DETERMINING RECHARGE IN COAL SURFACE MINING AREAS[1]

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Abstract.--Recharge is an important component of a mine's water budget. Data are seldom available and usual methods of measurement are complex and expensive. A mass-balance method relating chloride content of vadose water to recharge is simple but reliable. Applications of the method to areas in the San Juan Basin of New Mexico show promise.

INTRODUCTION

In the permitting of surface coal mines, both the applicant and regulatory agency are obliged to address the ultimate hydrologic impact of mining. The applicant does this in a statement of Probable Hydrologic Consequences (PHC) and the regulator does this in the Cumulative Hydrologic Impact Assessment (CHIA). In these documents, varioua hydrologic-balance parameters and water-quality indicators are scrutinized.

Of the hydrologic-balance components, recharge is perhaps the least understood. Nonetheless, it is important in the water budget of a mine area and regulations may specifically call for its protection. For example, New Mexico's Surface Coal Mining Regulations (Part 20, Section 51, p. 172) require that the premining recharge rate be restored through reclamation. But how can this be determined or verified? Data on premining recharge rates are rarely available, let alone post-mining recharge values. Furthermore, measurement or estimation of recharge by usual chemical methods (e.g. isotopes or tracers) or physical methods (e.g. soil physics instruments, or hydraulics) is complex, time-consuming, and expensive.

An alternative method of determining recharge, based on chloride content of water in the unsaturated zone is simple and relatively inexpensive. The method has immediate application in undisturbed settings; use in reclaimed settings is still being evaluated. The purposes of this paper are to describe the chloride mass-balance method and to illustrate its application to coal surface mining areas through the use of case histories from the San Juan Basin of New Mexico.

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CHLORIDE MASS-BALANCE METHOD

In the chloride method, recharge is determined from the relationship PClp = RClsw (Allison and Hughes, 1978) or R = Clp/Clsw P, where R = recharge (mm/yr), Clp = average annual chloride content of precipitation (mg/L), Clsw = average chloride content of soil (vadose) water (mg/L), and P = average annual precipitation (mm/yr). Clp and P are either obtained from the literature or measured. Clsw is determined from plots of chloride vs depth, based on core samples. Note that recharge is inversely proportional to Clsw; for example, the higher the Clsw, the lower the recharge.

Assumptions and Validity

Several assumptions are made in the chloride method: 1) recharge occurs only by piston flow, 2) recharge is only from precipitation, 3) precipitation is the sole source of chloride entering the ground, 4) precipitation has been constant through the time interval represented by the samples, and 5) chloride content of precipitation has also been constant through time. These assumptions are not always valid. For example, some recharge by non-piston flow may occur along fractures or root channels. Recharge may occur as a result of runon of surface waters or discharge from underlying or adjacent geologic units. The chloride in precipitation, originating from 1) salt particles formed by the evaporation of sea water, 2) dust from dry saline lake beds, and 3) industrial emissions, may not be the only source of chloride entering the soil. Chloride may also be added directly through dryfall of saline dust or fertilizer, in the case of revegetated land. In rare cases, some chloride may even be derived from the rock or soil material itself; the method is usually not applied where this is suspected. Average annual precipitation has no doubt varied through time. Of particular interest is the fact that the Pleistocene climate was wetter than that of the present. Similarly, chloride content of precipitation has also probably fluctuated. Chloride content of precipitation is related to distance from the

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ocean (Hutton, 1976). Lower sea levels in the Pleistocene would have resulted in increased distances from the coast and thus lower chloride concentrations in precipitation at that time.

In view of these deviations from the assumptions, results of the chloride method are considered estimates of recharge. However, values obtained by this method compare favorably (same order of magnitude) with results of more complex and expensive methods. A plot of recharge determined from chloride vs recharge from tritium data gave a straight line for a study in Australia (Allison and Hughes, 1978). Stable-isotope data also corroborated recharge estimates from chloride in another study in Australia (Allison and others, 1985). Chloride mass-balance results have been confirmed by chlorine 36 data as well (Phillips and others, 1984; Phillips and Stone, 1985).

Sampling and Analysis

Samples of the unsaturated zone are obtained by means of continuous coring with a hollow-stem auger rig. The core is subsampled at regular intervals (more closely spaced near the surface). Samples are protected against moisture loss by use of screw-top jars, sealing covers with plastic tape, and storing sample jars out of the sun in zip-top plastic bags.

Laboratory procedures include gravimetric moisture analysis, extraction of chloride-bearing salt by mechanical shaking with deionized water, and determination of chloride content of the extract after settling by colorimetric titration or a chloride electrode. Based on the volumetric moisture content, amount of deionized water added in extraction, and the chloride content of the extract, original soil-water-chloride content is determined. Specific procedures used in analyses appear to be valid (McGurk and Stone, 1985).

Presentation and Interpretation of Results

Resulting chloride values are plotted against depth on arithmetic graph paper. Profiles typically show an increase in chloride through the root zone to a maximum value that is more or less maintained to the water table; in some cases (fig. 1) chloride is lower below the peak but constant with depth. The average chloride content in the portion of the profile below the peak is used for Cl_{sw} in the recharge formula. Similar recharge rates (same order of magnitude) are generally obtained regardless of whether the median or mean chloride value is used (Stone, 1984b).

Some profiles are characterized by a decrease in chloride content with depth (fig. 2). In such profiles, one of three conditions may be assumed. Fresh water is reaching the lower part of the profile by other than piston flow, conditions at the site were more favorable for recharge at the time represented by the lower part of the profile, or the profile is the result of discharge from the water table. In the case of non-piston flow, fresh water moves rapidly downward along fractures, roots, animal burrows, or other highly conductive features. If this is not the case, precipitation, chloride input, and/or recharge may have changed with time. Plots of cumulative chloride content (g/m^2) vs cumulative water content (m) (fig. 3) help identify periods of change at sites where the chloride content decreases markedly with depth (Allison and others, 1985). In the case of ground-water discharge, chloride content increases toward the surface as a result of evapotranspiration. Stable-isotope data should clarify whether the profile is a result of recharge, discharge, or both.

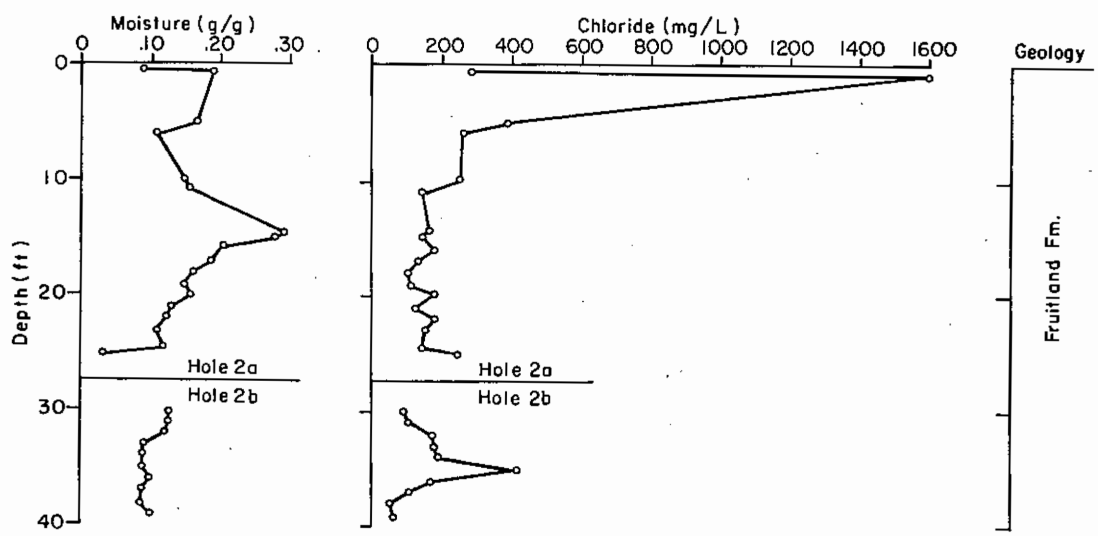

Figure 1.--Typical chloride vs depth plot (chloride constant below peak) from upland flat setting (Hole 2), Navajo Mine (Stone, 1984b).

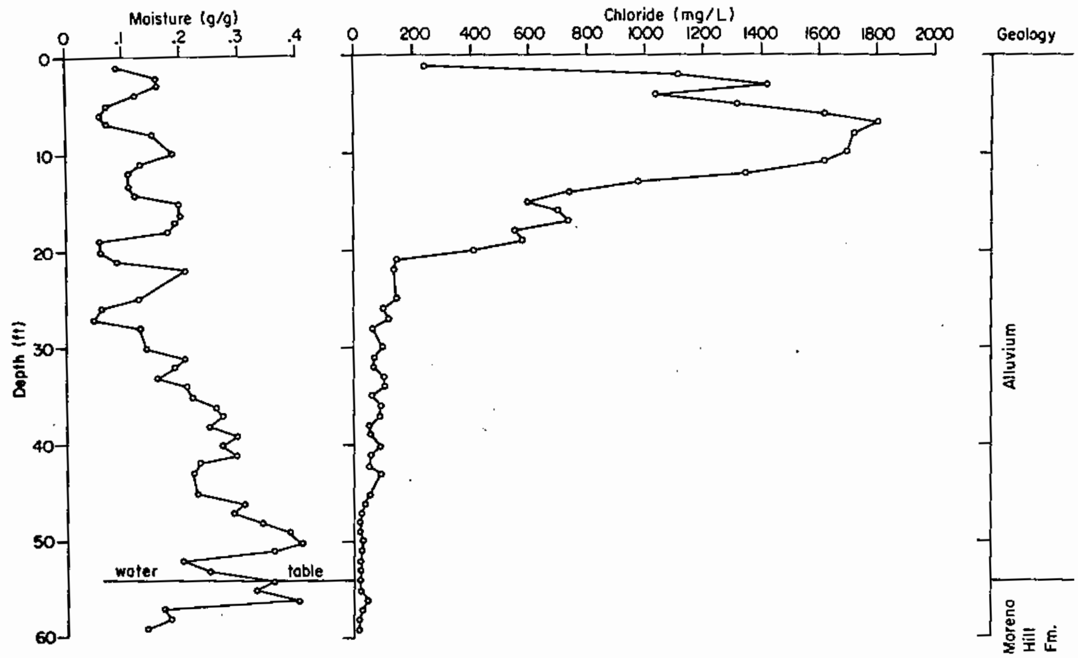

Figure 2.--Atypical chloride vs depth plot (chloride decreases below peak) from bedrock/grass setting (Hole 5), Salt Lake Coal Field (Stone, 1984c).

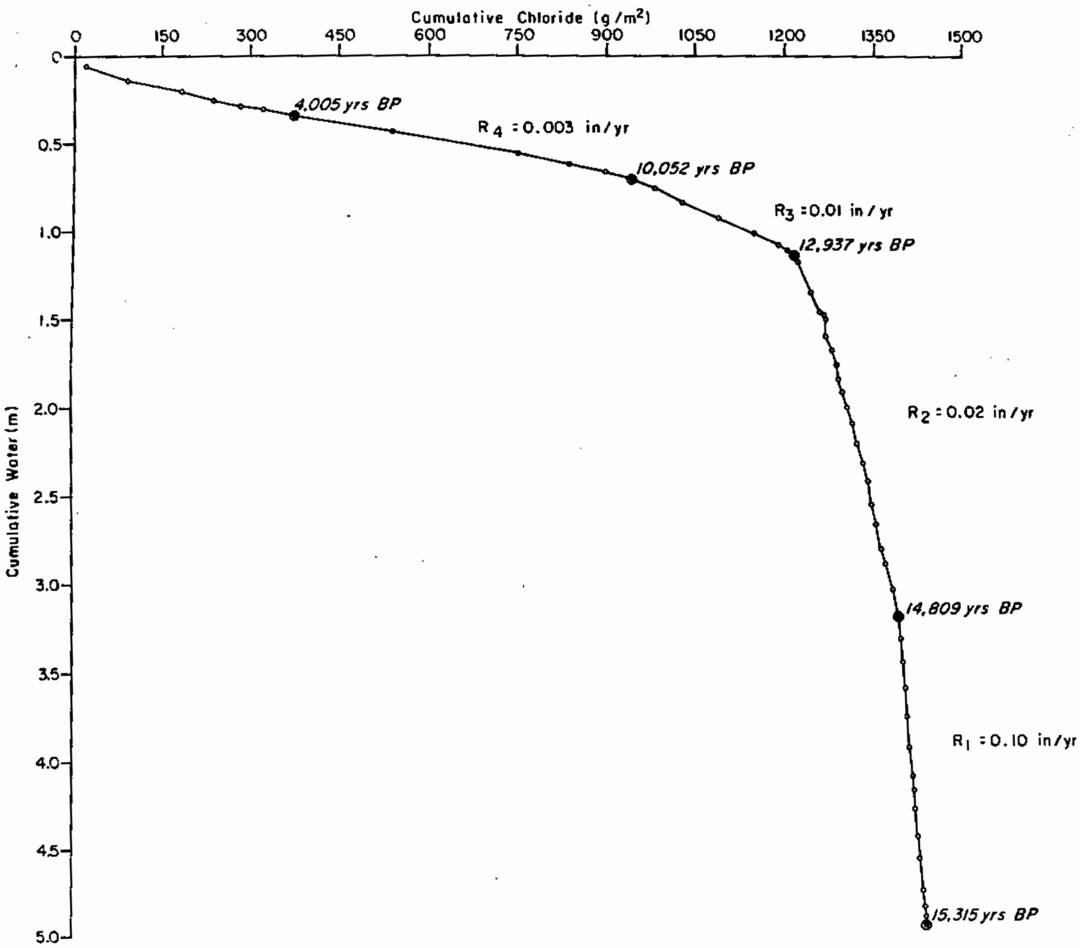

Figure 3.--Cumulative chloride vs cumulative water plot for data in figure 2 (Stone, 1984b).

APPLICATIONS TO COAL SURFACE MINING

The chloride method is readily applied to areas of active or potential coal surface mining. In such applications, consideration must be given to variation in recharge with landscape setting. Similarly, recharge may be viewed in terms of fluxes at three different scales or an average regional flux. The ultimate impact of mining is determined by comparing premining and post-mining recharge values at any or all of these scales.

In reclaimed areas, a premining recharge rate can be determined using the average chloride content of the lower part of the profile, whereas, post-mining recharge rate can be derived from the average chloride content of the upper part of the profile (if the system has regained equilibrium).

Landscape Setting

Surface mines are characterized by various landscape settings, some natural, some man-made. Each setting is a unique combination of geology, soils, topography, vegetation, and land use or land-use history. For example, settings may be distinguished as alluvium vs coal measures, rocky soil vs silty soil, valley bottom vs upland flat, undisturbed vs reclaimed ground, or various combinations of these.

Recharge varies with landscape setting (Allison and Hughes, 1983; Stone, 1984a, b, c; Allison and others, 1985). Sampling for the chloride method should, therefore, cover the range of major settings at a mine. Geologic, soils, topographic, and mining-plan maps should assist in identifying these settings.

Scale

Three different scales of recharge may be derived: local, areal, and regional. Local recharge may be defined as that associated with a given point in a specific landscape setting. It may be determined by applying the chloride method to samples from at least one site in each of the major landscape settings recognized in the mine region. Results are presented in the form of a linear flux having the dimensions length per unit time (e.g. mm/yr or m/yr). Areal recharge may be defined as that occurring over the entire extent of a given landscape setting in the mine region. This is determined by converting the local or point recharge value into a volumetric recharge, based on the area covered by that setting (e.g. m^2). Results are in the form of a volumetric flux with the dimensions volume per unit time (e.g. m^3/yr). Regional recharge is the total recharge occurring in the mine region (some arbitrarily defined, regularly shaped block of land covering the mine of interest). It is merely the sum of all of the areal recharge values. As in the case of areal recharge, results are presented in the form of a volumetric flux with the dimensions volume per unit time.

Alternatively, it may be desirable to evaluate impact in terms of change in an average regional flux. This average is determined by dividing the regional recharge value (total of the areal recharge volumes) by the total area of the study region.

Assessing Impact

In order to assess the impact of mining, both premining and post-mining recharge values must be compared. In some cases, comparison of local fluxes may be sufficient; in others, comparison of premining and post-mining values for regional recharge may be necessary. Alternatively, average premining and post-mining recharge values may be compared.

Premining recharge rates may not be available, because regulations requiring analysis of premining hydrologic conditions may not have been in effect at the time mining operations began. Reconstructing premining conditions is difficult, because mining and reclamation obliterate the nature and extent of original landscape settings. However, premining topographic maps and aerial photographs, together with mine plans, should provide such information. Local premining recharge rates may be estimated by application of the chloride method to samples from modern, undisturbed examples of these formerly more extensive landscape settings. Areal and regional premining recharge rates may be calculated by multiplying these local fluxes by the original areal extents of the premining landscape settings, as determined from old maps and photos.

Post-mining recharge may be predicted from results of work on undisturbed and reclaimed landscape settings and the post-mining areal distribution of these settings. The type and distribution of major post-mining settings may be determined from mine plans. Local recharge for these settings may be determined by applying the chloride method to present-day examples of such settings. Post-mining areal and regional recharge values are determined as for premining conditions.

Average premining and post-mining rates over the mine region may also be compared to assess impact of mining. Such averages are determined by dividing the volumetric regional recharge flux (e.g. acre-ft/day) by the regional area (e.g. acres).

CASE HISTORIES

The chloride method has been applied to two coal-resource areas in the San Juan Basin of northwest New Mexico (fig. 4). A study of recharge at the Navajo Mine (Stone 1984b) provides a case history for active mines. Work on recharge in the Salt Lake Coal Field (Stone, 1984c) provides a case history for areas of proposed mining.

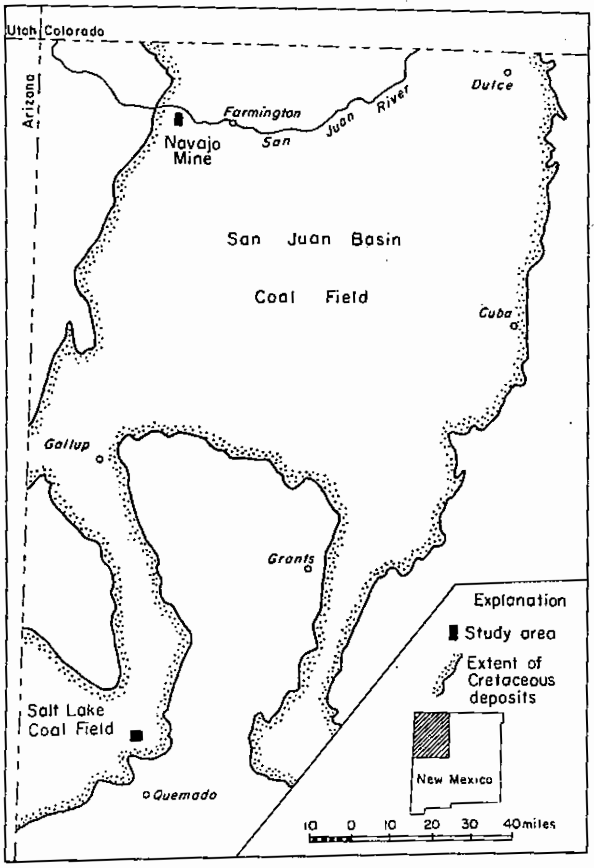

Figure 4.--Location of study areas in San Juan Basin, New Mexico.

Navajo Mine

The Navajo Mine lies in the northwestern part of the structural feature known as the San Juan Basin, a late-Cretaceous/early-Tertiary depression at the eastern edge of the Colorado Plateau. Coal is mined by stripping from the Fruitland Formation (Cretaceous). This unit is generally 60-90 m thick and consists of interbedded sandy shale, carbonaceous shale, clayey sandstone, coal, and sandstone (Stone and others, 1983). The climate is arid with an average annual precipitation of 145 mm and an annual potential evaporation rate of 1,420 mm (Utah International, Inc., 1981).

Five landscape settings deemed typical of the mine property were sampled: valley bottom, upland flat, badlands, depression in reclaimed area, and flat in reclaimed area (fig. 5). In the undisturbed settings (valley bottom, upland flat, and badlands) samples were exclusively from the Fruitland coal measures (fig. 1). At the reclaimed settings (depression and flat), samples included spoil and alluvium, as well as Fruitland Formation (fig 6).

Local recharge fluxes for the Navajo mine are summarized in Table 1. Values range from 0.05 to 0.51 mm/yr. The reason that recharge is so low for the valley bottom setting is not clear, because material sampled at this site was the same as that at the upland flat and badlands. Differences in topography and vegetation may be responsible, but a change in the hydrology of the valley bottom site due to erosion in this badlands area is also plausible. The upland flat typifies premining conditions (fig. 1).

The highest fluxes are associated with reclaimed settings, however, differences between these and other recharge values from the region are very small (Table 1). Of special interest in this study was the fact that recharge through the depression was not higher than that through the flat (fig. 6). Greater recharge would be expected in the depression, because of periodic ponding of runoff water there. However, reclamation in general is responsible for the slightly enhanced recharge rates rather than the final topographic form. Alternatively, these rates may be erroneous, because the system has not regained equilibrium. Further work in the area, including isotope analysis, should facilitate interpretation of results.

Local recharge fluxes were felt to be sufficient, because they show how recharge varies with setting and how post-mining reclamation may have effected recharge. Final post-mining regional recharge can be projected using these local recharge fluxes and final areal extents of the landscape settings, as determined from current maps and mining plans.

Additional work at the Navajo Mine this past year, has expanded the recharge study to all major areas of the mine and involved sampling for stable isotopes and tritium. Isotope data will provide a check of the chloride method and aid in interpreting profiles of the unsaturated zone for reclaimed settings.

Salt Lake Coal Field

The Salt Lake Coal Field lies in a southwestern extension of the San Juan Basin (fig. 4). Coal may eventually be mined by stripping from the Moreno Hill Formation (Cretaceous), which lies at the surface or beneath various thicknesses of alluvium throughout the area. The Moreno Hill Formation is approximately 270 m thick in the area and consists of a lower coal-bearing member and an upper mudstone member (Campbell, 1984). The climate is arid with an average annual precipitation of 251.5 mm and an annual potential evaporation rate of 788.4 mm (Gabin and Lesperance, 1977).

As in the Navajo mine study, five landscape settings were selected as typical of the region: thick alluvium, ephemeral lake, thin alluvium, tree-covered bedrock, and grass-covered bedrock (fig. 7). Samples from the thick-alluvium, ephemeral-lake, and thin-alluvium settings consisted exclusively of alluvium. In the grass-covered-bedrock setting most samples were alluvium as the Moreno Hill Formation was only encountered in the lower 1.52 m of the hole (fig.

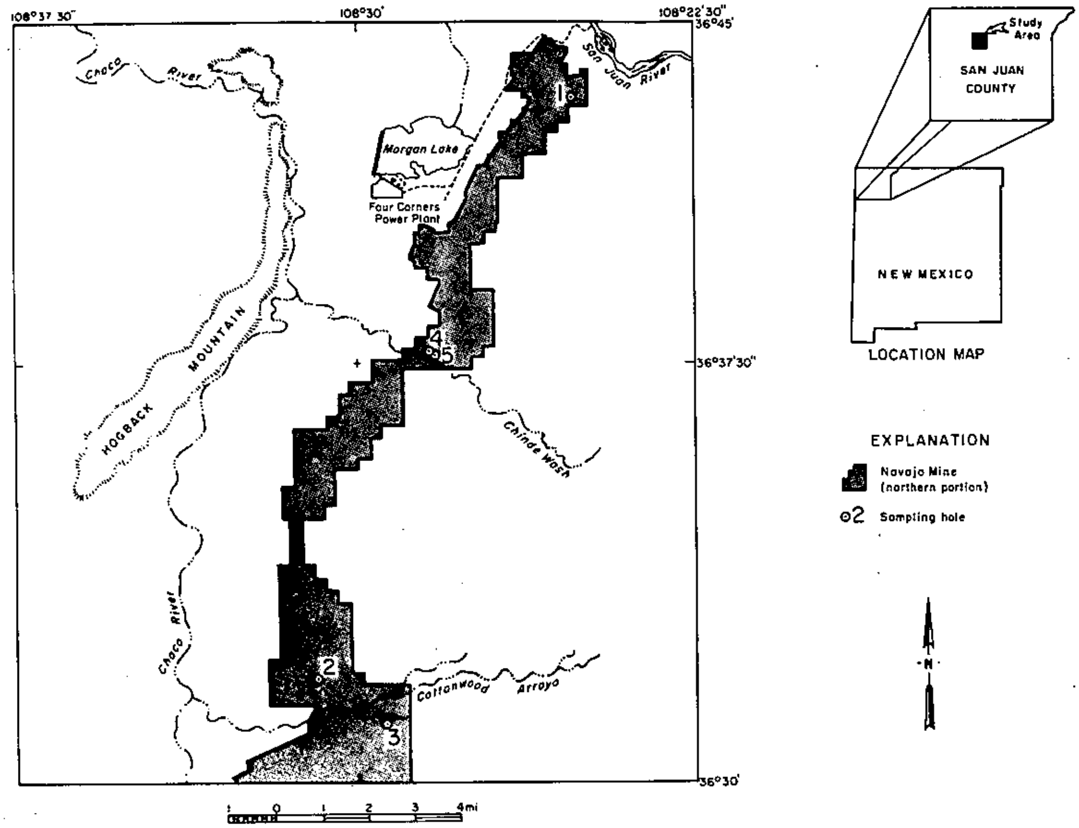

Figure 5.--Source of samples, Navajo Mine.

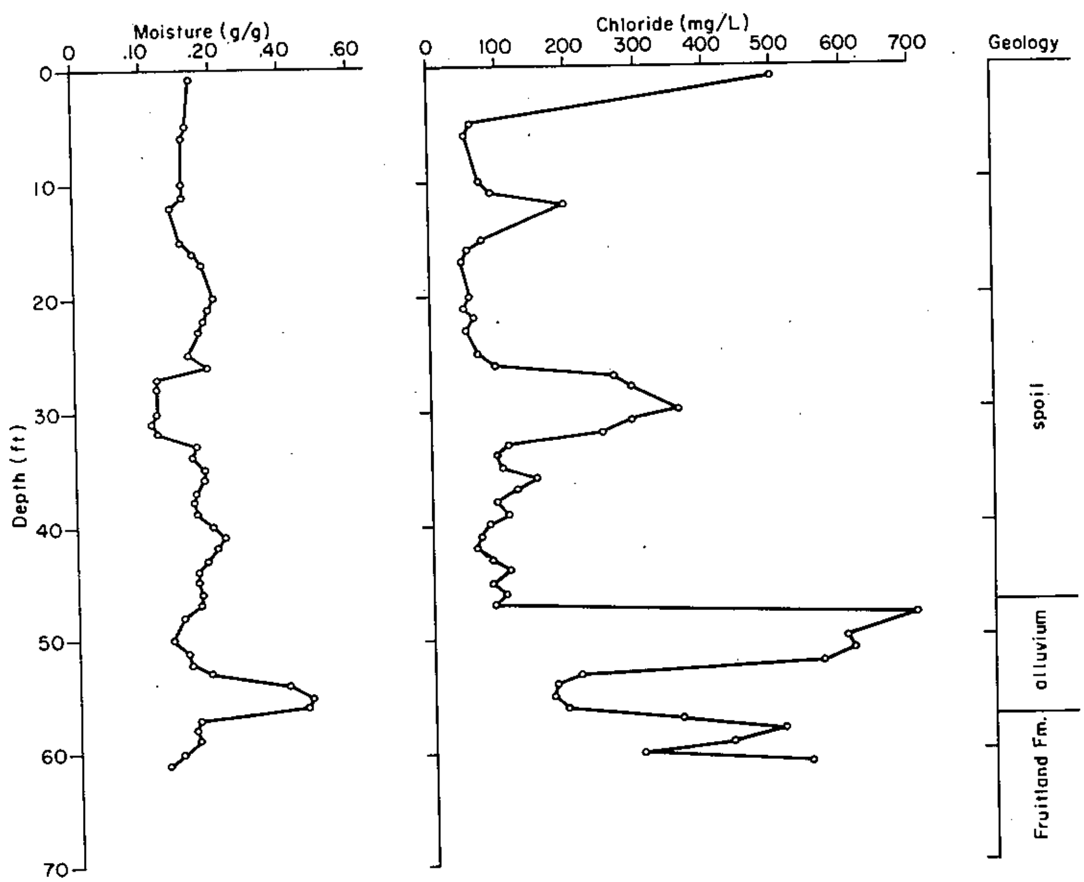

Figure 6.--Results from reclaimed area/flat setting (Hole 5), Navajo Mine (Stone, 1984b).

Table 1. Representative local, areal, regional, and average recharge data from selected San Juan Basin localities (from Stone, 1984b, c).

Landscape Setting	Interval (m)	Clsw (mg/L)	Local Recharge (mm/yr)	Area (m^3)	Areal Recharge (m^3/yr)
NAVAJO MINE (active mine, Utah International, Inc.)					
Valley bottom	0-23	1394	0.05	--[1]	--
Upland flat	0-12	241	0.51	--	--
Badlands	0-21	437	0.25	--	--
Reclaimed	0-8	211	0.51	--	--
depression	8-21	511	0.25	--	--
Reclaimed	0-14	206	0.51	--	--
flat	14-19	439	0.25	--	--
SALT LAKE COAL FIELD (proposed mine area, Salt River Project)					
Thick alluvium	0-20	46	2.03		
Ephemeral lake	0-5	44	2.03		
	5-15	243	0.51		
Thin alluvium	0-13	44	2.03	16,277,034[2]	33,332[3]
Bedrock/grass	0-18	81	1.27		
Bedrock/trees	0-13	76	1.27	12,948,781	15,812

Total area = 29,225,815

Regional premining recharge = 49,144

Average premining recharge = total regional/area recharge = 0.00168 m/yr or 1.68 mm/yr

[1] -- = not determined; local fluxes deemed sufficient.
[2] area calculated for all alluvium and all bedrock; averaged from measurements on soils and geologic maps.
[3] areal recharge calculated for all alluvium and all bedrock.

2). In the tree-covered-bedrock setting, samples from the upper 1.83 m were alluvium but the rest were Moreno Hill Formation (fig. 8).

Local recharge fluxes for the Salt Lake Coal Field are given in Table 1. Values range from 0.51 to 2.03 mm/yr. The lowest value is associated with the lower part of the profile for the ephemeral lake site. This low may correspond to lower recharge there before through-flowing irainage became blocked and the ephemeral lake formed. Highest values are generally associated vith thick alluvium. Figure 3 shows that much of he soil water was added during times of greater echarge (late Pleistocene/early Holocene).

From these local recharge fluxes, areal and egional recharge volumes were calculated. The irst step was definition of a study region; a egular, rectangular region covering major lease reas was selected. Then the area covered by ach landscape setting was determined from both eologic and soils maps (fig. 9). Next, areas ere measured by planimeter and areal recharge lumes were calculated. Finally, the regional echarge volume was determined by summing these eal volumes (Table 1). The areas obtained and gional recharges calculated differed only ightly. Areas based on geology gave 686 m^3/yr more regional recharge than did areas based on soils (Stone, in press).

It should be noted that no samples were taken from Cerro Prieto, a volcanic neck, because it is inaccessible to drilling. Furthermore, it is unlikely to be disturbed by mining. Although it covers a significant portion of the study (5.2% based on geologic maps and 7.5% based on soils maps), this need not be a problem as long as this area is omitted from both the premining and post-mining regional-recharge calculations. In fact, omitting a landscape setting which will not be disturbed by mining from the sampling saves time in calculating areas. If the area of the setting to be ignored is ever needed, it can be obtained by subtracting the sum of all the other areas from the area of the study region.

Once mining of the Salt Lake Coal Field is undertaken, local and areal recharge values can be calculated for the various reclaimed settings that result and perhaps additional examples of the undisturbed settings that remain. Comparison of premining and post-mining values for local recharge should indicate whether mining will have an impact on recharge. If a significant difference is indicated, regional fluxes should be examined.

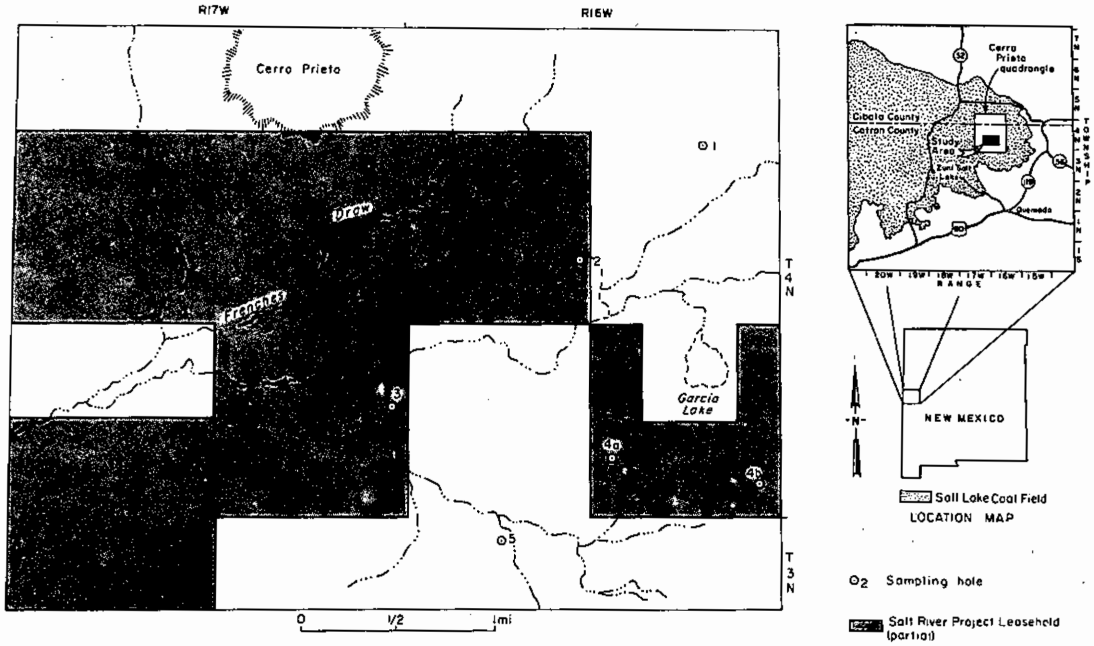

Figure 7.--Source of samples, Salt Lake Coal Field.

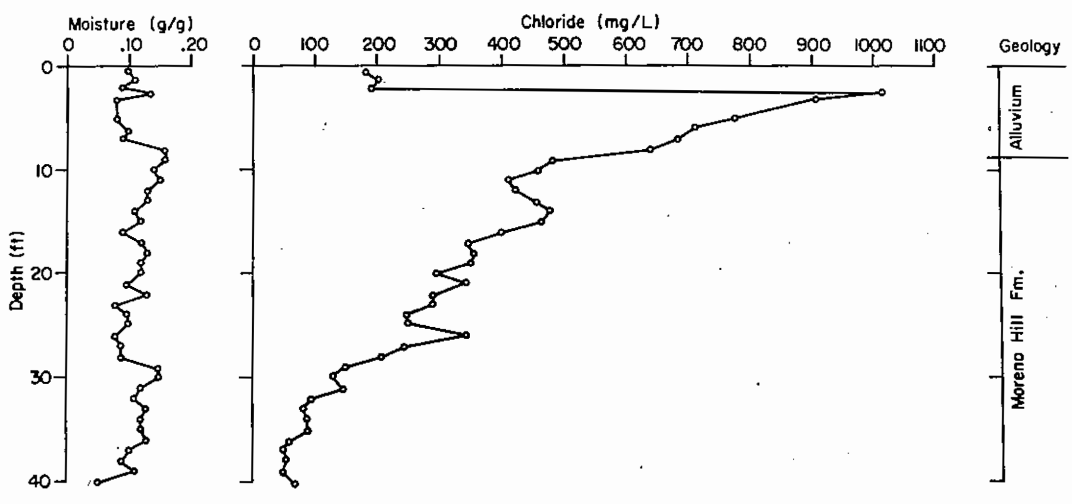

Figure 8.--Results from bedrock/trees setting (Hole 4a), Salt Lake Coal Field (Stone, 1984c).

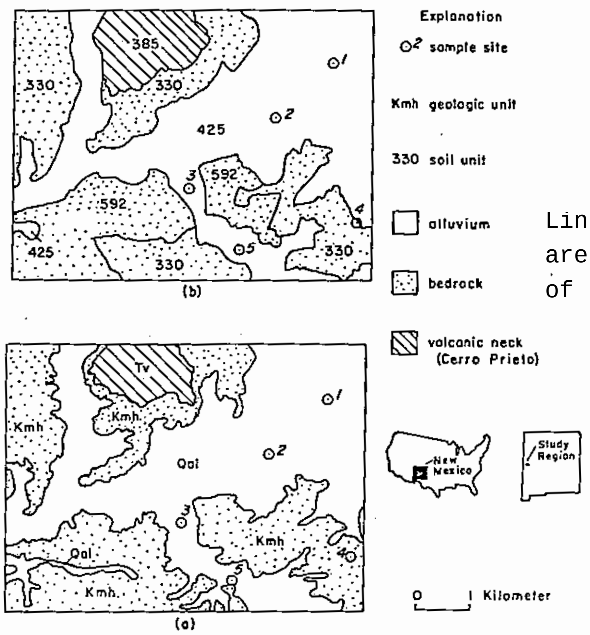

Figure 9.--Extent of landscape settings based on a) geology (Campbell, 1981) and b) soils (U.S. Soil Conservation Service, in preparation). Kmh = Moreno Hill Formation (Cretaceous), Tv = Tertiary volcanic rocks, Qal = Quaternary alluvium; 330 = Tejana-rock outcrop soil complex, 385 = aridic argiustolls-rock outcrop soil complex, 425 = Catman-Hickman soil complex, 592 = Celacy-rock outcrop soil complex.

DISCUSSION AND SUMMARY

There has been some criticism of using hydrologic models to predict post-mining conditions for the preparation of PHC's (Betson and Poe, 1983). As regards recharge, the chloride mass-balance method seems to provide an alternative approach.

The chloride method is simple, requiring only ordinary lab equipment and procedures. The method is relatively inexpensive because the main cost is that associated with coring by hollow-stem auger. It is also reliable and results have been confirmed by other methods (chemical and physical). The chloride method may be used to obtain local, areal, regional, or average recharge values. Such values for premining and post-mining conditions provides a means of assessing the impact of coal surface mining on recharge. Plots of cumulative chloride vs cumulative water may provide worst-case recharge values associated with the wetter climates of the Quaternary.

ACKNOWLEDGMENTS

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