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ASSESSING IMPACT OF SURFACE MINING ON RECHARGE

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ABSTRACT

Recharge is an important consideration in assessing hydrologic impact of surface mining, because it is a major component of the water budget of the area. However, recharge data are often not available and measurement by usual chemical and physical methods is complex, time-consuming, and expensive. An alternative chemical method, based on the chloride content of water in the unsaturated zone, is simple and relatively inexpensive. Application of this method to areas of active and proposed coal surface mining in the southwestern United States has made it possible to compare premining and present recharge rates so that the impact of post-mining reclamation on recharge may be assessed. Plots of cumulative chloride content vs cumulative water content provided a means of estimating late Pleistocene and Holocene recharge rates. These higher rates may be considered worst-case values inasmuch as the Quaternary climate was wetter than the present climate. Recharge estimates based on the chloride method have generally been corroborated by those of other chemical and physical methods where this has been attempted. The chloride method should prove useful in assessing impact of most surface mining operations on recharge.

INTRODUCTION

Surface mining disturbs not only the ground surface, but also the regional water budget. Net runoff, evapotranspiration, and recharge may be increased or decreased by the presence of mine structures and excavation. Revegetation requires irrigation in arid regions. Water added in irrigation supplements that added naturally by precipitation. Introduced vegetation may consume more or less water than the original native species.

Of all the components of the water budget, impacts on recharge are the most difficult to assess. Although changes in runoff and evapotranspiration can be documented fairly directly, recharge is generally determined by various indirect methods. Chemical methods include the use of isotopes and tracers, whereas, physical methods involve various types of field instrumentation. Methods in common use are complex, time-consuming, and expensive.

An alternative chemical method, based on chloride content of water in the unsaturated zone, is simple and relatively inexpensive. The main purposes of this paper are to describe the chloride method and to illustrate its application to areas of active and proposed surface mining by means of case histories from the San Juan Basin of northwest New Mexico (USA).

THE CHLORIDE MASS-BALANCE METHOD

In the chloride method, recharge is determined from the relationship R = Clp/Clsw · P (Allison and Hughes, 1978), 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.

Several assumptions are made in the chloride method: 1) recharge occurs only by piston flow, 2) precipitation is the sole source of chloride entering the ground, 3) precipitation has been constant through the time interval represented by the samples, and 4) 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. 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 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).

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

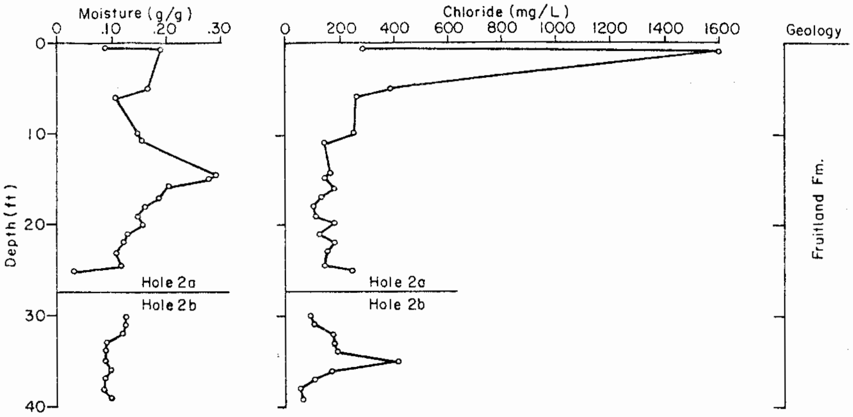

Figure 1. Typical chloride vs depth plot (upland flat setting, Navajo Mine; Stone, 1984 b).

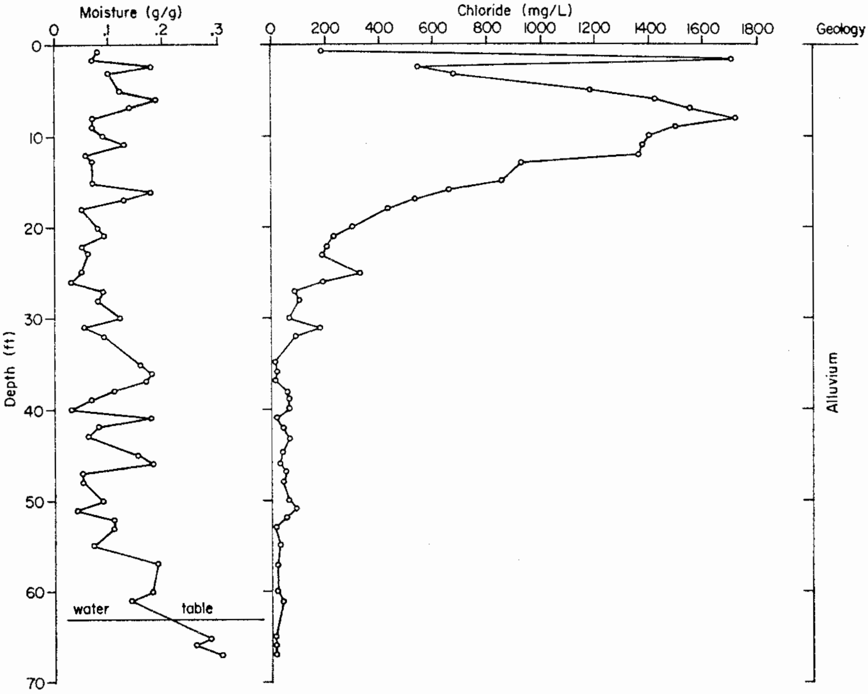

Figure 2. Atypical chloride vs depth plot (thick alluvium setting, Salt Lake Coal Field; Stone, 1984 c).

determination of chloride content of the extract after settling by colorimetric titration or a chloride electrode. Based on the 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).

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 (Figure 1). The average chloride content in the portion of the profile below the peak is used for Clsw 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).

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).

Some profiles are characterized by a decrease in chloride content with depth (Figure 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) (Figure 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.

APPLICATIONS

Recharge rates vary with landscape setting (Allison and Hughes, 1983; Stone, 1984a, b, c; Allison and others, 1985). Surface mines are characterized by various landscape settings, some natural, some man-made. Each of these settings is a unique combination of geology, soils, topography, vegetation, and land use or land-use history. Thus, recharge studies in mine areas must be designed to cover this variability.

Additionally, recharge must be viewed in terms of three different scales: 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,

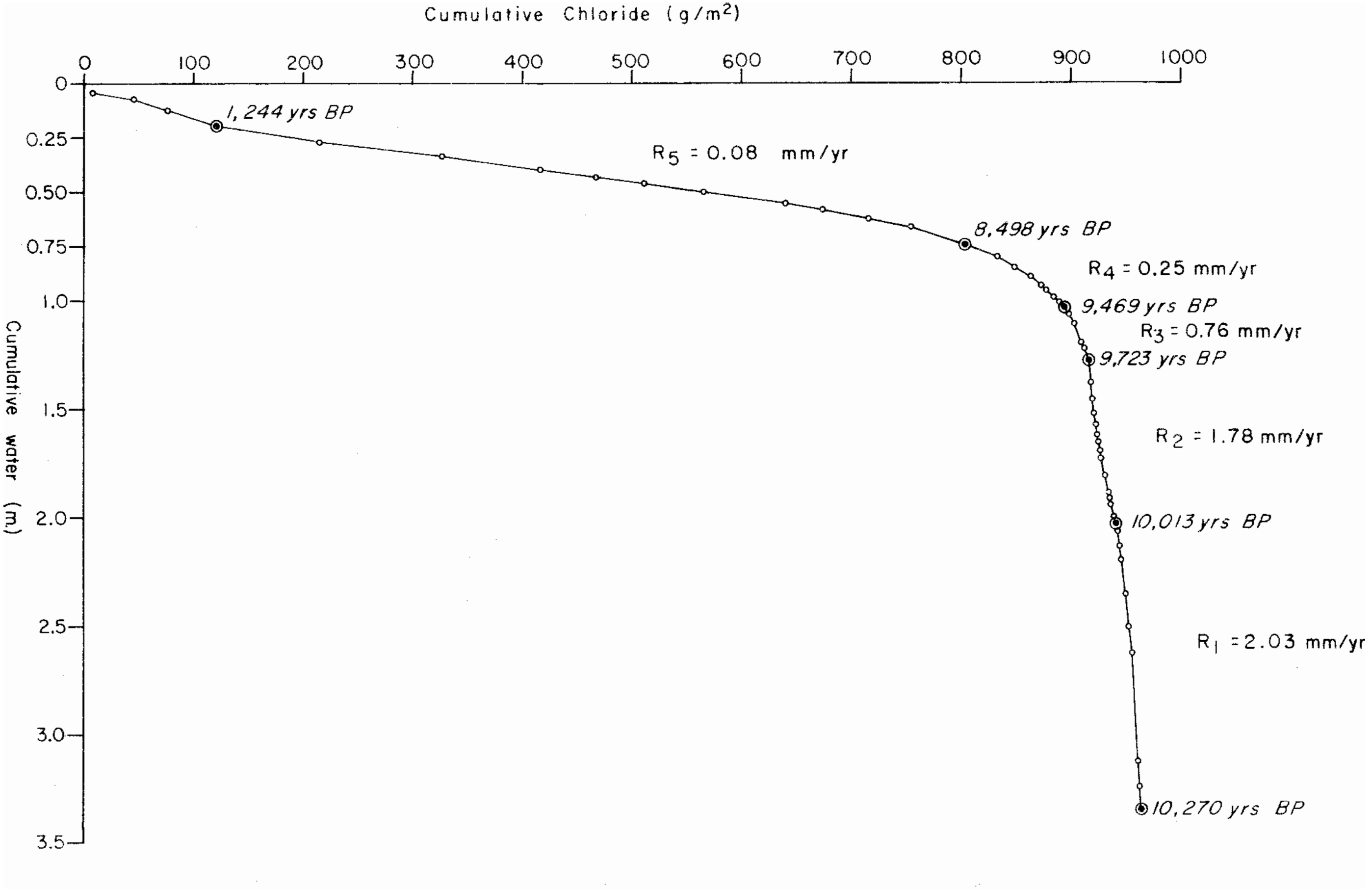

Figure 3. Typical cumulative chloride vs cumulative water content plot (thick alluvium setting, Salt Lake Coal Field; Stone, 1984 c).

Table 1. Local recharge at Navajo Mine (Stone, 1984a).

Landscape Setting	Inverval (m)	Clsw (mg/L)	Local Recharge (mm/yr)
Valley bottom	0-23	1394	0.05
Upland flat	0-12	241	0.51
Badlands	0-21	437	0.25
Reclaimed depression	0-8	211	0.51
	8-21	511	0.25
Reclaimed flat	0-14	206	0.51
	14-19	439	0.25

Table 2. Local recharge in Salt Lake Coal Field (Stone, 1984b); sample sites shown on Figure 4.

Landscape Setting	Sample Site	Inverval (m)	Clsw (mg/L)	Local Recharge (mm/yr)
Thick Alluvium	1	0-20	46.37	2.03
Ephemeral Lake	2	0-5	44.00	2.03
		5-15	243.22	0.51
Thin Alluvium	3	0-13	43.84	2.03
Bedrock/Grass	4	0-18	80.8	1.27
Bedrock/Trees	5	0-13	76.3	1.27

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.

In order to assess the impacts of mining, both premining and post-mining recharge rates must be compared. In some cases, local fluxes may be sufficient to characterize the impact; in others, comparison of premining and post-mining values for regional recharge may be necessary. Such comparisons should show whether changes in areal recharge rates due to mining cancel out or a net change in regional recharge has been produced.

Active Mining Areas

In areas of active mining, 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.

A preliminary study of recharge at the Navajo coal mine in northwest New Mexico (Stone, 1984a) provides a case history for active mine areas. This 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. In the undisturbed settings (valley bottom, upland flat, and badlands) samples were exclusively from the Fruitland coal measures (Figure 1). At the reclaimed settings (depression and flat), samples included spoil and alluvium, as well as Fruitland Formation.

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 (Figure 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. 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. Additional work in the area, including stable-isotope analysis should facilitate interpretation 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.

Proposed Mining Areas

Premining recharge is most readily determined in areas where mining has not yet begun. In such cases, attention can focus on the specific area where mining is planned. These results can be compared with post-mining recharge values, when they become available.

A study of recharge in the Salt Lake Coal Field (Stone, 1984c) provides a case history for proposed mining areas. The Salt Lake Coal Field lies in a southwestern extension of the San Juan Basin (northwestern New Mexico). Coal will 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. 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. In the tree-covered-bedrock setting, samples from the upper 1.83 m were alluvium but the rest were Moreno Hill Formation.

Local recharge fluxes for the Salt Lake Coal Field are given in Table 2. 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 drainage became blocked and the ephemeral lake formed. Highest values are generally associated with thick alluvium. Figure 3 shows that much of the soil water was added during times of greater recharge (late Pleistocene/early Holocene).

From these local recharge fluxes, areal and regional recharge volumes were calculated. The first step was definition of a study region; a regular, rectangular region covering major lease areas was selected. Then the area covered by each landscape setting was determined from both soils and geologic maps (Figure 4). Next, areas were measured by planimeter and areal recharge volumes were calculated. Finally, the regional recharge volume was determined by summing these areal volumes (Tables 3 and 4).

It should be noted that no samples were taken from Cerro Prieto, because it is a volcanic neck and inaccessible to drilling. Furthermore, it is unlikely to be disturbed by mining. Although it covers a significant portion

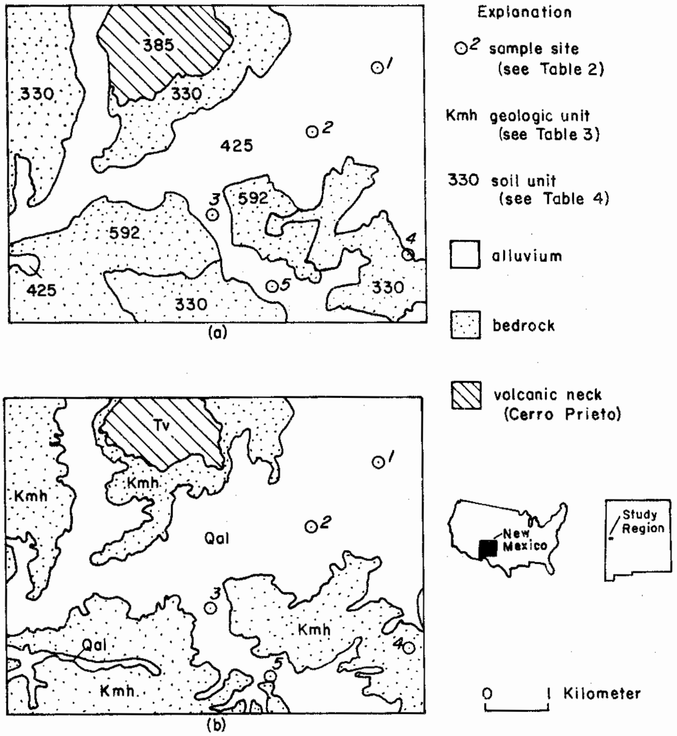

Figure 4. Extent of landscape settings, Salt Lake Coal Field; a) based on soils map (U.S. Soils Conservation Service, in preparation), b) based on geologic map (Campbell, 1981).

Table 3. Areal and regional recharge in Salt Lake Coal Field using areal extent of settings from soils map (Figure 4a).

Setting	Soil Unit[1]	Area (m^2)	% of Region	Local Recharge[2] (m/yr)	Areal Recharge (m^3/yr)
Alluvium (thin, thick)	425	16,562,347.5	53.7	0.00203	33,621.57
Bedrock (trees, grass	330 592	11,952,409.8	38.8	0.00127	15,179.56
Cerro Prieto	385	2,306,385	7.5	---	---
		30,821,142.3	100.00	REGIONAL RECHARGE =	48,801.13

[1] 425 = Catman-Hickman complex (drainageways)
330 = Tejana-Rock Outcrop complex (plains and mesas)
592 = Celacy-Rock outcrop complex (upland plains)
385 = Aridic Argiustolls-Rock outcrop complex (steep slopes)

[2] from values given in Table 2; --- = not measured

Table 4. Areal and regional recharge in Salt Lake Coal Field using areal extent of settings from geologic map (Figure 4b).

Setting	Geologic Unit[1]	Area (m^2)	% of Region	Local Recharge[2] (m/yr)	Areal Recharge (m^3/yr)
Alluvium (thin, thick)	Qal	16,277,034.0	52.8	0.00203	33,042.38
Bedrock (trees, grass)	Kmh	12,948,781.2	42.0	0.00127	16,444.95
Cerro Prieto	Tv	1,595,327.4	5.2	---	---
		30,821,142.6	100.00	REGIONAL RECHARGE =	49,487.33

[1] Qal = alluvium (Quaternary)
Kmh = Moreno Hill Formation (Cretaceous)
Tv = volcanic rocks, undifferentiated (Tertiary)

[2] from values in Table 2; --- = not measured

of the study region (5.2% based on geologic maps and 7.5% based on soils maps; Tables 3 and 4), 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.

CONCLUSIONS

The case histories presented herein support several conclusions. The chloride method is simple: only ordinary laboratory equipment and methods are required. The chloride method is relatively inexpensive: the main cost is coring with a hollow-stem auger. The chloride method is reliable: results have been confirmed by other methods (tritium, stable isotopes, chlorine 36, soil physics). The method permits assessing impact on recharge at three different scales in the mine region: local, areal, and regional. Local recharge is a linear flux (mm/yr). Areal and regional recharge are volumetric fluxes (m^3/yr). Plots of cumulative chloride vs cumulative water may provide worst-case recharge rates. The method is not restricted to use in coal mining areas, but should be applicable to any area of surface mining where samples may be taken by augering.

ACKNOWLEDGMENTS

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