge calculations was provided by a contract with BHP-Utah International Inc. Mapping and determination of areal extents of landscape settings was done by Dr. Bruce A. Buchanan (Department of Crop and Soil Science, New Mexico State University) and Thomas B. Korsmo (graduate research assistant, New Mexico State University). Sterling Grogan (manager of environmental quality), and Orlando Estrada (senior environmental specialist), BHP-Utah/Navajo Mine, provided valuable assistance during the work. Darla Curtis (undergraduate student, New Mexico Tech) assisted in the laboratory.

REFERENCES CITED

Allison, C. B., Barnes, C. J., Hughes, M. W., and Leaney, F. W. J., 1983, Effect of climate and vegetation on oxygen-18 and deuterium profiles in soils: International Atomic Energy Agency, Report SM-270120, p. 105-121.

Allison, G. B., and Hughes, M. W., 1978, The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer: Australian Journal of Soil Research, v. 16, p. 181-195.

Allison, G. B., Stone, W. J., and Hughes, M. W., 1985, Recharge through karst and dune elements of a semiarid landscape as indicated by natural isotopes and chloride: Journal of Hydrology, v. 76, p. 1-25.

Buchanan, B. A., and Korsmo, T. B., 1987, Distribution and extent of pre-mine and post-mine landscapes on the Navajo Mine, New Mexico: unpublished report to BHP-Utah International Inc., 12 p.

Craig, H., 1961, Isotopic variations in meteoric water: Science, v. 133, p. 1702.

Keetch, C. W., Ruiz, J. E., Parham, T. L., Bulloch, H. E., Anderson, T. J., King, D., Seagraves, C., Boyer, J., Kossie, A., Roybal, M. W., and Childs, S., 1980, Soil survey of San Juan County, New Mexico--eastern part: Soil Conservation Service, 173 pp.

McCord, J. T., and Stephens, D. B., 1987, Lateral moisture flow beneath a sandy hillslope without an apparent impeding layer: Hydrological Processes, v. 1, p.225-238.

Snell, F. D., and Biffen, F. M., 1964, Commercial methods of analysis: Chemical Publishing Company, Incorporated, New York, p. 41-43.

Stone, W. J., 1984a, Preliminary estimates of Ogallala-aquifer recharge using chloride in the unsaturated zone, Curry County, New Mexico: Proceedings, Ogallala Aquifer Symposium II, Lubbock, p. 376-391.

Stone, W. J., 1984b, Preliminary estimates of recharge at the Navajo Mine based on chloride in the unsaturated zone: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 213, 60 p.

Stone, W. J., 1985a, Determining recharge in coal surface mining areas: Proceedings, 2nd National Meeting of the American Society for Surface Mining and Reclamation, Denver, p. 394-403.

Stone, W. J., 1985b, A simple approach to determining recharge in surface coal mining areas; a study guide for a mini-course taught at the 1985 National Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, Lexington, Kentucky, 63 p.

Stone, W. J., 1986a, Phase-II recharge study at the Navajo Mine based on chloride, stable isotopes, and tritium in the unsaturated zone: New Mexico Bureau of Mines and Mineral Resources, Open-file Report 216, 244 p.

Stone, W. J., 1986b, Comparison of ground-water recharge rates based on chloride, stable-isotope, and tritium content of vadose water at the Navajo Mine (abs.): New Mexico Geology, v. 8, no. 3, p. 70.

Stone, W. J., 1986c, Natural recharge in Southwestern landscapes --examples from New Mexico: Proceedings, National Water Well Association Focus Conference on Southwestern Ground-Water Issues, Tempe, p. 595-602.

Stone, W. J., Lyford, F. P., Frenzel, P. F., Mizell, N. H., and Padgett, E. T., 1983, Hydrogeology and water resources of San Juan Basin, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 6, 70 p.

Utah International Inc., 1981, Permit application for Navajo Mine, v. 1, chpt. 15.

APPENDIX A

ISOTOPE DATA

Hole 1 Custer Depression

Sample	Depth (ft)	Vol. (ml)	O18 (o/oo)	D(o/oo)	T (Tu)
1	0.5	35	- 3.03	- 51.6	51+/-8
2	1	35	- 6.48	- 74.7	50+/-7
3	1.5	25	NES*	NES	NES
4	2	23	-14.63	-108.5	22+/-8
5	2.5	45	-12.46	- 97.6	<6+/-8
6	3	2	NES	NES	NES
7	5	45	NES	NES	NES
8	6	43	-17.38	-123.7	<6+/-8
9	7	36	-13.78	-112.5	<6+/-7
10	8	25	-17.44	-132.8	<6+/-7
11	10	34	-14.73	-125.5	34+/-8
12	15	35	- 9.70	-111.1	9+/-8
13	20	50	-11.67	-112.9	<6+/-7
14	25	45	- 9.94	-104.4	19+/-7
15	30	43	- 9.70	-100.6	9+/-8
16	35	30	-12.83	-108.8	18+/-8
17	40	32	NES	NES	<6+/-7
18	45	32	- 8.24	- 87.9	21+/-7
19	51	1	NES	NES	NES
20	56	38	- 9.80	- 70.0	<6+/-7

* NES = lab reported not enough sample

Hole 2 Pinto Depression

Sample	Depth (ft)	Vol. (ml)	O18 (o/oo)	D(o/oo)	T (Tu)
21	1	43	- 1.29	- 66.2	38+/-8
22	2	35	- 5.60	- 81.8	7+/-7
23	3	32	- 8.22	- 87.5	13+/-8
24	5	42	-10.87	-100.1	11+/-7
25	6	48	-12.58	-103.8	12+/-8
26	7	38	-13.54	-107.5	21+/-7
27	10	27	-14.17	-101.5	<6+/-7
28	15	22	-13.80	-106.7	<6+/-7
29	20	35	-14.21	-123.1	<6+/-7
30	25	33	-14.77	-123.5	<6+/-8

Hole 3 North Barber Depression

Sample	Depth (ft)	Vol. (ml)	O18 (o/oo)	D(o/oo)	T (Tu)
31	0.5	37	- 3.23	- 37.7	41+/-7
32	1	26	- 3.90	- 51.6	20+/-8
33	1.5	46	- 6.64	- 62.1	<6+/-7
34	2	46	- 8.72	- 67.1	36+/-8
35	2.5	37	-12.80	- 80.2	<6+/-7
36	3	35	- 9.39	- 83.3	61+/-7
37	5	45	-12.94	-116.1	<6+/-7
38	6	38	-12.54	- 97.6	70+/-8
39	7	42	-12.89	-101.0	6+/-7
40	10	35	NES	NES	8+/-7
41	15	42	-11.70	-104.2	<6+/-7
42	20	28	NES	NES	7+/-7
43	25	26	NES	NES	49+/-9
44	30	21	NES	NES	42+/-8
45	35	27	-13.17	-111.8	<6+/-7
46	40	29	-13.51	-109.5	<6+/-7
47	45	49	- 9.06	- 80.9	<6+/-8
48	50	35	- 7.38	- 60.0	19+/-8
49	55	70	NES	NES	35+/-9
50	60	70	- 6.95	- 72.0	7+/-8
51	65	27	NES	NES	54+/-8

APPENDIX B

BRIEF FIELD DESCRIPTION OF SAMPLES

Hole 1 Custer Depression

Drilled 10 ft due east of hole 16 of Phase-II study.

Sample No.	Depth (ft)	General Lithology
1-6	0.5-3	Spoil - light gray sandstone and some green claystone
7-10	3-8	Spoil - sandstone as above with carbonaceous shale, coaly spoil at base.
11	8-10	Spoil - gray carbonaceous shale/coaly spoil.
12-14	10-75	Spoil - upper 6" carbonaceous shale, rest sandstone as above.
15	25-30	Spoil - as above except lower 1 ft carbonaceous shale.
16	30-35	Spoil - mostly green carbonaceous shale.
17	35-40	Spoil - coaly spoil in upper half; lower half gray claystone.
18	40-45	Spoil - green claystone as above; some sandstone at base
	45-50	Hard zone - no sample.
19	50-51	Spoil - hard, white sandstone
	51-55	Hard zone - no sample.
20	55-56	Spoil - mostly carbonaceous sandstone.

Hole 2 Pinto Depression

Drilled 20 ft northeast of hole 19 of Phase-II study.

Sample No.	Depth (ft)	General Lithology
21, 22, 23	0-4	Spoil - yellow sand and green claystone
24, 25, 26, 27	4-14	Spoil - green claystone as above
28	15-19	Spoil - top half yellow sand; lower half claystone as above.
29	19-21	Spoil - upper 6" spoil; rest Fruitland Fm(?)-moist, very carbonaceous dark gra shale
	21-24	Hard zone - no sample.
30	24-25	Fruitland Fm(?) as above.

Hole 3 North Barber Depression

Drilled 25 ft southwest of hole 24 of Phase-II study.

Sample No.	Depth (ft)	General Lithology
31-36	0-3	Spoil - clayey, carbonaceous mudstone
37-39	3-8	Spoil - as above, but dark green
40, 41	8-13	Spoil - as above, moist; gray sandstone at base
42-43	13-23	Spoil - as above, but with bits of hard carbonaceous mudstone
44	23-28	spoil as above with fissile carbonaceous siltstone
45	28-33	Spoil - dark gray carbonaceous claystone
46, 47	33-48	Spoil - carbonaceous shale and claystone
48	48-53	Spoil - loose, very coaly; some hard blocks
49	53-58	Spoil - loose, clayey; very wet near base
50	58-63	Spoil - carbonaceous claystone/ mudstone
	cable problem; dropped rod	no further sampling

APPENDIX C

SUMMARY OF PREMINING LANDSCAPES
(modified from Buchanan and Korsmo, 1987)

Setting	Description	Associated Soil Series
Badlands	barren uplands dissected by ephemeral streams, breaks, hills, and mesas where bedrock (Fruitland Fm) is exposed or covered by very thin soils	Farb Persayo Monierco
Upland Flats	plateaus, mesas, high terraces, and alluvial fans underlain by Fruitland Fm and capped by alluvial and/or eolian deposits; soils may be thick; most complex setting with greatest variety of soil types	Avalon Blackston Blancot Doak Farb Huerfano Mayqueen Monierco Muff Notal Persayo Sheppard Shiprock Stumble Uffens
Valley/Terrace	ephemeral stream-channel floors and associated floodplains and terraces; consist of alluvium; soils are young but typically thick	Beebe Fruitland Glenton Stumble Turley Youngston