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# Integrated Soil Processes Studies at Emerald Lake Watershed

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY

AIR RESOURCES BOARD
Research Division

# INTEGRATED SOIL PROCESSES STUDIES AT EMERALD LAKE WATERSHED

**Final Report**
**Contract No. A5-204-32**

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# ABSTRACT

We have studied the physical, chemical, and biological properties and processes of subalpine soils of the Emerald Lake Watershed (ELW), Sequoia National Park. Soils cover about 20% of the surface area of the watershed but other surficial materials not mapped as soils may have soil-like properties of weathering, cation and anion retention. In general most ELW soils can be classified as Cryorthents or Cryumbrepts with slightly different properties. A depression in pH and alkalinity were observed in response to the 1987 snowmelt in soil solutions extracted from a Cryumbrept in the field. The same degree of response was not observed at four other sites. Weathering of soil minerals to release $Al^{3+}$ is a major mechanism of rapid acid neutralization in soils. Cation exchange is also important in affecting solution base cation composition. Sulfate adsorption appears to maintain relatively constant sulfate concentrations in soil solutions and surface waters through the critical snowmelt period, but adsorption levels are near capacity. Nitrate uptake, denitrification and mineralization moderate soil solution and surface water N concentrations, particularly during the summer months. In general, subalpine Sierra Nevada soils have significant capacity for neutralization of acidic deposition. The fact that snowmelt can reduce Cryumbrept soil solution ANC to negative levels is an indication that the rates of neutralization processes may be exceeded even under present conditions.

# ACKNOWLEDGEMENTS

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# DISCLAIMER

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# *SUMMARY*

## TYPICAL SUBALPINE SOILS OF EMERALD LAKE WATERSHED

The ELW study area soil map has been reviewed and redrawn. Approximately 20% of the watershed is covered by surficial materials which can be classified as soils on the basis of their ability to support plant growth. They can be classified into two soil orders, Entisols and Inceptisols. The great group classifications of these soils which predominate are the Cryorthents and the Cryumbrepts.

### Cryorthents

These soils are found in positions of high relief and high elevation throughout ELW. They occupy about 3.7 ha of the total area of the watershed. Surficial materials which have similar properties would include 3.2 ha of felsenmeer and 16.9 ha of talus. The Entisols are sandy soils, less than 1% organic carbon (OC), low nutrient nitrogen (N) and sulfur (S), exchangeable base cations (EBC) often less than 1 mEq/100g, and very strongly acid (pH 4.5 to 5.0 in 1:1 $H_2O$ extract). Common clay and silt sized minerals of these soils include vermiculite, hydroxyinterlayered vermiculite (HIV), mica, kaolinite, gibbsite, feldspars and quartz.

### Cryumbrepts

These soils are found in older glacial till, glacial benches, and the master joint on the eastern side of ELW. Including 2.1 ha of a Spodosol map unit, they occupy about 20.7 ha of the total area of the watershed. These soils are sandy to sandy loam in texture, some have more than 1% OC in the surface horizon, they have modest sized pools of nutrient N and S, EBC between 1 and 10 mEq/100g, and are extremely acid soils ($pH < 4.5$). The clay and silt mineralogy of these soils is very similar to the Entisols, except that there is less gibbsite and more smectite minerals.

The physical extent of soils in ELW was tabulated and estimates were made of the area, volume, and mass of soils in the map units. The spatial variability of chemical and physical measurements of selected ELW soil map units was evaluated and found to be fairly typical for such surveys.

## IMPACT OF SOILS ON THE HYDROLOGY OF ELW

Estimates of total water storage in soil map units were made and found to be consistent with estimates of water storage calculated using water balance methods. The potential rates of water movement through ELW soils are quite high (0.1 to 0.01 mm/s). As a consequence, the soil reactions which would have the most influence on soil solution and surface water composition would have to be the fastest reactions, such as cation exchange and sulfate adsorption. Observations of the freeze-thaw cycle of soils at ELW indicate that it is likely that they interact extensively with snowmelt.

## THE EFFECT OF MAJOR HYDROLOGIC EVENTS ON SOILS

### Snowmelt

The snowmelt event of the 1987 water year was successfully monitored in the field using soil water extractor ("lysimeter") systems installed in 1985 and 1986. Of particular importance is the fact that during this event we observed a depression of pH and acid neutralizing capacity (ANC, also known as alkalinity) in the soil solution. Data were limited for various reasons, but one Lithic Cryumbrept was sufficiently acidified for the ANC to drop below zero and remain below zero until moisture levels became too low for the extractors to operate successfully. Recovery of ANC and pH was complete by fall 1987. The ANC depression was correlated with nitrate concentrations in the soil solution and not correlated with sulfate concentrations. This implies that nitric acid deposition was responsible for the drop in pH and ANC. These data indicate that the acid neutralization mechanisms of this soil could not respond quickly enough to compensate for this acidification episode during snowmelt. Four other soils monitored during the same snowmelt event did not exhibit as dramatic a response.

### Rainfall

The effect of rainfall on soil solutions in the field is still essentially unknown. Some rainfall mixed with snowmelt in the spring 1987, but soil water would have been dominantly from snow. Rainfall events in the summer and fall fell on soils with water contents which were too low to be extracted in the field. Other extraction methods will have to be employed in order to study rainfall-soil interactions *in situ.*

## WHAT PROCESSES ARE AFFECTING SOIL SOLUTION COMPOSITION?

### Mineral Weathering

This is the ultimate source of neutralization for anthropogenic inputs of nitric and sulfuric acid to ELW. Our laboratory studies indicate that a rapid reaction involving the solubilization of $Al(OH)_3$ has the potential for consumption of acidity on the order of 130 mEq for each square meter of soil to a depth of 10 cm ($m^2$-10cm). Other weathering reactions involve the decomposition of minerals derived from granite or granodiorite bedrock including feldspars, hornblende, and biotite. The base cations $Ca^{2+}$, $Na^{+}$, $Mg^{2+}$, and $K^{+}$ are released in this reaction. These minerals also release $Al^{3+}$ and $Si^{4+}$, which are in part recombined to form kaolinite. Overall, in the field this reaction could result in a net increase in soil solution ANC. Under laboratory conditions we measured rates of acid consumption from weathering on the order of 10 mEq/m$^2$-10cm/da. The rate of acid consumption will increase as pH decreases. Quantitatively this is expressed as the rate acid consumption is first order with respect to $H^+$ concentration. Calculations based on our laboratory studies and others indicate that weathering rates are potentially high enough to produce an amount of ANC on an annual basis which is equivalent to the acidic deposition received by the watershed.

### Cation Exchange

The capacity of the soil to neutralize $H^+$ is in direct proportion to the quantity of base cations $Ca^{2+}$, $Mg^{2+}$, $Na^{2+}$, and $K^+$ present on the exchange complex. Exchange of base cations for $H^+$ is a very rapid reaction. The retention and release of base cations and also $Al^{3+}$ and $H^+$ is controlled by the preference of the cation exchange complex for some cations over others. This is why $Ca^{2+}$ dominates the exchange complex of ELW soils. The distribution of base cations in ELW soils was tabulated and most soil map units were found to have 0.1 to 1.0 mEq/m$^2$ exchangeable base cations. Annual $H^+$ deposition rates are between 1 to 10 % of the potential ANC stored as exchangeable cations. Based on current understanding of the influence of exchangeable bases in soils on acidic deposition, it is possible that during a given snowmelt event, soil solution ANC could become negative. This phenomenon was observed in the field in 1987.

### Adsorption

Sulfate concentrations in ELW soil solutions and surface waters do not change as rapidly as the concentrations in precipitation. The adsorption of $SO_4^{2-}$ on the surfaces of variable charge minerals such as kaolinite and gibbsite may account for this phenomenon. Reanalysis of adsorption data collected in 1985 (Lund et al., 1987) allows estimates that annual sulfate deposition is 5-24% of total sulfate adsorption capacity of ELW soils at present. In fact, sulfate adsorption may be near capacity for much of the soil in ELW, since the influence of soils on surface water concentrations of sulfate appears to be to delay its transport relative to water inputs. Calculation of a hydrologic budget for S in an ELW subbasin indicates that nearly all of the annual wet deposition input of S can be accounted for in surface water runoff the spring-summer snowmelt period. Sulfate adsorption was also observed in a soil acidification study connected with a stream acidification experiment.

## Nitrogen Uptake, Denitrification, and Mineralization

Mass balance calculations for comparison of nitrate ($NO_3^-$) and ammonium ($NH_4^+$) deposition with soil solution show that N is accumulating in the terrestrial component of ELW. Concentrations in the soil solution and surface waters are minimal during the summer months when soil temperature is highest. This is also the period when maximum plant and microbial growth would be expected.

One potential sink for N which we investigated was denitrification. In this process soil $NO_3^-$ is converted to gaseous $N_2O$ and $N_2$ and lost to the atmosphere. Rates of N loss on the order of 4 to 8 mEq($NO_3^-$)/$m^2$/da were measured in two Entisols May and June, 1987. Denitrification rates were near zero in July when soils were dry and at one site in May because of frozen soil. Denitrification may have a significant impact on the N budget of limited areas of ELW soils but probably does not have a very great impact on the overall watershed budget.

During the summers mineralization, the release of N and S from organic matter by microbial activity, was measured *in situ*. Rates of N mineralization were on the order of 0.3 to 1.6 mEq(as $NH_4^+$)/$m^2$-10cm/da. Not all $NH_4^+$ produced by mineralization is converted to $NO_3^-$. About 50% was converted in the Entisol measured and less than 10% in the Inceptisols. Rates of S mineralization were on the order of 0.7 mEq($SO_4^{2-}$)/$m^2$-10cm/da. In many measurements N and S were consumed rather than released, resulting in a net negative mineralization rate. Field mineralization rates were related to soil temperature and moisture and laboratory measurements of potential mineralization rates. At low temperature and low soil moisture content, mineralization is least.

## Throughfall

The interaction of rainfall with foliage has a concentrating effect on deposition. *Pinus monticola* is an effective dry deposition collector and calculations indicate that in the summer, dry deposition rates on a soil area basis are similar in magnitude to wet deposition. The *Salix orestera* canopy apparently absorbs N from rainfall, raising the alkalinity of throughfall.

## $CO_2$ Respiration

Natural acidity in pure waters is attributed to dissolved $CO_2$. The concentration of $CO_2$ in the air at ELW is on the order of 0.045%. Concentrations in ELW Entisols were as high as 0.1% and in Inceptisols as high as 5%. This is probably due to greater microbial and plant root respiration in Inceptisols. The annual cycle of $CO_2$ concentrations in ELW soils is typical for subalpine conditions. The highest concentrations were measured in the early summer, June and July, but a second peak occurs in the late winter, in March or April. This is caused by the reduced rate of diffusion from wet soil under the melting snowpack. High soil $CO_2$ may lower slightly the actual pH of the soil solution in the field.

## *CONCLUSIONS*

Subalpine and alpine soils of ELW have significant capacity for neutralization of acidic deposition. The most important mechanisms are: $Al^{3+}$ release from mineral weathering, cation release from cation exchange, sulfate adsorption and N uptake. ELW soils are a significant hydrologic pathway for the transport and neutralization of snowmelt. The observation of a depression in soil solution pH and alkalinity in a Cryumbrept is an indication that neutralization mechanisms may not be rapid enough to compensate for episodic acidification. Soils also have a significant influence on the composition of surface waters in ELW. Adsorption of sulfate and N uptake are related to increases in ANC during the spring and summer. Mineral weathering and cation exchange are also important sources of ANC for surface waters in ELW.

## *RECOMMENDATIONS*

1. We observed an episode of pH and ANC depression in the soil solution an ELW Entisol in response to snowmelt. For scientific validation this observation should be repeated along with simultaneous snowmelt measurements.

2. A major problem integrating soil process and hydrologic data is the lack of good information about water residence time and pathways through soils. The quantification of hydrologic pathways through, over and around the complex association of bare rock and soil should be carried out using tracer studies *in situ*. A statistical approach should be employed, such as the transfer function, analyzing a limited number of parameters for retention characteristics of the soil/rock complex.

3. The retention mechanism for N in ELW is not clear. The best means of clarifying this would be to conduct a stable isotope $^{15}N$-tracer study *in situ*. Soil solution, soil solids, possibly denitrification, above and below ground biomass would have to be sampled over a 2-year period in a statistically meaningful manner. Much less information would be obtained by a simple N-enrichment or fertilization study.

4. During major hydrologic events, such as snowmelt and rain storms, the role of weathering versus cation exchange as the primary acid-neutralizing mechanism in these subalpine soils is ambiguous. The mechanism of retention and release of cations and production of alkalinity should be studied in the field via a tracer or enrichment study.

5. These data suggest that ELW soils, typical of high elevation Sierra Nevada soils, are low in exchangeable base cations, have typical mineral weathering rates, low sulfate adsorption capacity, and shallow profiles and are therefor sensitive to acidic deposition inputs, and have only marginal capacity to maintain the ANC of surface waters. Changes in acidic deposition below or above current levels may have a measurable effect on these soils.

## *CHAPTER 1*

## *INTRODUCTION*

The Emerald Lake Watershed (ELW) is the site of the California Air Resources Board integrated watershed study of which this investigation of soil physical, chemical, and microbial processes and their interactions with vegetation and surface waters is a part. Emerald Lake ($36^{o}$ 35' 49" N, $118^{o}$ 40' 30" W) is located in Tulare County, California, in Sequoia National Park. The watershed is a sparsely vegetated, subalpine to alpine landscape ranging in elevation from Emerald Lake at 2800 m to Alta Peak at 3416 m, typical of the Sierra Nevada (Figure 1-1). The watershed area is approximately 120 ha and the lake area 2.85 ha.

The primary form of precipitation at ELW is snow which is present in patches nearly year-round. The annual precipitation for ELW for the 1985, 1986, and 1987 water years has been 1157, 2625 and 959 mm of which rain was only 1, 1, and 17% of the total (Williams and Melack, 1990). Snowmelt occurs between April and June and most of the water stored in snow leaves the watershed during this period. Acidic deposition in the Sierra is relatively low compared with the Eastern U.S. or the Los Angeles area, but maximum rates measured for summer rainfall events in the vicinity of Giant Forest, Sequoia National Park, have been two to five times more acidic than other remote areas (Stohlgren and Parsons, 1987). Although deposition rates are apparently lower in the Sierra than other areas impacted by acidic deposition, the threat to the aquatic ecosystem may be just as great. The potential for acidification of Sierra Nevada lake watersheds has been documented in reports on the very low and weakly buffered alkalinity (less than 100 uEq/L) of many lakes (Tonnessen and Harte, 1982; Melack et al., 1982, 1985).

Like most of the Sierra Nevada, the bedrock of ELW is granite and granodiorite (Figure 1-2). The majority of the watershed above 2900 m is granite of Cretaceous or Jurrasic origin (Clow, 1987; Moore and Wahrhaftig, 1984). Below this elevation is aplite and granodiorite of the Cretaceous. The area was subjected to glaciation in the Pleistocene and, apparently, briefly in the Holocene, within about 2000-3000 years ago. Till from the most recent glaciation is evident in the area north of Alta Peak and till from an earlier era, probably Tioga, is found in an area 400 m NE of the lake.

An important consequence of this geologic history is that the soils of ELW and vicinity have formed over a relatively short period of geologic time, 10,000 years or less. Soils older than this would have been removed by glaciation. As a result, only approximately 22% of the watershed area was mapped as having surficial materials which could be considered soils on the basis of supporting plant growth (Huntington and Akeson, 1987). These soils were nearly all classified in the great groups Cryumbrept and Cryorthent on the basis of their temperature regime (average annual temperature between 0-8$^{O}$C), and the development of little or no changes in the surface soil horizon due to forces of soil development. Although ELW soils are shallow and rocky, they do support growth of quite a variety of subalpine vegetation (Rundel et al., 1987). Some of the prominent coniferous species found include *Pinus contorta var. murrayana, P. monticola, P. jeffreyi,* and *P. balfouriana.* Common shrubs include *Phyllodoce breweri, Crysolepis sempervirens,* and *Salix orestera.*

Given that the natural course of soil development is toward increasing acidification the potential influence of acidic deposition on soil is generally considered to be minimal to undetectable (Tabatabai, 1985; Binkley and Richter, 1987). Among the processes which have been identified in soils which are capable of neutralizing acidic deposition are: cation exchange, mineral weathering, sulfate adsorption, and nutrient uptake. Only very limited conditions have been identified under which acceleration of soil acidification might occur in response to acidic deposition (Binkley and Richter, 1987). The circumstances under which a soil is likely to be sensitive include the following: 1) low cation exchange capacity, 2) moderate or high pH, 3) low in weatherable minerals, 4) low sulfate adsorption capacity, 5) shallow profiles, and 6) atmospheric inputs of concentrated mineral acids.

Soils can have a significant mitigating influence on the effects of acidic deposition on surface waters. Important moderating effects of soils on surface water composition which have been observed include the supply of alkalinity and base cations to surface waters through weathering and cation exchange (Chen et al., 1984; Brown et al., 1990), the retention of sulfate by adsorption (Johnson et al., 1986), the retention of N by biotic accumulation (Knight et al., 1985), and the control of Al chemistry (Lawrence et al., 1988).

The processes which occur in ELW soils which interact with acidic deposition and may either enhance or ameliorate its effects on ecosystem components were the subject of an earlier report (Lund et al., 1987). This work included a survey of physical-chemical characteristics of ELW soils, evaluation of biological activity which could have an influence on the $H^+$ budget in soils, and field sampling of soil solutions and streams in ELW in order to observe the net interaction among deposition, soils, and surface water. Among the conclusions of that report were that ELW soils were potentially sensitive to acidic deposition and that they had some influence on the composition of surface water.

The purpose of continuing work on soil processes at ELW was to obtain more quantitative evidence of these observations. We have studied biological, physical, and chemical processes which were thought to have an influence on the neutralization of acidic deposition by soils or which might lead to detrimental effects on these soils. The overall objectives of this research directly related to the concerns of the California Air Resources Board (CARB) were:

1. To determine if the subalpine to alpine soils of ELW are affected by acidic deposition, and,
2. To determine if soil processes have the capacity to mitigate or modify the effects of acidic deposition on surface waters.

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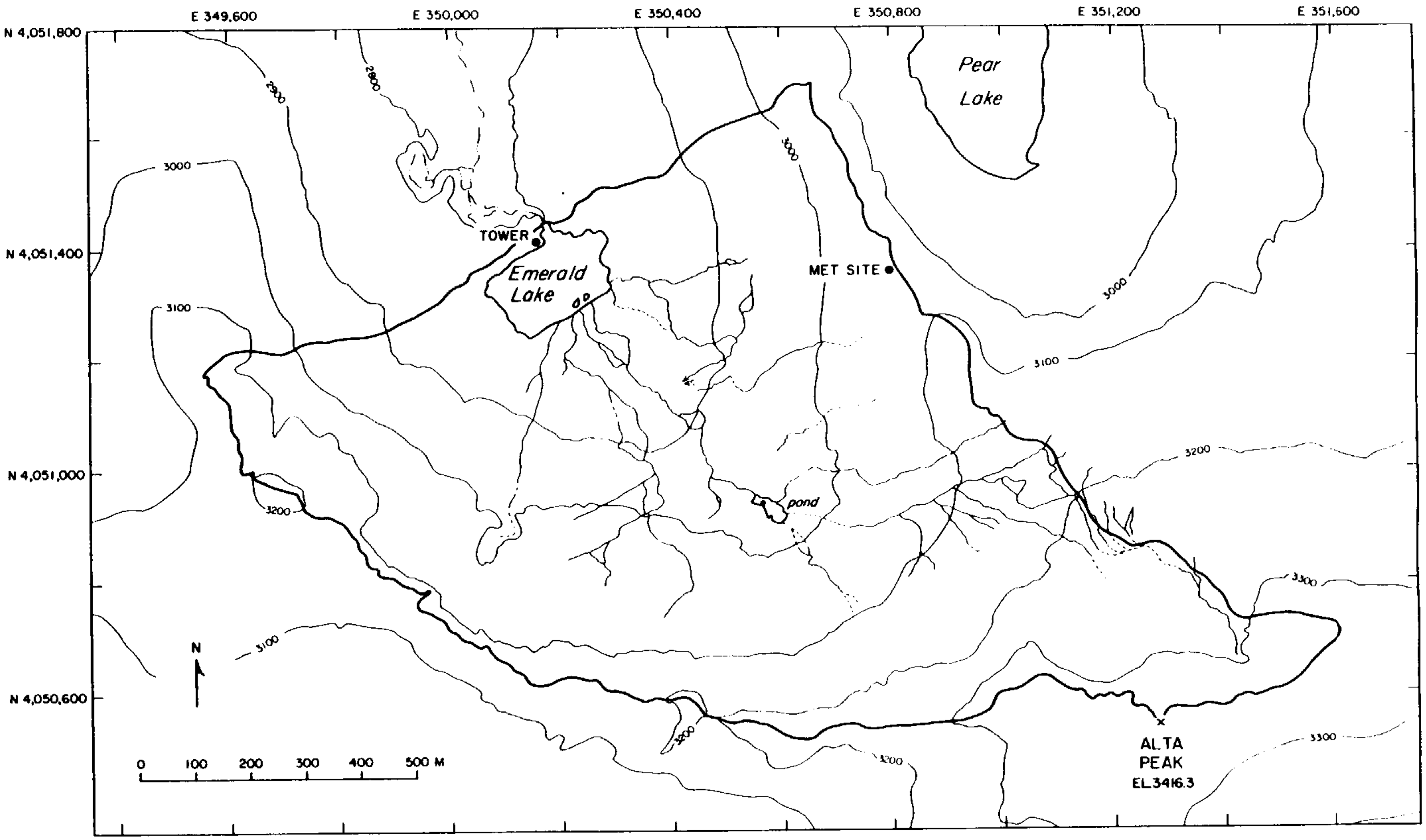

Figure 1-1. Topographic map of Emerald Lake Watershed.

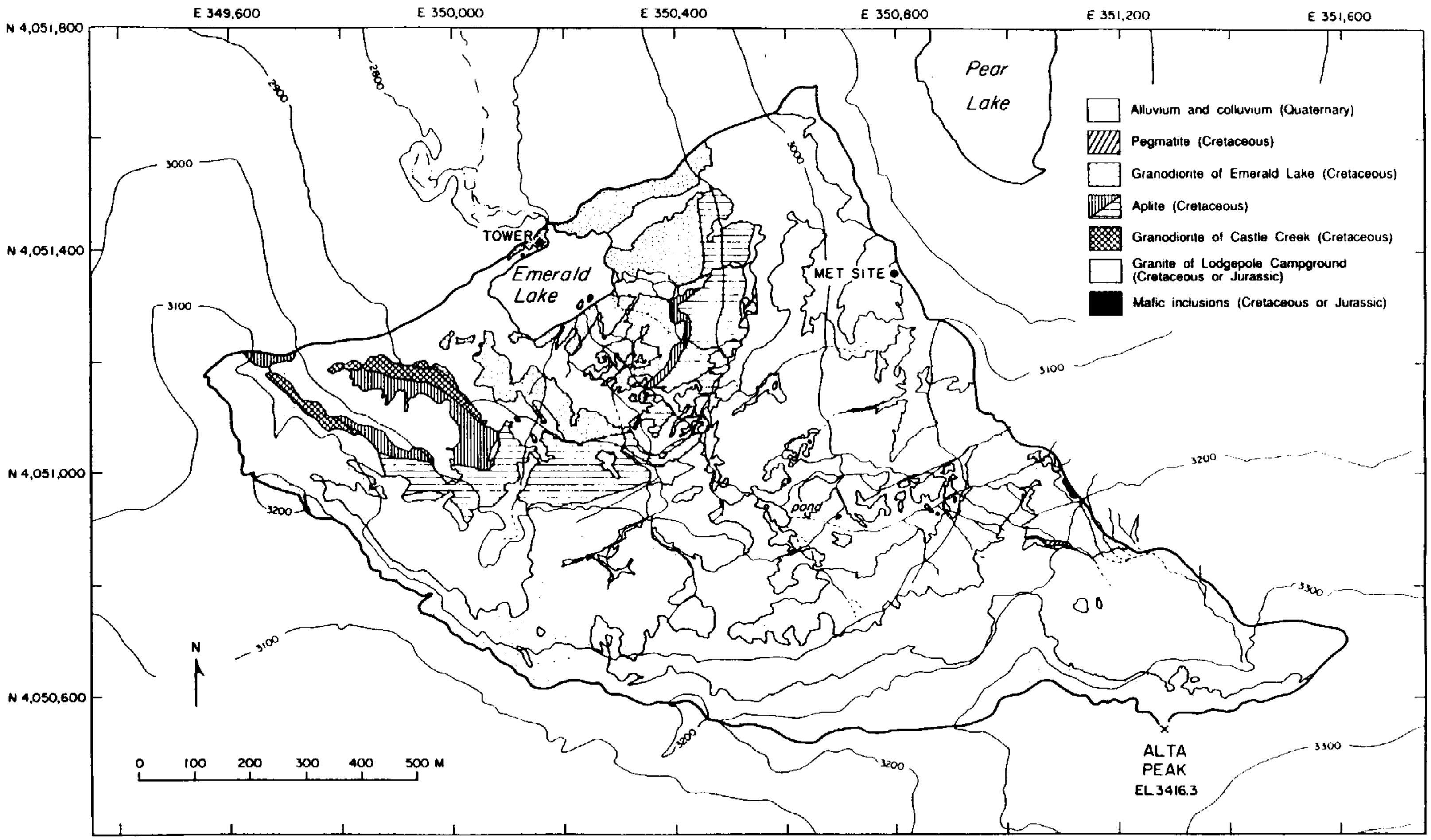

Figure 1-2. Geologic map of ELW (after Clow, 1987).

# *CHAPTER 2*

## *SOILS OF EMERALD LAKE WATERSHED*

The soils of Emerald Lake Watershed were mapped during an order one survey in 1982 and 1983 conducted by G. Huntington and M. Akeson (1987). Their report was published in 1987. The map unit delineations were plotted on aerial photographs which were published as the final soils map of ELW. Because of the distortions in these photos, accurate areal estimations of soil bodies could not be made. One of the undertakings on our project was to transfer the published soil map to an orthophoto of ELW. Huntington and Akeson determined basic soil characteristics for a number of typifying pedons to aid in taxonomic placement. However, they did not study the spatial variability in soil characteristics beyond general observations in the field. An assessment of spatial variability is needed if accurate modeling is to be carried out by the California Air Resources Board. Information is also needed on the spatial variability of soil characteristics in ELW to guide any future efforts related to soil sampling in ELW.

### OBJECTIVES

The objectives of this project related to characterization of ELW soils were:

1) to develop a soil map of ELW on an orthophoto,
2) to develop estimates of the area and mass of the various soils found in ELW, and
3) to assess the spatial variability of selected physical and chemical characteristics of some of the dominant soils in ELW.

### METHODS

Soil boundaries were transferred from the published soil map to the orthophoto developed for the ELW project by visual observation. Rock outcrops and other prominent surface features found on both photos were used as a guide for placement of delineations on the orthophoto.

After the orthophoto soil map was completed, it was our intention to have the soil boundaries digitized by other ARB contractors and overlain on the topographic map developed for ELW. This would have then allowed for accurate determinations of area for each mapping unit. However, digitization of the soil map was not possible and we reverted to manual techniques for areal estimation of the various mapping units. The area of each delineation on the orthophoto soil map was measured and the total area for each mapping unit was estimated by summing the measurements of individual delineations. These areas were then used in all calculations of soil area and mass.

The proportion of soil (as compared to bedrock outcrop) in each mapping unit was determined from mapping unit descriptions given by Huntington and Akeson (1987). The range of slopes given in Table 2-2 were also taken from mapping unit descriptions. The mean depth associated with each mapping unit was developed from field measurements or mapping unit descriptions. Relative to the ultimate objective of assessing potential effects of acidic deposition, very conservative estimates were made for talus and colluvium map units. Depth and other physical parameters were estimated assuming they were similar to the TsD map unit. These estimates may yield higher calculated volumes of material than actually present. Bulk densities were based on field measurements (the development of which is described in Chapter 3). The slope percentages and proportions of soil were used to calculate actual soil areas for each mapping unit. These data were combined with the soil depth information to calculate soil volume. The bulk density data were used to calculate soil mass for the various mapping units.

Twenty-nine mapping units were identified on the soil map of ELW. These mapping units consisted of soils classified as Entisols, Inceptisols and a Spodosol and of miscellaneous land classes. Miscellaneous land classes account for 71 of the 121 ha found in ELW. The remaining 50 ha are considered "soil" mapping units, recognizing that in some cases rock outcrop accounts for a significant percentage of the mapping unit area. Because it was not possible to conduct detailed work with all of the soil mapping units of ELW, a few soils were selected for study to assess the variability of soil properties within ELW. Soil mapping units having similar properties were then grouped with the studied soils to calculate soil mass.

Three soil mapping units (EaD, LeC-R, TdoF-R) were selected for an intensive study of soil characteristics. The major delineation of each mapping unit (EaD - referred to as Bench Meadow; TdoF-R - Pimo Stand; LeC-R - Inlet Meadow) was selected for study. A grid was overlain on the orthophoto soil map and four sampling locations were randomly identified. At each of the sampling locations, pits were dug and soil samples were collected in 10-cm depth increments from three soil profiles located 0.5 m apart. The samples were returned to UCR where they were air-dried and gently crushed to pass a 2-mm sieve. Coarse fragments were determined on a whole soil basis. Particle size distributions were determined by the pipette method (Gee and Bauder, 1986). Total C was determined by dry oxidation. Ammonium-nitrogen and nitrate-nitrogen were determined on KCl and water extracts by colorimetric analysis using an autoanalyzer (Keeney and Nelson, 1982). Phosphate-phosphorus was determined on Bray and water extracts also using a colorimetric technique (Olson and Sommers, 1982). Sulfate-sulfur was determined on a water extract. Total nitrogen was determined using Kjeldahl digestion and titration of ammonium-nitrogen (Bremner and Mulvaney, 1982). The statistical methods used to analyze the variability of soil characteristics within the mapped units follow those described by Lund et al. (1980).

## RESULTS AND DISCUSSION

Mapping unit delineations were transferred from the maps published by Huntington and Akeson to an orthophoto of ELW (Fig. 2-1). Map unit names and symbols were not changed from the original survey (Table 2-1). Following the development of the orthophoto soil map, areas and proportions of the various soil bodies found in the watershed were determined (Table 2-2). The total area calculated for ELW using our manual techniques was

121.4 ha. This area is in quite good agreement with the "officially accepted" area for ELW of 120 ha. Difficulties in visually locating the watershed boundary on the orthophoto likely accounts for the small difference in watershed area. If the soil map had been digitized, the total areas would be the same because a single boundary would have been used.

The soils groups developed for ELW are given in Table 2-2. The twenty-nine mapping units can be placed in nine groups on the basis of similar properties. The major soils of the watershed are classified as Umbrepts and Orthents. The various Umbrepts were grouped into four groups on the basis of wetness and vegetation. These groups ranged from the deep soils (EbF, EcF) in the master joint, to the wet bench meadow soil (EaD), to the soils along stream channels with willow cover, to the well-drained Umbrepts on slopes and ridges. The Orthents were also well-drained and the six mapping units can be grouped together. Individual mapping units were maintained for the one Aquept in the watershed, the one Fluvent and the one Orthod and Umbrept association. The remaining six mapping units are miscellaneous land classes, including talus and colluvium which are unconsolidated and may have soil-like properties but are not classified as soils.

Soils are estimated to occupy approximately 22% of the area of ELW (Table 2-3). The well-drained Umbrepts and Orthents account for a large percentage of the soil area in ELW, 34 and 17% respectively. The wetter Umbrepts account for approximately 37% of the area. These rankings change somewhat when converted to a mass basis. The Umbrept found in the master joint becomes much more important on a mass basis, 29% of the total, because of the deeper soils found in this area. The Orthents become proportionally less important (area 17%, mass 11%) because they are typically much thinner. Overall, the ranking according to soil mass is as follows: well-drained Umbrepts (36%), master joint Umbrepts (29%), stream channel Umbrepts (12%), well-drained Orthents (11%), soils of white pine stand (8%), bench meadow soils (2%) and the Aquept and Fluvent each 1%.

Soils in three of the principal mapping units found in ELW were sampled to assess the variability of selected soil characteristics in order to determine how well measured values represented the actual field situations. The mapping units selected for sampling were EaD (Entic Cryumbrept) found in the bench meadow, TdoF-R (Orthod-Umbrept) found in the pine stand, and LeC-R (Lithic Cryumbrept, wet) found in the inlet meadow. The results of the analyses of soils from each of these locations are reported in Table 2-4. The samples are identified as follows: 1-4, 11-14, and 21-24 represent the four locations in the bench meadow, pine stand and inlet meadow, respectively; A, B, and C represent the three sites sampled at each location. Even though all four sampling locations were within a single mapping unit, the variability among locations was much greater than among the three sites within a location. This is expected as even in an order one soil survey mapping units are generally composed of more than one soil taxon. Therefore, random sampling of a map unit may result in individual samples representing different soil taxons.

The data for the 0-10 cm depth at each of the four sites were pooled to assess how accurately measured values represented actual values for individual soil mapping units. The results of this analysis are given in Table 2-5 for selected soil characteristics. Particle size data generally had less variation within soils and the resulting mean values would be expected to be quite close to the actual means. For example, considering the sand percentage of soils in pine stand, 74.2% would be expected to be within 3.3% of the true mean (95% confidence level). The low variation found in the sand contents in the pine stand indicated that one sample could be taken in this area and the resulting value would be expected to be within 10% of the true value. The chemical constituents were found to be much more variable. Mean nitrate-nitrogen values would be expected to be within 93.6%, 71.7% and 81.5% of the true means for the bench, pine and inlet soils, respectively. If highly accurate values (for example within 10% of the true mean) were needed for these constituents, hundreds of samples may need to be analyzed. This is not an unusual finding. The number of samples required to achieve 10% accuracy for nitrate-nitrogen leaching from a relatively uniform 25 ha agricultural field exceeded 300 (Lund et al, 1980). If soil sampling is to be conducted at ELW or other Sierra watersheds in the future, the levels of accuracy desired should be considered in designing a sampling program.

## CONCLUSIONS

A soil map was developed on an orthophoto by transferring map unit boundaries from the published soil map of ELW. Surface features seen on both the orthophoto and the aerial photos used as the base for the published soil map were to used to guide placement of map unit boundaries. The map units depicted on the orthophoto soil map were used to determine areas of various soil bodies and to estimate the mass of soil found in ELW. Mapping units containing significant soil account for 40% of the area in ELW. Miscellaneous land classes account for 60% of the area. On a mass basis, well-drained Umbrepts account for the greatest amount of soil in ELW.

Selected physical and chemical characteristics of the dominant soils of ELW are quite variable. Average particle size distributions could be determined generally more accurately than soil chemical parameters. Total pools of C and N could be determined with greater accuracy than could extractable pools of N and P. If additional soil sampling of Sierra watersheds for assessment of nutrient pools is to be done, the large number of samples required for accurate estimates must be considered.

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Table 2-1. Soil map unit names and symbols for Emerald Lake Watershed (taken from Huntington and Akeson, 1987).

| Symbol | Map Unit Name |
|---|---|
| CqB | Cryaquepts, 0-5% slopes |
| EaD | Entic Cryumbrepts, moderately deep, wet, 15-30% slopes |
| EbF | Entic Cryumbrepts, deep, 45-75% slopes |
| EcF | Entic Cryumbrepts, deep, cobbly, 45-75% slopes |
| F-K | Felsenmeer-Stony colluvial land association |
| G | Glacial rubble land |
| K | Stony colluvial land |
| LcF | Lithic Cryumbrepts, very shallow, 45-75% slopes |
| LcF-R | Lithic Cryumbrepts, very shallow-Rock outcrop complex, 45-75% slopes |
| LdF | Lithic Cryumbrepts, very shallow, stony, 45-75% slopes |
| LdF-R | Lithic Cryumbrepts, very shallow, stony-Rock outcrop complex, 45-75% slopes |
| LeC-R | Lithic Cryumbrepts, shallow-Rock outcrop complex, 5-15% slopes |
| LeD | Lithic Cryumbrepts, shallow, 15-30% slopes |
| LfqC | Lithic Cryumbrepts, shallow, wet-Histic Lithic Cryaquepts complex, 5-15% slopes |
| Rj | Rock outcrop, jointed |
| R-LcE | Rock outcrop-Lithic Cryumbrepts, very shallow complex, 30-45% slopes |
| R-LcF | Rock outcrop-Lithic Cryumbrepts, very shallow complex, 45-75% slopes |
| R-LeF | Rock outcrop-Lithic Cryumbrepts, shallow complex, 45-75% slopes |
| Ru | Rock outcrop, unjointed |
| T | Talus |
| T-LeF | Talus-Lithic Cryumbrepts, shallow complex, 45-75% slopes |
| TdoF-R | Typic Cryorthods-Lithic Cryorthents-Rock outcrop complex, 45-75% slopes |
| TfB | Typic Cryofluvents, 0-5% slopes |
| ToC | Typic Cryorthents, shallow, 5-15% slopes |
| ToF | Typic Cryorthents, shallow, 45-75% slopes |
| TpD-R | Typic Cryorthents, moderately deep-Rock outcrop complex, 15-30% slopes |
| TrF | Typic Cryorthents, moderately deep, very cobbly, 45-75% slopes |
| TrF-R | Typic Cryorthents, moderately deep, very cobbly-Rock outcrop complex, 45-75% slopes |
| TsD | Typic Cryorthents, deep, cobbly, 15-30% slopes |

Table 2-2. Physical characteristics of ELW soil map units.

| Map |  | Map Unit |  | Range of Slopes |  | Mean | Mean |
|---|---|---|---|---|---|---|---|
| Unit |  | Area | %Soil | Low | High | Depth | Bulk Dens |
|  |  | ha |  | % | % | m | Mg/m3 |
| Cryaquept-"Parson's" Pond |  |  |  |  |  |  |  |
| CqB | * | 0.26 | 100% | 0 | 5 | 0.5 | 1.02 |
| Cryofluvent-"Aplite Dike" inlet to the lake |  |  |  |  |  |  |  |
| TfB | * | 0.07 | 100% | 0 | 5 | 1.5 | 1.35 |
| Entic Cryumbrept-bench meadow, wet |  |  |  |  |  |  |  |
| EaD | 1 | 0.59 | 100% | 15 | 30 | 0.373 | 1.35 |
| Lithic Cryumbrepts-well drained on slopes and ridges |  |  |  |  |  |  |  |
| LcF |  | 0.21 | 100% | 45 | 75 | 0.337 | 1.41 |
| LcF-R | 2 | 4.29 | 45% | 45 | 75 | 0.337 | 1.41 |
| R-LcF |  | 22.06 | 20% | 45 | 75 | 0.337 | 1.41 |
| R-LcE |  | 2.58 | 20% | 30 | 45 | 0.337 | 1.41 |
| R-LeF |  | 2.13 | 30% | 45 | 75 | 0.337 | 1.41 |
| LeD |  | 0.31 | 100% | 15 | 30 | 0.337 | 1.41 |
| Lithic Cryumbrepts-wetter, along stream channels, willow (Salix) cover |  |  |  |  |  |  |  |
| LdF |  | 3.45 | 100% | 45 | 75 | 0.237 | 1.02 |
| LdF-R |  | 1.51 | 45% | 45 | 75 | 0.237 | 1.02 |
| LeC-R | 3 | 1.83 | 55% | 5 | 15 | 0.237 | 1.02 |
| LfqC |  | 0.10 | 100% | 5 | 15 | 0.237 | 1.02 |
| T-LeF |  | 0.84 | 25% | 45 | 75 | 0.237 | 1.02 |
| Entic Cryumbrepts-in the master joint east and west of the lake, very well drained |  |  |  |  |  |  |  |
| EbF | * | 0.32 | 100% | 45 | 75 | 0.7 | 1.35 |
| EcF | * | 2.88 | 100% | 45 | 75 | 0.7 | 1.35 |
| "Cryorthod" and Cryumbrept association-Western White Pine Pinus monticola, "Pimo" stand |  |  |  |  |  |  |  |
| TdoF-R | 4 | 2.54 | 70% | 45 | 75 | 0.326 | 1.35 |

Table 2-2. (cont.)

| Map | Map Unit | | Range of Slopes | | Mean | Mean |
|---|---|---|---|---|---|---|
| Unit | Area | %Soil | Low | High | Depth | Bulk Dens |
| | ha | | % | % | m | Mg/m3 |
| Cryorthents-very well drained glacial till and colluvium | | | | | | |
| TrF | 1.48 | 100% | 45 | 75 | 0.249 | 1.21 |
| TsD 5 | 1.48 | 100% | 15 | 30 | 0.249 | 1.21 |
| ToF | 0.58 | 100% | 45 | 75 | 0.249 | 1.21 |
| TpD-R | 0.51 | 70% | 15 | 30 | 0.249 | 1.21 |
| TrF-R | 0.25 | 50% | 45 | 75 | 0.249 | 1.21 |
| ToC | 0.09 | 100% | 5 | 15 | 0.249 | 1.21 |
| Miscellaneous Map Units-not supporting terrestrial vegetation | | | | | | |
| Rj | 33.69 | Rock | | | | |
| T | 19.03 | Talus | | | | |
| Ru | 8.21 | Rock | | | | |
| G | 3.84 | Colluvium | | | | |
| Water | 2.86 | | | | | |
| K | 2.18 | Colluvium | | | | |
| F-K | 1.19 | Colluvium | | | | |
| | 121.36 | ha watershed area | | | | |
| | 50.36 | ha soil map unit area | | | | |

* Depths estimated from soil survey, bulk density estimated from similar soils at ELW.

The following five map units were sampled intensively for depth, physical, and chemical variability:

1 (EaD) sample series 0 and 6

2 (LcF-R) sample series 4

3 (LeC-R) sample series 2 and 7

4 (TdoF-R) sample series 1 and 5

5 (TsD) sample series 8.

Sources: this report and Huntington and Akeson (1987).

Table 2-3. Estimates of areas, volumes, and masses of soils in ELW.

| Map | | Soil Area | | Soil Volume | | Soil Mass | |
|---|---|---|---|---|---|---|---|
| Unit | | Low | High | Low | High | Low | High |
| | | ha | ha | m3 x10-3 | m3 x10-3 | Mg x10-3 | Mg x10-3 |
| Cryaquept-"Parson's" Pond | | | | | | | |
| CqB | * | 0.26 | 0.26 | 1.3 | 1.3 | 1.3 | 1.3 |
| Cryofluvent-"Aplite Dike" inlet to the lake | | | | | | | |
| TfB | * | 0.07 | 0.07 | 1.0 | 1.0 | 1.4 | 1.4 |
| Entic Cryumbrept-bench meadow, wet | | | | | | | |
| EaD | 1 | 0.60 | 0.62 | 2.2 | 2.3 | 3.0 | 3.1 |
| Lithic Cryumbrepts-well drained on slopes and ridges | | | | | | | |
| LcF | | 0.23 | 0.26 | 0.8 | 0.9 | 1.1 | 1.2 |
| LcF-R | 2 | 2.12 | 2.41 | 7.1 | 8.1 | 10.1 | 11.5 |
| R-LcF | | 4.84 | 5.51 | 16.3 | 18.6 | 23.0 | 26.2 |
| R-LcE | | 0.54 | 0.57 | 1.8 | 1.9 | 2.6 | 2.7 |
| R-LeF | | 0.70 | 0.80 | 2.4 | 2.7 | 3.3 | 3.8 |
| LeD | | 0.32 | 0.33 | 1.1 | 1.1 | 1.5 | 1.6 |
| Lithic Cryumbrepts-wetter, along stream channels, willow (Salix) cover | | | | | | | |
| LdF | | 3.78 | 4.31 | 9.0 | 10.2 | 9.1 | 10.4 |
| LdF-R | | 0.74 | 0.85 | 1.8 | 2.0 | 1.8 | 2.0 |
| LeC-R | 3 | 1.01 | 1.02 | 2.4 | 2.4 | 2.4 | 2.5 |
| LfqC | | 0.10 | 0.10 | 0.2 | 0.2 | 0.2 | 0.2 |
| T-LeF | | 0.23 | 0.26 | 0.5 | 0.6 | 0.6 | 0.6 |
| Entic Cryumbrepts-in the master joint east and west of the lake, very well drained | | | | | | | |
| EbF | * | 0.36 | 0.41 | 2.5 | 2.8 | 3.4 | 3.8 |
| EcF | * | 3.16 | 3.60 | 22.1 | 25.2 | 29.9 | 34.0 |
| "Cryorthod" and Cryumbrept association-Western White Pine Pinus monticola, "Pimo" stand | | | | | | | |
| TdoF-R | 4 | 1.95 | 2.22 | 6.3 | 7.2 | 8.6 | 9.8 |
| Cryorthents-very well drained glacial till and colluvium | | | | | | | |
| TrF | | 1.62 | 1.85 | 4.0 | 4.6 | 4.9 | 5.6 |
| TsD | 5 | 1.50 | 1.55 | 3.7 | 3.9 | 4.5 | 4.7 |
| ToF | | 0.63 | 0.72 | 1.6 | 1.8 | 1.9 | 2.2 |
| TpD-R | | 0.36 | 0.38 | 0.9 | 0.9 | 1.1 | 1.1 |
| TrF-R | | 0.14 | 0.16 | 0.3 | 0.4 | 0.4 | 0.5 |
| ToC | | 0.09 | 0.09 | 0.2 | 0.2 | 0.3 | 0.3 |
| Totals: | | 25.34 | 28.33 | 89.7 | 100.5 | 116.3 | 130.5 |

Table 2-4. Data from analyses of soil samples collected for soil variability study.

| Sample # & Depth | Coarse Frags. | Profile Depth | Sand | Silt | Clay | Total C | KCl Extract NH$_4$-N | KCl Extract NO$_3$-N | Bray PO$_4$-P | Water Extractable NH$_4$-N | Water Extractable NO$_3$-N | Water Extractable PO$_4$-P | Total N | C:N Ratio | SO$_4$-S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | % | cm | --------%------------ | | | | -----------------mg/kg--------------------- | | | | | | | | mg/kg |
| BENCH MEADOW Soils 1-4 | | | | | | | | | | | | | | | |
| 1A 0-10 | 12.0 | 55.0 | 43 | 53 | 5 | 5.4 | 210.2 | 3.1 | 36.3 | 62.6 | 1.0 | 47.4 | 7850 | 6.9 | 26.9 |
| 1A 10-20 | 31.0 | | 62 | 37 | 1 | 2.5 | 20.6 | 0.9 | 5.4 | 4.5 | 1.3 | 22.1 | 1770 | 14.0 | 10.6 |
| 1A 20-30 | 46.0 | | 83 | 17 | 0 | 1.3 | 10.3 | 1.0 | 1.9 | 0.8 | 1.5 | 19.8 | 1080 | 12.1 | 8.5 |
| 1A 30-40 | 43.0 | | 85 | 14 | 1 | 0.8 | 5.1 | 0.5 | 10.5 | 0.1 | 1.0 | 21.6 | 380 | 21.8 | 7.3 |
| 1A 40-50 | 64.0 | | 87 | 12 | 1 | 1.0 | 7.3 | 0.6 | 0.8 | 0.0 | 1.1 | 24.4 | 433 | 22.9 | 8.5 |
| 1A 50-57 | 61.0 | | 82 | 18 | 0 | 0.8 | 8.6 | 0.9 | 3.1 | 0.0 | 1.2 | 24.4 | 420 | 18.8 | 6.5 |
| 1B 0-10 | 25.0 | 66.0 | 47 | 49 | 4 | 5.4 | 167.2 | 1.8 | 4.6 | 36.6 | 2.5 | 38.2 | 4460 | 12.0 | 24.1 |
| 1B 10-20 | 49.0 | | 68 | 31 | 1 | 1.8 | 18.6 | 0.6 | 6.8 | 2.8 | 1.6 | 26.7 | 1240 | 14.2 | 10.6 |
| 1C 0-10 | 19.0 | 85.0 | 39 | 57 | 4 | 5.2 | 132.0 | 9.3 | 0.9 | 33.4 | 10.5 | 29.9 | 4230 | 12.3 | 20.8 |
| 1C 10-20 | 56.0 | | 73 | 27 | 0 | 2.5 | 16.2 | 1.7 | 2.8 | 0.8 | 2.3 | 22.1 | 2420 | 10.1 | 9.4 |
| 1C 20-30 | 57.0 | | 84 | 13 | 3 | 1.7 | 11.3 | 0.7 | 5.2 | 0.9 | 1.6 | 24.4 | 1180 | 14.1 | 8.5 |
| 1C 30-40 | 38.0 | | 87 | 10 | 3 | 0.8 | 2.2 | 0.3 | 4.8 | 0.0 | 1.0 | 22.5 | 775 | 10.3 | 8.5 |
| 1C 40-50 | 49.0 | | 86 | 12 | 2 | 0.9 | 7.5 | 0.8 | 0.7 | 0.5 | 1.4 | 23.5 | 893 | 10.5 | 10.6 |
| 1C 50-60 | 51.0 | | 87 | 11 | 2 | 0.5 | 5.3 | 0.6 | 8.7 | 0.0 | 1.3 | 22.1 | 601 | 8.7 | 8.5 |
| 1C 60-70 | 55.0 | | 90 | 9 | 1 | 0.6 | 4.9 | 1.4 | 5.8 | 0.0 | 1.9 | 19.8 | 429 | 14.5 | 6.9 |
| 2A 0-10 | 48.0 | 34.5 | 77 | 18 | 5 | 6.5 | 19.0 | 1.6 | 18.2 | 0.0 | 0.3 | 52.1 | 6310 | 10.3 | 24.9 |
| 2A 10-20 | 54.0 | | 84 | 14 | 2 | 1.9 | 8.6 | 0.9 | 11.5 | 1.1 | 1.5 | 24.4 | 1010 | 18.4 | 14.6 |
| 2A 20-30 | 36.0 | | 68 | 30 | 2 | 1.7 | 9.8 | 8.0 | 1.3 | 1.8 | 8.5 | 10.5 | 1330 | 12.8 | 12.6 |
| 2A 30-35 | 44.0 | | 85 | 14 | 1 | 1.8 | 8.9 | 2.1 | 0.9 | 1.7 | 2.7 | 15.1 | 1150 | 16.0 | 8.5 |
| 2B 0-10 | 37.0 | 30.5 | 72 | 23 | 5 | 8.2 | 20.1 | 0.9 | 15.7 | 1.1 | 0.3 | 52.1 | 8280 | 9.8 | 24.5 |
| 2B 10-20 | 34.0 | | 69 | 26 | 5 | 2.6 | 8.1 | 1.2 | 2.0 | 1.0 | 1.7 | 22.1 | 1960 | 13.2 | 14.6 |
| 2B 20-28 | 41.0 | | 68 | 29 | 3 | 1.4 | 7.9 | 2.2 | 1.6 | 1.0 | 2.9 | 15.1 | 962 | 14.2 | 10.6 |
| 2C 0-10 | 46.0 | 25.5 | 75 | 20 | 5 | 6.0 | 15.8 | 1.0 | 7.9 | 2.9 | 0.3 | 43.8 | 4540 | 13.3 | 26.9 |
| 2C 10-20 | 52.0 | | 68 | 29 | 3 | 2.2 | 10.9 | 1.1 | 0.9 | 0.4 | 1.9 | 19.8 | 2000 | 11.1 | 12.6 |
| 2C 20-30 | 36.0 | | 68 | 31 | 1 | 1.7 | 6.6 | 1.6 | 1.0 | 0.7 | 2.0 | 15.1 | 962 | 17.3 | 10.2 |
| 2C 30-38 | 45.0 | | 86 | 10 | 4 | 1.5 | 6.9 | 2.6 | 6.0 | 0.0 | 3.3 | 19.8 | 970 | 15.3 | 8.5 |
| 3A 0-10 | 47.0 | 21.0 | 69 | 26 | 5 | 3.0 | 0.0 | 0.1 | 89.0 | 0.0 | 0.3 | 29.0 | 2500 | 12.1 | 12.6 |
| 3A 10-20 | 48.0 | | 60 | 33 | 7 | 3.3 | 2.3 | 0.5 | 14.1 | 0.0 | 0.1 | 26.7 | 2210 | 14.8 | 15.5 |
| 3A 20-22 | 47.0 | | 61 | 32 | 7 | 3.7 | 2.0 | 0.5 | 0.9 | 0.0 | 0.2 | 23.5 | 2630 | 14.2 | 18.8 |
| 3B 0-10 | 58.0 | 22.0 | 67 | 28 | 5 | 4.2 | 10.2 | 0.6 | 95.7 | 0.0 | 0.3 | 30.4 | 3530 | 11.9 | 14.6 |
| 3B 10-17 | 50.0 | | 53 | 43 | 4 | 3.2 | 2.8 | 0.4 | 46.4 | 0.0 | 0.2 | 26.7 | 2540 | 12.5 | 17.9 |
| 3C 0-10 | 44.0 | 10.0 | 65 | 30 | 5 | 4.0 | 8.7 | 0.4 | 75.0 | 0.0 | 0.2 | 31.3 | 3250 | 12.3 | 13.0 |
| 4A 0-10 | 41.0 | 38.0 | 62 | 36 | 2 | 5.5 | 6.9 | 0.6 | 14.9 | 2.7 | 0.2 | 42.8 | 3470 | 16.0 | 23.3 |
| 4A 10-20 | 44.0 | | 66 | 33 | 1 | 2.5 | 0.4 | 0.8 | 10.8 | 1.4 | 1.1 | 29.8 | 1540 | 16.2 | 15.9 |
| 4A 20-30 | 22.0 | | 56 | 42 | 1 | 2.3 | 0.8 | 0.5 | 3.8 | 0.0 | 1.4 | 15.1 | 1620 | 14.0 | 12.6 |
| 4A 30-36 | 38.0 | | 75 | 24 | 1 | 1.2 | 0.3 | 0.5 | 12.8 | 0.0 | 1.3 | 15.1 | 915 | 13.2 | 9.4 |
| 4B 0-10 | 35.0 | 33.0 | 67 | 30 | 3 | 9.4 | 12.9 | 0.3 | 11.2 | 0.0 | 0.4 | 47.5 | 5490 | 17.1 | 20.8 |
| 4B 10-20 | 38.0 | | 71 | 29 | 0 | 2.6 | 2.3 | 0.6 | 7.8 | 2.7 | 1.7 | 17.9 | 1860 | 14.1 | 14.0 |
| 4B 20-30 | 29.0 | | 60 | 39 | 1 | 2.0 | 0.0 | 0.3 | 1.5 | 0.0 | 1.0 | 3.9 | 1540 | 12.8 | 10.6 |
| 4B 30-40 | 34.0 | | 65 | 35 | 0 | 1.6 | 0.0 | 0.2 | 4.3 | 0.0 | 1.2 | 8.7 | 1340 | 12.1 | 6.8 |
| 4C 0-10 | 46.0 | 27.0 | 65 | 32 | 3 | 6.3 | 12.2 | 0.2 | 15.1 | 0.2 | 0.2 | 40.5 | 4230 | 14.8 | 25.0 |
| 4C 10-20 | 24.0 | | 56 | 40 | 4 | 3.0 | 0.0 | 0.1 | 0.9 | 1.3 | 0.9 | 15.1 | 1950 | 15.2 | 17.8 |
| 4C 20-29 | 25.0 | | 63 | 35 | 2 | 2.4 | 0.5 | 0.2 | 0.3 | 1.0 | 1.2 | 11.5 | 1830 | 13.0 | 15.4 |

Table 2-4. (cont.)

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PIMO STAND Cryorthod Association, soils 11-14 | | | | | | | | | | | | | | | |
| 11A 0-10 | 36.0 | 24.5 | 75 | 29 | 6 | 3.5 | 1.0 | 1.2 | 64.2 | 0.0 | 1.4 | 30.4 | 2220 | 15.7 | 16.7 |
| 11A 10-20 | 50.0 | | 81 | 14 | 5 | 2.7 | 0.0 | 2.3 | 55.2 | 1.3 | 3.1 | 26.7 | 1420 | 18.8 | 12.5 |
| 11A 20-28 | 44.0 | | 78 | 20 | 2 | 2.5 | 0.9 | 2.3 | 23.9 | 3.6 | 3.2 | 23.5 | 1660 | 15.2 | 14.2 |
| 11B 0-10 | 50.0 | 18.0 | 78 | 17 | 5 | 3.4 | 0.0 | 1.2 | 54.9 | 0.0 | 1.0 | 32.2 | 1620 | 21.2 | 10.5 |
| 11B 10-18 | 45.0 | | 83 | 14 | 3 | 2.4 | 0.0 | 2.5 | 60.0 | 0.0 | 3.0 | 29.0 | 1340 | 17.8 | 10.1 |
| 11C 0-10 | 38.0 | 50.5 | 77 | 16 | 7 | 3.5 | 0.6 | 0.7 | 46.5 | 0.9 | 1.3 | 30.4 | 1920 | 18.4 | 10.5 |
| 11C 10-20 | 42.0 | | 83 | 15 | 2 | 2.5 | 2.2 | 2.2 | 21.3 | 1.9 | 3.0 | 25.8 | 1320 | 18.9 | 14.6 |
| 11C 20-30 | 49.0 | | 82 | 16 | 2 | 1.0 | 1.1 | 2.6 | 6.0 | 3.2 | 2.9 | 22.1 | 1300 | 7.5 | 13.8 |
| 11C 30-40 | 52.0 | | 86 | 13 | 1 | 1.6 | 5.1 | 2.3 | 2.7 | 1.6 | 2.6 | 17.9 | 1340 | 12.2 | 13.8 |
| 11C 40-47 | 58.0 | | 83 | 16 | 1 | 1.5 | 5.7 | 2.3 | 1.8 | 2.7 | 2.6 | 18.9 | 1400 | 10.9 | 12.5 |
| 12A 0-10 | 42.0 | 20.5 | 69 | 24 | 7 | 1.6 | 2.9 | 1.2 | 16.1 | 1.8 | 1.7 | 24.4 | 1270 | 12.8 | 10.5 |
| 12A 10-20 | 42.0 | | 75 | 24 | 1 | 1.2 | 3.4 | 0.6 | 17.6 | 1.0 | 1.1 | 22.1 | 925 | 12.5 | 9.2 |
| 12B 0-10 | 41.0 | 17.0 | 77 | 19 | 4 | 2.6 | 2.6 | 0.9 | 32.2 | 1.8 | 1.5 | 25.8 | 1280 | 20.0 | 14.6 |
| 12B 10-20 | 46.0 | | 76 | 21 | 3 | 1.4 | 5.9 | 0.4 | 5.4 | 2.3 | 1.2 | 23.5 | 761 | 18.4 | 8.8 |
| 12C 0-10 | 44.0 | 14.0 | 81 | 15 | 4 | 3.1 | 4.3 | 1.4 | 22.6 | 2.2 | 2.0 | 25.8 | 1810 | 17.3 | 14.6 |
| 12C 10-14 | 41.0 | | 70 | 24 | 6 | 1.2 | 4.2 | 0.8 | 5.2 | 1.9 | 1.4 | 20.2 | 748 | 16.2 | 9.6 |
| 13A 0-10 | 31.0 | 18.5 | 72 | 22 | 6 | 4.2 | 6.5 | 1.9 | 90.1 | 1.8 | 2.2 | 39.6 | 1830 | 23.0 | 14.2 |
| 13A 10-18 | 37.0 | | 70 | 23 | 7 | 2.4 | 7.6 | 4.9 | 6.6 | 0.3 | 5.0 | 28.1 | 1470 | 16.3 | 20.0 |
| 13B 0-10 | 38.0 | 24.5 | 71 | 24 | 5 | 3.5 | 2.0 | 2.8 | 111.8 | 3.2 | 2.7 | 32.7 | 2400 | 14.7 | 15.9 |
| 13B 10-20 | 34.0 | | 69 | 28 | 3 | 2.0 | 0.2 | 5.7 | 49.3 | 0.0 | 5.4 | 28.1 | 1290 | 15.1 | 18.8 |
| 13B 20-24 | 63.0 | | 76 | 18 | 6 | 2.0 | 0.4 | 4.8 | 5.5 | 0.7 | 5.2 | 25.8 | 1310 | 15.4 | 21.2 |
| 13C 0-10 | 20.0 | 28.5 | 67 | 22 | 11 | 6.5 | 16.8 | 9.2 | 94.8 | 15.2 | 11.8 | 90.9 | 4030 | 16.2 | 41.5 |
| 13C 10-20 | 41.0 | | 74 | 18 | 8 | 3.2 | 18.0 | 6.7 | 7.6 | 2.6 | 8.4 | 39.5 | 1980 | 16.2 | 39.4 |
| 13C 20-25 | 32.0 | | 75 | 17 | 8 | 4.4 | 3.0 | 8.0 | 3.2 | 2.3 | 8.4 | 34.1 | 2260 | 19.4 | 29.1 |
| 14A 0-10 | 40.0 | 35.0 | 72 | 23 | 5 | 1.9 | 5.8 | 1.0 | 3.2 | 0.2 | 1.7 | 23.5 | 1400 | 13.3 | 12.5 |
| 14A 10-20 | 41.0 | | 77 | 19 | 4 | 1.7 | 5.7 | 1.3 | 8.0 | 0.0 | 1.6 | 22.1 | 976 | 17.8 | 11.3 |
| 14A 20-25 | 41.0 | | 78 | 19 | 3 | 1.6 | 2.9 | 1.0 | 1.5 | 0.0 | 1.7 | 18.9 | 1300 | 11.9 | 10.5 |
| 14B 0-10 | 39.0 | 24.0 | 75 | 20 | 5 | 2.3 | 6.8 | 1.4 | 0.7 | 0.5 | 1.6 | 23.9 | 1320 | 17.7 | 8.4 |
| 14B 10-20 | 39.0 | | 78 | 18 | 4 | 2.3 | 3.5 | 1.1 | 2.7 | 1.5 | 1.9 | 23.5 | 1330 | 17.1 | 9.2 |
| 14B 20-25 | 40.0 | | 76 | 20 | 4 | 2.2 | 4.4 | 2.2 | 4.8 | 0.7 | 2.3 | 25.8 | 1340 | 16.1 | 10.5 |
| 14C 0-10 | 34.0 | 25.5 | 76 | 19 | 5 | 1.9 | 1.7 | 0.9 | 18.3 | 0.0 | 1.3 | 30.4 | 931 | 20.0 | 9.2 |
| 14C 10-20 | 38.0 | | 78 | 17 | 5 | 1.7 | 6.9 | 2.1 | 5.8 | 2.7 | 1.7 | 23.5 | 1040 | 16.7 | 3.4 |
| 14C 20-22 | 60.0 | | 81 | 16 | 3 | 1.6 | 5.9 | 1.3 | 3.3 | 0.6 | 2.0 | 25.3 | 1120 | 13.8 | 6.8 |
| INLET MEADOW Lithic Cryaquent soils 21-24 | | | | | | | | | | | | | | | |
| 21A 0-10 | 4.0 | 18.0 | 36 | 44 | 20 | 12.6 | 29.9 | 1.5 | 0.9 | 30.6 | 2.2 | 69.6 | 8060 | 15.6 | 27.4 |
| 21A 10-18 | 20.0 | | 63 | 28 | 9 | 4.6 | 12.1 | 0.6 | 6.3 | 4.9 | 1.4 | 29.6 | 2900 | 15.7 | 17.8 |
| 21B 0-10 | 0.0 | 17.0 | 46 | 36 | 18 | 13.0 | 50.3 | 0.9 | 4.1 | 19.4 | 1.6 | 77.9 | 8190 | 15.9 | 30.8 |
| 21B 10-17 | 7.0 | | 33 | 54 | 13 | 6.2 | 11.7 | 0.3 | 0.9 | 7.9 | 1.1 | 30.4 | 3790 | 16.3 | 20.2 |
| 21C 0-10 | 5.0 | 15.5 | 40 | 40 | 20 | 15.8 | 46.8 | 0.9 | 34.8 | 8.6 | 2.3 | 92.7 | 8840 | 17.9 | 28.9 |
| 21C 10-14 | 6.0 | | 37 | 49 | 14 | 4.7 | 13.5 | 0.8 | 18.0 | 0.5 | 2.0 | 35.0 | 4110 | 11.4 | 15.4 |
| 22A 0-10 | 41.0 | 22.0 | 73 | 13 | 14 | 12.8 | 31.6 | 0.5 | 74.0 | 0.0 | 0.4 | 89.0 | 7200 | 17.8 | 51.4 |
| 22A 10-20 | 9.0 | | 42 | 37 | 21 | 9.1 | 20.3 | 0.1 | 0.4 | 5.8 | 1.4 | 41.9 | 5630 | 16.2 | 29.8 |
| 22A 20-24 | 8.0 | | 53 | 29 | 18 | 9.7 | 11.3 | 0.2 | 0.4 | 5.1 | 1.7 | 13.3 | 4460 | 21.8 | 14.0 |
| 22B 0-10 | 31.0 | 30.0 | 57 | 25 | 18 | 8.1 | 17.4 | 0.3 | 21.2 | 2.1 | 1.2 | 58.1 | 4730 | 17.1 | 29.8 |
| 22B 10-20 | 15.0 | | 43 | 37 | 20 | 10.5 | 21.6 | 0.4 | 2.3 | 3.9 | 2.3 | 51.2 | 5640 | 18.6 | 51.9 |
| 22B 20-30 | 21.0 | | 55 | 32 | 13 | 5.5 | 8.1 | 0.0 | 0.4 | 4.2 | 2.0 | 14.2 | 3520 | 15.5 | 19.3 |

Table 2-4. (cont.)

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 22C | 0-10 | 49.0 | 21.0 | 65 | 24 | 11 | 8.0 | 11.3 | 0.2 | 23.6 | 0.0 | 0.3 | 56.7 | 3890 | 20.6 | 32.2 |
| 22C | 10-20 | 19.0 | | 53 | 35 | 12 | 6.7 | 24.6 | 1.3 | 20.1 | 9.9 | 2.1 | 75.6 | 6890 | 9.8 | 53.8 |
| 23A | 0-10 | 3.0 | 31.0 | 35 | 42 | 23 | 10.9 | 66.2 | 7.9 | 1.5 | 22.6 | 13.4 | 30.4 | 8070 | 13.5 | 22.6 |
| 23A | 10-20 | 30.0 | | 57 | 26 | 17 | 6.0 | 31.9 | 1.3 | 0.0 | 9.7 | 3.4 | 14.2 | 4490 | 13.3 | 15.4 |
| 23A | 20-30 | 6.0 | | 57 | 28 | 15 | 6.5 | 26.1 | 1.5 | 0.0 | 7.8 | 9.0 | 9.6 | 5160 | 12.6 | 20.7 |
| 23B | 0-10 | 5.0 | 32.0 | 34 | 40 | 26 | 11.7 | 66.5 | 12.1 | 0.1 | 10.2 | 3.6 | 20.2 | 9550 | 12.2 | 35.6 |
| 23B | 10-20 | 7.0 | | 47 | 32 | 21 | 7.1 | 37.0 | 1.6 | 0.0 | 29.3 | 23.5 | 15.6 | 5070 | 13.9 | 20.7 |
| 23B | 20-30 | 5.0 | | 47 | 37 | 16 | 4.9 | 23.1 | 1.5 | 0.0 | 16.6 | 5.6 | 14.2 | 4360 | 11.2 | 20.2 |
| 23C | 0-10 | 2.0 | 36.0 | 35 | 44 | 21 | 9.8 | 92.1 | 6.5 | 0.3 | 8.3 | 4.6 | 37.3 | 7330 | 13.4 | 18.3 |
| 23C | 10-20 | 2.0 | | 50 | 29 | 21 | 6.9 | 35.5 | 1.4 | 0.0 | 16.1 | 4.6 | 16.6 | 5960 | 11.5 | 23.6 |
| 23C | 20-30 | 3.0 | | 58 | 26 | 16 | 6.3 | 18.1 | 1.3 | 0.0 | 8.5 | 4.8 | 11.9 | 4730 | 13.4 | 16.4 |
| 23C | 30-36 | 8.0 | | 62 | 27 | 11 | 3.2 | 9.7 | 0.6 | 0.0 | 6.3 | 3.5 | 12.1 | 2660 | 12.2 | 15.4 |
| 24A | 0-10 | 2.0 | 39.0 | 62 | 26 | 12 | 12.3 | 47.9 | 1.4 | 0.0 | 24.7 | 5.7 | 41.9 | 7890 | 15.5 | 63.4 |
| 24A | 10-20 | 1.0 | | 30 | 53 | 17 | 10.0 | 43.8 | 3.4 | 0.0 | 24.1 | 7.1 | 21.2 | 7190 | 13.9 | 20.2 |
| 24A | 20-30 | 0.0 | | 37 | 60 | 3 | 3.0 | 11.8 | 1.3 | 0.0 | 8.5 | 3.4 | 9.6 | 2020 | 14.8 | 10.6 |
| 24A | 30-39 | 40.0 | | 76 | 21 | 3 | 4.2 | 13.3 | 0.9 | 2.6 | 9.4 | 3.5 | 18.9 | 3510 | 12.1 | 11.1 |
| 24B | 0-10 | 2.0 | 40.0 | 56 | 32 | 12 | 10.3 | 27.9 | 1.3 | 0.2 | 15.4 | 4.7 | 32.7 | 7370 | 14.0 | 49.0 |
| 24B | 10-20 | 1.0 | | 35 | 49 | 16 | 6.6 | 43.6 | 3.5 | 0.0 | 27.2 | 7.6 | 19.8 | 6600 | 10.0 | 38.0 |
| 24B | 20-30 | 0.0 | | 27 | 69 | 4 | 2.4 | 11.2 | 0.5 | 0.0 | 6.0 | 3.2 | 7.3 | 1760 | 13.5 | 13.0 |
| 24B | 30-40 | 6.0 | | 71 | 25 | 5 | 4.3 | 15.5 | 2.1 | 0.0 | 7.5 | 4.5 | 16.6 | 4850 | 8.8 | 11.6 |
| 24C | 0-10 | 2.0 | 30.0 | 66 | 33 | 1 | 9.1 | 41.2 | 0.8 | 0.0 | 18.7 | 4.2 | 37.3 | 6830 | 13.3 | 42.8 |
| 24C | 10-20 | 60.0 | | 79 | 13 | 8 | 4.3 | 32.5 | 2.3 | 28.2 | 10.5 | 3.9 | 25.3 | 3280 | 13.2 | 26.0 |
| 24C | 20-30 | 20.0 | | 68 | 31 | 1 | 5.4 | 17.9 | 1.8 | 0.9 | 9.7 | 5.0 | 15.2 | 3820 | 14.0 | 25.0 |

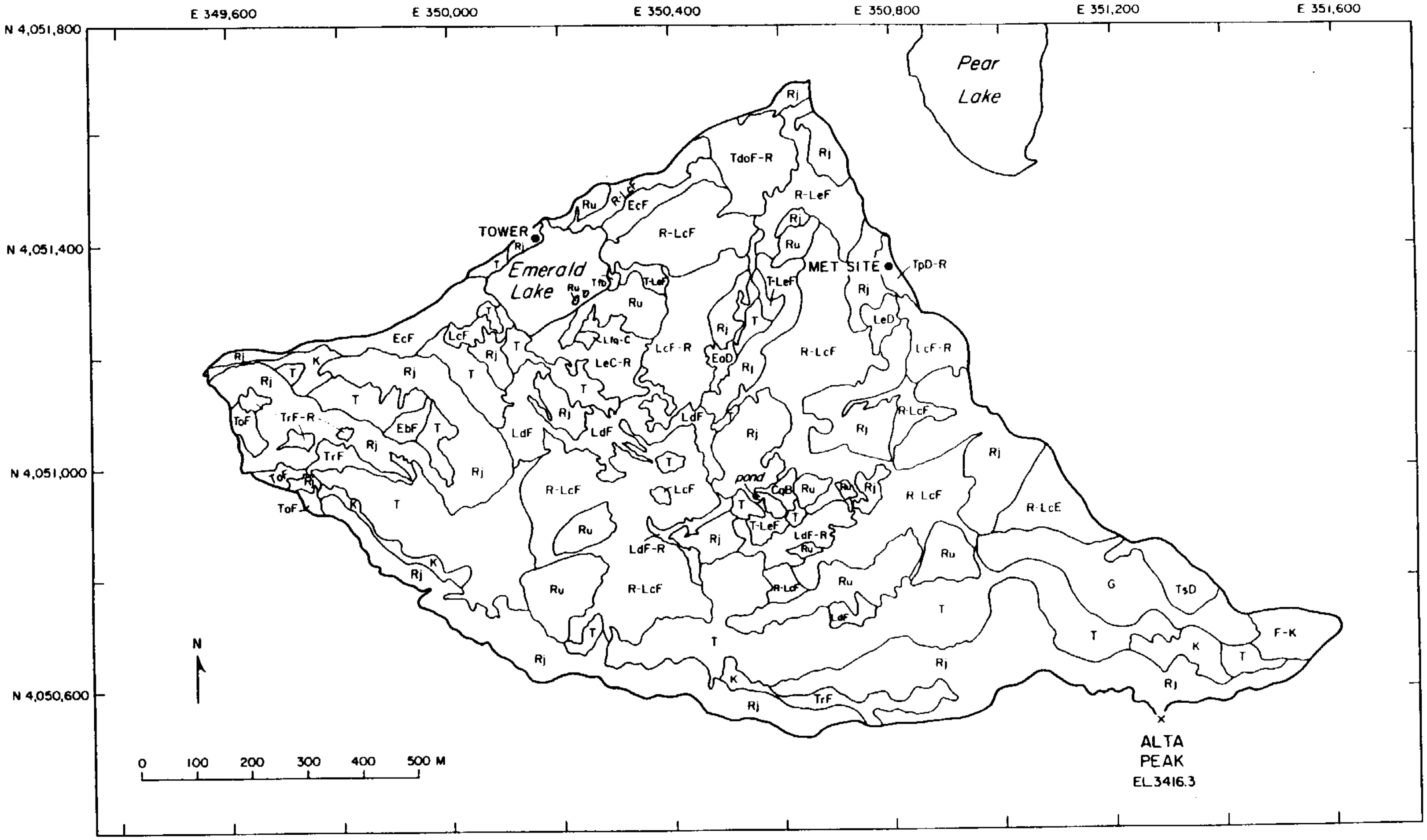

Figure 2-1. Soils of the Emerald Lake Watershed study area (redrawn from Huntington and Akeson, 1987).

# *CHAPTER 3*

# *PHYSICAL PROPERTIES OF EMERALD LAKE WATERSHED SOILS*

Physical-chemical and biological processes and properties of soils at Emerald Lake Watershed (ELW) were described intensively in earlier work (Lund et al. 1987). These processes and properties could not be scaled to the watershed level because data were not available for estimation of soil depth and volume and the relationship between soil mass and volume (bulk density). Furthermore, in order to link snowmelt/runoff models of ELW, estimates were needed of fundamental soil physical properties including soil water storage and flow rates. Temporal data on soil temperature and moisture regimes were also deemed useful for biochemical models of soil processes such as N mineralization.

Measurement of these physical properties were needed to achieve ARB objectives for three reasons. First, the capacity of ELW soils for neutralizing acidic deposition depends in a very fundamental way on the quantity of soil present. Data on soil area, volume, and bulk density are used to estimate this quantity. Second, because there is only one main "deposition" event affecting the entire watershed, namely snowmelt, the quantity of water in contact with soil and the rate of transport through soil are needed to assess the dynamics of soil/water interactions. Soil water content, moisture potential, and hydraulic conductivity provide information important for assessing the ability of ELW to respond to a single event. Third, soils are dynamic and the ability of biological processes to remove and release N may be an important mechanism for mitigation of deposition of anthropogenic N. Biological processes in soils, whether microbial decomposition or root uptake by higher plants, are dependent on soil moisture potential and temperature. The ambitious soil moisture and temperature monitoring program of this project will be valuable in quantifying the rate of these processes relative to the rates of N deposition.

## Soil Water Storage Capacity and Transport

Soil water storage is an important parameter needed to calculate the water balance for ELW. The role of soil water storage is best seen in the expression for an annual water cycle:

$$P - Et - Ro = \Delta S \qquad [3.1]$$

where P is precipitation, Et is evapotranspiration, Ro is runoff, and $\Delta S$ is the annual change in basin storage in soil as soil moisture or groundwater. Snowmelt, rainfall, and runoff have been measured for the basin for several years (Williams et al., Pers. Com., Dozier et al. 1987). The first approximation of $\Delta S = 0$ is not entirely satisfactory, for the reasons that soil is obviously present and that careful analysis of the runoff hydrograph will show that water storage is occurring.

If soil storage is an important component of the water balance for ELW, then it is important to determine the rate of snow melt water or rainfall infiltration and water percolation through soil. Saturated hydraulic conductivity is a useful estimate of potential infiltration rates when the soil is saturated. This condition compares well with soil moisture conditions during snowmelt, the major annual water event for ELW (Dozier et al., 1987).

## Soil Moisture and Temperature.

Measurements of N mineralization rates for ELW soils in 1985 showed that mineralization processes were significantly related to temperature and moisture (Lund et al., 1987). In order to use the process functions obtained in that study, temporal soil temperature and moisture content data were needed. Another critical need was a precise assessment of the dates of soil freezing and thawing. This has obvious implications for the cessation of most biological activity, an also for the hydrologic problem of determining potential for water movement into soil from snowmelt (Thorn, 1979).

## OBJECTIVES

The objectives of this portion of the study were:

1) To determine parameters that lead to an estimate of basin-wide soil water storage,
2) To estimate potential rates of water movement into and through soils, and
3) To measure variations in soil temperature and soil moisture content over at least one annual cycle.

## METHODS

### Sample Collection

Five soil map units of the ELW were selected for intensive study of the variability of physical and chemical properties. Three were sampled in 1986, primarily for analysis of chemical properties. These three plus two more were sampled for analysis of physical properties in 1987. Undisturbed soil cores were collected from all five map units in 1987 (Figure 3-1).

The sample procedure was designed to reduce bias in selecting the site and collecting the soil. Sample sites within each map unit were selected randomly from an arbitrary grid superimposed on the soil map developed in an earlier study (Huntington and Akeson, 1987). Because the sample sites were chosen in a completely random method, we can assume that the means and standard errors obtained in this study could be reproduced by any similar selection of points within the same map unit boundaries.

Soil depth at each sample site was determined by driving a 1-cm diameter metal rod into the soil until it reached a boulder or bedrock. This was repeated 3 times within a 1 m triangle of the sample site. The average of the three depths was recorded as the depth for that site.

Bulk soil samples were collected at 10 cm depth intervals for analyses of particle size distribution, saturation percentage, and chemical constituents. Samples were collected in new, clean plastic bags, carried out of the watershed and kept cool ($4^{o}C$) until they could be spread and dried on kraft paper in the UCR greenhouse. A 2-mm sieve was used to separate coarse rock fragments, which were weighed and discarded. Physical and chemical parameters determined on the sieved soil were scaled to account for the coarse fragments assuming they would have no effect other than on the mass of the sample.

Undisturbed 6 cm diameter soil cores were collected in brass cylinders using a double-cylinder, hammer-driven coring device. The brass cylinders were driven into the soil at the desired depth in a small soil pit using a specially designed hammer (Blake and Hartage, 1986). Cores of two lengths were collected at each point; 3 cm and 6 cm. The sample was checked to make sure the soil was not cracked or compressed, then the soil-filled cylinders were capped, wrapped in aluminum foil, and stored at $4^{o}C$ until used.

## Laboratory Analysis

Bulk density and soil moisture release curves were determined on 3-cm long cores. Moisture content was measured using pressure plate apparatus at three pressures between 0 and 100 kPa, and at a minimum of three pressures between 100 and 1500 kPa (Klute, 1986). These values were used to calculate a relation between soil water content and soil water potential for these soils (Campbell, 1974). The bulk density of the soil in the same soil cores was determined after drying the cores for several days at $105^{o}C$ to drive off the moisture remaining at -1500 kPa water potential (Blake and Hartage, 1986).

Saturated hydraulic conductivity was measured using 6-cm long cores (Klute and Dirksen, 1986). Field moist samples were saturated with water. A constant head of water was then applied to the top. Measurements of flux were made only after water had been flowing through the core for at least 2 hours. Flow measurements were made at 30 to 60 second intervals for 1 to 2 hours or until constant. Saturated hydraulic conductivity was calculated using Darcy's equation:

$$J_w = -K_w \, d\Psi_h/ds \qquad [3.2]$$

where $J_w$ is flux density, a measure of the quantity of water passing through a given area, $K_w$ is hydraulic conductivity, and $d\Psi_h/ds$ is the change in matric potential ($\Psi$) with distance (s), called hydraulic gradient (Hanks and Ashcroft, 1980).

## Soil Moisture and Temperature Measurements

Soil temperature and moisture profiles were monitored continuously at five sites from the fall of 1986 to spring, 1988 (Figure 3-2). Measurement points were at or near soil lysimeter sites where solar panels could augment the internal power supply of the data recorders. Three sites were maintained by UCR and two sites were maintained by cooperating ARB researchers.

Continuous data collection at one hour (temperature) and two hour (moisture) intervals was made possible through the use of durable electronic data recorders (Easy Logger; OmniData Inc., Logan, UT) similar to the equipment described by Dozier et al.(1987). These recorders were connected to standard, precalibrated, sealed thermocouple temperature probes (TP10, OmniData) and uncalibrated Colman-type fiberglass, resistivity moisture sensors (SM300, Omnidata).

The Colman moisture sensor was selected because of its durability under alternate wet/dry and freezing/thawing conditions, low salinity of the soil solution at ELW, and expected life span of several years. The properties of this class of sensors are well known and predictable, although individual calibration is necessary (Colman and Hendrix, 1949; Campbell and Gee, 1986). The moisture sensors were calibrated in the laboratory at several moisture contents using a sandy loam soil. The matric potential of the soil was determined for each water content used by the same method described for the ELW soil cores. The potential (voltage) of the sensor was measured, converted to resistance (ohms) using the conversion supplied by the manufacturer, and a log resistance versus log matric potential relation derived for each individual sensor. Potential measurements were recorded for these sensors in the field. Calculations of matric potential and water content were made after completion of the analysis of the soil moisture release data (Campbell, 1974).

## RESULTS AND DISCUSSION

### Particle Size Distribution

The five soil map units sampled contain a large proportion of coarse fragments or gravel larger than 2 mm. The Lithic Cryumbrept map unit sampled (LeC-R) in the meadow at the lake inlet has a much lower proportion of coarse fragments than any of the other map units sampled (Table 3-1). It also has a higher proportion of silt and clay compared with the other map units. This map unit has a markedly higher water holding capacity than the other soils, exceeding a saturation percentage of 100% (weight/weight) near the surface. The water holding capacity of this soil is related to the high proportion of silt and clay and high organic matter content. The two Lithic Cryumbrept map units, LeC-R in the inlet meadow and LcF-R on the ridge near the meteorological tower have strongly contrasting physical properties. The LcF-R has a higher proportion of coarse fragments and lower saturation percentage (Table 3-1). These map units are classified as Lithic Cryumbrepts on the basis of their depths and the presence of a distinct surface horizon. This illustrates that caution needs to be used in comparing map units where the taxons used are subgroups.

### Depths

The exact depths of the five map units considered cannot be inferred from the classification assigned in all cases. The Lithic Cryumbrepts (LeC-R and LcF-R) are both less than 50 cm deep, which is implied by the "Lithic" designation (Table 3-2). The Entic Cryumbrept (EaD), Typic Cryorthod-Lithic Cryorthent association (TdoF-R) and Typic Cryorthent (TsD) all also average less than 50 cm deep, although they are deeper in places (Table 3-1). In contrast to the Lithic Cryumbrepts, classification gives no indication of soil depth. On the whole, ELW soils are quite shallow. These data provide an estimate of soil depth which is based on random selection of sample sites. Soil depth is a critical parameter for many hydrologic calculations. Estimates of soil depth for unsampled map units were made based on their similarity to the intensively sampled map units. Criteria for the estimates included similarity in classification, moisture regime based on observed vegetation, and topography.

### Bulk Density

The bulk densities of soil cores collected in the five map units exhibited a general pattern of increasing bulk density with depth (Table 3-3). This is most clearly seen in the TdoF-R and LeC-R map units (Table 3-4). Both of these sites support relatively dense vegetation. The bulk densities of the LeC-R map unit were lower than the other map units. This is related to the lower proportions of coarse fragments and sand and the higher proportions of silt, clay, and organic matter (Table 3-1). Bulk density is the critical parameter for conversion of intensive physical or chemical measurements from a mass to volume basis. For example, this enables the estimation of total exchangeable cations for the basin based on laboratory measurements in units of mEq/100g (Chapter 4).

### Moisture Release Data

The energy with which a soil retains water (matric potential) is related to the water content of the soil. The relation between matric potential and soil water content (moisture release curve) is a better measure of the ability of soil to retain water than the saturation percentage, which is a measure of total pore space (Table 3-1). The volumetric water content (volume water/volume soil) data are presented in Table 3-5a through Table 3-5e as a function of matric potential.

Plant available moisture is a measure of water retention which assumes that water held between -30 kPa and -1500 kPa is roughly the water which is available for plant growth (Cassel and Nielsen, 1986). These matric potentials are defined as the potential at which water no longer drains "freely" (field capacity) and the potential at which a typical plant wilts (wilting point), respectively. Available water capacity was calculated for the intensively sampled map units (Table 3-7) and these data were used to estimate the available water for ELW soil map units (Table 3-8). The total available water for soil map units is approximately 9000 $m^3$. Inclusion of estimates for talus and colluvium, assuming these map units have properties similar to the TsD unit, increases the total estimated available water capacity to 16000 $m^3$. This estimate assumes that a fairly large quantity of fine, soil-like colluvial, alluvial, or glacial till material has been trapped in the base of the talus. Because of this, the estimates for water holding capacity for talus should be considered "high" estimates.

The available water of the LcF-R, TdoF-R, and EaD map units is distinctly less than the TsD or the LeC-R map units (Figure 3-3). The latter two map units are wet meadows because of topography and the water retention properties of the soils. It is interesting to note that the TdoF-R map unit has a relatively low available water capacity, yet supports growth of large specimens of <u>Pinus</u> <u>monticola</u>. This could have some important implications regarding the ability of this stand to regenerate following catastrophic disturbance. Although considerable available water capacity is present at higher elevations in the south half of ELW, the temperature regime, aspect, and instability of these soils may prevent growth of vegetation. Growth of <u>Salix</u> <u>orestera</u> is very dense in the LeC-R and related map units in the central portion of ELW.

Free water capacity is defined as the difference between the saturation percentage, or the maximum amount of water the soil will hold, and the field capacity of the soil. This water will flow freely from saturated soil into streams and the lake and might be considered soil or ground water storage relative to the watershed hydrologic balance. Using estimates of the depths and physical properties of ELW soil map units based on the five map units that were intensively surveyed, free water capacity in ELW basin soils is on the order of 2.9 x $10^4$ $m^3$. This is about 16% of the volume of Emerald Lake (Table 3-8). If estimates are made of the water holding capacity of talus and colluvial map units assuming properties similar to the TsD soil map unit, the total free water capacity of the watershed is 4.8 x $10^4$, about 40% of the volume of Emerald Lake. Because of the assumptions about the amount of fine material trapped in the talus, this is a "high" estimate. For comparison, the peak daily discharge from ELW during snowmelt in May 1986 was 3.6 x $10^4$ $m^3$. This implies that at the time of peak snowmelt, soil water storage could turn over almost daily. Given this high rate, in the absence of rapid soil/solution reactions one would expect the soil solution to have the same composition as snowmelt.

The storage of free water in ELW estimated by these data coincides well with hydrologic mass balance calculations of basin storage. The peak daily residual storage calculated for ELW in the 1986 water year was approximately 3 x $10^4$ (Gupta et al., 1989; Figure 10). This residual declined through the summer in a manner one would expect for drainage of soil water. Since snowmelt and soil drainage is not uniform across the watershed one would expect the peak residual storage to be less than the calculated free water capacity of the soil.

The spatial distribution of free water ($m^3/m^2$) is illustrated in Figure 3-4. From this it is apparent that water storage density is less in soil, talus, and colluvium at the higher elevations of ELW and increases in the central portion, adjacent to the streams, pond, and Emerald Lake. Using the "high" estimate of water content, the free water capacity of the talus and colluvium is potentially very significant, however, comprising more than half of the total capacity of the watershed. These data are important in determining the effect of soil water storage on the deposition/runoff relation for the ELW basin.

Saturated Hydraulic Conductivity

The maximum rate at which a soil can conduct water is measured under conditions of complete saturation of the soil pores. The saturated hydraulic conductivity may be used to derive other important transport parameters for a soil. Conductivity decreased with depth for all ELW soils (Table 3-7). The range of conductivities was on the order of 0.1 to 0.01 mm/s, which precisely fits the range expected for sandy soils (Hillel, 1980). The hydraulic conductivity of sand is the maximum found for any soil texture. Clayey soils can have conductivities as slow as $10^{-6}$ mm/s.

The high conductivity values for ELW soils are consistent with the calculations of the hydrologic response of the watershed on the order of 11 hours during the 1986 snowmelt event (Gupta, et al., 1989). Under saturated conditions and with the high conductivities of these soils, water would be expected to pass through a meter of soil in a matter of a few minutes. Since contact time is very limited, the neutralizing capacity of soils would depend only on reactions with the highest rates. Cation exchange reactions, for example, have reaction half-times on the order of a half hour (Sparks, 1989). For these conditions at ELW it is likely that these reactions would have a greater influence on solution concentrations than mineral weathering reactions, which have half-times ranging from days to years depending on the mineral (Berner, 1981).

Conductivity values may also be used as estimates of infiltration rates under saturated conditions. Infiltration is not the same as saturated hydraulic conductivity ($K_W$), however, during the spring melt, soils are saturated and water movement into soil may be well described by $K_W$. There is a very porous layer of up to about 5 cm on the surface of ELW Orthents, Umbrepts, Fluvents and Orthods which may accommodate very high infiltration rates. During July though perhaps January, unsaturated flow predominates in ELW soils. During this period it may not be appropriate to use $K_w$ as an estimate of infiltration rate.

## Temporal Variations in Soil Temperature and Moisture

The relationships between soil temperature and depth and soil moisture are approximately inversely related (Figure 3-5). This is due to the greater heat capacity of a wet soil compared with a dry soil (Hillel, 1980).

Soil temperatures were more stable at the 50 cm depth than at the soil surface. Only the cirque and ridge sites showed freezing to that depth in the 1987 water year, and not at all in the 1988 water year. The soil surface froze at all sites, but temperatures under the snow pack increased to $0^{o}C$ in the midwinter of both years. Because of the low matric potential readings of the moisture sensors (Colman and Hendrix, 1949) we know that the water in the surface layer did not become liquid until snowmelt in May. For the same reason we also know that the soil froze at the surface for brief periods in the fall at the ridge (TpD-R) and pine stand (TdoF-R) sites in 1987. Only the low elevation site at the lake inlet (LeC-R) did not freeze in the winter. The abundance of vegetation at that site and lack of vegetation at other sites is almost certainly related to depth and period of freezing of soils.

Measured matric potentials were very low when soils were dry in the summer. The decline in soil moisture potential was most dramatic in the pine stand (TdoF-R) in the summer. This may be due to topography, water extraction by the plants, and the relatively low available water capacity of the TdoF-R map unit. Conversion of matric potentials to water contents (Campbell, 1974) show that peak water contents at all sites coincided with snowmelt in May (Figure 3-6). Water contents declined during the summer. Major rainfall events in September, October and November had a distinct impact on soil moisture contents at all sites, although soil water recharge did not reach winter-spring levels in the pine stand until after the November rain/snow event. These data will be extremely valuable for extrapolating temporal variations in soil water storage for the watershed.

Based on these data we know that ELW soils are either already thawed or thaw very rapidly at the time of snowmelt. This, combined with the seasonal peak water contents, high measured hydraulic conductivities, and observations of snowmelt infiltration (Thorn, 1979) lead us to infer that ELW soils may interact extensively with snowmelt.

## CONCLUSIONS

Potential soil water storage in ELW has been calculated by extending the results of an intensive survey of soil depth, bulk density, and water potential-water content relations for five soil map units. We estimate that ELW soil, talus and colluvium map units can store up to 64000 $m^3$ of water compared with approximately 180000 $m^3$ stored in Emerald Lake. Of the 64000 $m^3$ approximately 16000 $m^3$ are retained as water available to plants and 48000 $m^3$ are able to drain freely to surface water. The last value agrees well with the residual storage calculated for the hydrologic mass balance for ELW (Gupta et al., 1989). During snowmelt, daily watershed discharge rates of 30000 $m^3$ and more imply that water stored in soils could turn over in a matter of days.

Based on hydraulic conductivity measurements of 0.1 to 0.01 mm/s, typical for sandy soils, the potential rates of flow of water through ELW soils are very high. These rates correspond well with the hydrologic response of the lake inflows to snowmelt (Gupta et al., 1989). The soil reactions which would have the most influence on soil solution and surface water would have to be the fastest reactions, such as cation exchange. Otherwise, one would expect soil solution concentrations to become similar to snowmelt within hours or days.

Variations in soil temperature and soil moisture content were measured from October 1986 through spring 1988, covering the 1987 water year. Soils froze in the fall but at some sites, the soils thawed under the snowpack. The spatial variation of freezing and water depletion has probably influenced the pattern of plant communities at ELW. Patterns of soil water depletion and recharge correspond to snowmelt and rainfall events, however, soils at different locations respond differently. Based on these temporal data seasonal freeze/thaw cycle and peak water contents, combined with high measured hydraulic conductivities, and observations of snowmelt infiltration we can conclude that soils can interact extensively with snowmelt.

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Table 3-1. Spatial variability of soil physical characteristics.

| Soil Sample | Depth | Coarse Fragments | Profile Depth | Sand | Silt | Clay | Saturation Percent |
|---|---|---|---|---|---|---|---|
| | cm | % | cm | ----------%--------- | | | |
| | | | Entic Cryumbrept (EaD) Bench Meadow | | | | |
| 1A | 0-10 | 12.0 | 55.0 | 43 | 53 | 5 | 100.0% |
| 1A | 10-20 | 31.0 | | 62 | 37 | 1 | 45.2% |
| 1A | 20-30 | 46.0 | | 83 | 17 | 0 | 30.0% |
| 1A | 30-40 | 43.0 | | 85 | 14 | 1 | 30.0% |
| 1A | 40-50 | 64.0 | | 87 | 12 | 1 | 32.4% |
| 1A | 50-57 | 61.0 | | 82 | 18 | 0 | 28.4% |
| 1B | 0-10 | 25.0 | 66.0 | 47 | 49 | 4 | 79.6% |
| 1B | 10-20 | 49.0 | | 68 | 31 | 1 | 40.4% |
| 1C | 0-10 | 19.0 | 85.0 | 39 | 57 | 4 | 82.4% |
| 1C | 10-20 | 56.0 | | 73 | 27 | 0 | 42.8% |
| 1C | 20-30 | 57.0 | | 84 | 13 | 3 | 29.6% |
| 1C | 30-40 | 38.0 | | 87 | 10 | 3 | 31.6% |
| 1C | 40-50 | 49.0 | | 86 | 12 | 2 | 30.2% |
| 1C | 50-60 | 51.0 | | 87 | 11 | 2 | 30.6% |
| 1C | 60-70 | 55.0 | | 90 | 9 | 1 | 26.2% |
| 2A | 0-10 | 48.0 | 34.5 | 77 | 18 | 5 | 92.4% |
| 2A | 10-20 | 54.0 | | 84 | 14 | 2 | 40.0% |
| 2A | 20-30 | 36.0 | | 68 | 30 | 2 | 39.6% |
| 2A | 30-35 | 44.0 | | 85 | 14 | 1 | 37.6% |
| 2B | 0-10 | 37.0 | 30.5 | 72 | 23 | 5 | 100.0% |
| 2B | 10-20 | 34.0 | | 69 | 26 | 5 | 56.0% |
| 2B | 20-28 | 41.0 | | 68 | 29 | 3 | 38.8% |
| 2C | 0-10 | 46.0 | 25.5 | 75 | 20 | 5 | 78.4% |
| 2C | 10-20 | 52.0 | | 68 | 29 | 3 | 52.8% |
| 2C | 20-30 | 36.0 | | 68 | 31 | 1 | 42.0% |
| 2C | 30-38 | 45.0 | | 86 | 10 | 4 | 35.0% |
| 3A | 0-10 | 47.0 | 21.0 | 69 | 26 | 5 | 46.0% |
| 3A | 10-20 | 48.0 | | 60 | 33 | 7 | 46.4% |
| 3A | 20-22 | 47.0 | | 61 | 32 | 7 | 49.2% |
| 3B | 0-10 | 58.0 | 22.0 | 67 | 28 | 5 | 53.2% |
| 3B | 10-17 | 50.0 | | 53 | 43 | 4 | 53.6% |
| 3C | 0-10 | 44.0 | 10.0 | 65 | 30 | 5 | 53.6% |
| 4A | 0-10 | 41.0 | 38.0 | 62 | 36 | 2 | 62.4% |
| 4A | 10-20 | 44.0 | | 66 | 33 | 1 | 45.2% |
| 4A | 20-30 | 22.0 | | 56 | 42 | 1 | 52.4% |
| 4A | 30-36 | 38.0 | | 75 | 24 | 1 | 35.6% |
| 4B | 0-10 | 35.0 | 33.0 | 67 | 30 | 3 | 74.6% |
| 4B | 10-20 | 38.0 | | 71 | 29 | 0 | 47.6% |
| 4B | 20-30 | 29.0 | | 60 | 39 | 1 | 47.6% |
| 4B | 30-40 | 34.0 | | 65 | 35 | 0 | 40.0% |
| 4C | 0-10 | 46.0 | 27.0 | 65 | 32 | 3 | 74.8% |
| 4C | 10-20 | 24.0 | | 56 | 40 | 4 | 48.8% |
| 4C | 20-29 | 25.0 | | 63 | 35 | 2 | 46.4% |

Table 3-1. (cont.)

| Soil Sample | Depth | Coarse Fragments | Profile Depth | Sand | Silt | Clay | Saturation Percent |
|---|---|---|---|---|---|---|---|
| | cm | % | cm | | ----------%--------- | | |
| | | Cryorthod Association (TdoF-R) Pimo Stand | | | | | |
| 11A | 0-10 | 36.0 | 24.5 | 75 | 29 | 6 | 44.8% |
| 11A | 10-20 | 50.0 | | 81 | 14 | 5 | 36.4% |
| 11A | 20-28 | 44.0 | | 78 | 20 | 2 | 36.8% |
| 11B | 0-10 | 50.0 | 18.0 | 78 | 17 | 5 | 39.2% |
| 11B | 10-18 | 45.0 | | 83 | 14 | 3 | 35.6% |
| 11C | 0-10 | 38.0 | 50.5 | 77 | 16 | 7 | 40.4% |
| 11C | 10-20 | 42.0 | | 83 | 15 | 2 | 36.4% |
| 11C | 20-30 | 49.0 | | 82 | 16 | 2 | 34.0% |
| 11C | 30-40 | 52.0 | | 86 | 13 | 1 | 34.8% |
| 11C | 40-47 | 58.0 | | 83 | 16 | 1 | 33.2% |
| 12A | 0-10 | 42.0 | 20.5 | 69 | 24 | 7 | 32.8% |
| 12A | 10-20 | 42.0 | | 75 | 24 | 1 | 31.6% |
| 12B | 0-10 | 41.0 | 17.0 | 77 | 19 | 4 | 35.6% |
| 12B | 10-20 | 46.0 | | 76 | 21 | 3 | 36.0% |
| 12C | 0-10 | 44.0 | 14.0 | 81 | 15 | 4 | 38.8% |
| 12C | 10-14 | 41.0 | | 70 | 24 | 6 | 38.0% |
| 13A | 0-10 | 31.0 | 18.5 | 72 | 22 | 6 | 41.6% |
| 13A | 10-18 | 37.0 | | 70 | 23 | 7 | 36.0% |
| 13B | 0-10 | 38.0 | 24.5 | 71 | 24 | 5 | 42.0% |
| 13B | 10-20 | 34.0 | | 69 | 28 | 3 | 38.0% |
| 13B | 20-24 | 63.0 | | 76 | 18 | 6 | 34.8% |
| 13C | 0-10 | 20.0 | 28.5 | 67 | 22 | 11 | 62.8% |
| 13C | 10-20 | 41.0 | | 74 | 18 | 8 | 41.6% |
| 13C | 20-25 | 32.0 | | 75 | 17 | 8 | 42.4% |
| 14A | 0-10 | 40.0 | 35.0 | 72 | 23 | 5 | 33.2% |
| 14A | 10-20 | 41.0 | | 77 | 19 | 4 | 34.0% |
| 14A | 20-25 | 41.0 | | 78 | 19 | 3 | 34.8% |
| 14B | 0-10 | 39.0 | 24.0 | 75 | 20 | 5 | 33.2% |
| 14B | 10-20 | 39.0 | | 78 | 18 | 4 | 32.8% |
| 14B | 20-25 | 40.0 | | 76 | 20 | 4 | 31.6% |
| 14C | 0-10 | 34.0 | 25.5 | 76 | 19 | 5 | 30.8% |
| 14C | 10-20 | 38.0 | | 78 | 17 | 5 | 31.2% |
| 14C | 20-22 | 60.0 | | 81 | 16 | 3 | 32.8% |
| 51 | | | 44.3 | | | | |
| 52 | | | 30.4 | | | | |
| 53 | | | 52.8 | | | | |
| 54 | | | 34.6 | | | | |
| 55 | | | 76.3 | | | | |
| 56 | | | 48.2 | | | | |

Table 3-1. (cont.)

| Soil Sample | Depth | Coarse Fragments | Profile Depth | Sand | Silt | Clay | Saturation Percent |
|---|---|---|---|---|---|---|---|
| | cm | % | cm | ---------- | % | --------- | |
| | | Lithic | Cryumbrept | (LeC-R) | Inlet | Meadow | |
| 21A | 0-10 | 4.0 | 18.0 | 36 | 44 | 20 | 119.6% |
| 21A | 10-18 | 20.0 | | 63 | 28 | 9 | 60.4% |
| 21B | 0-10 | 0.0 | 17.0 | 46 | 36 | 18 | 117.2% |
| 21B | 10-17 | 7.0 | | 33 | 54 | 13 | 75.6% |
| 21C | 0-10 | 5.0 | 15.5 | 40 | 40 | 20 | 150.6% |
| 21C | 10-14 | 6.0 | | 37 | 49 | 14 | 82.2% |
| 22A | 0-10 | 41.0 | 22.0 | 73 | 13 | 14 | 90.0% |
| 22A | 10-20 | 9.0 | | 42 | 37 | 21 | 75.6% |
| 22A | 20-24 | 8.0 | | 53 | 29 | 18 | 69.2% |
| 22B | 0-10 | 31.0 | 30.0 | 57 | 25 | 18 | 73.6% |
| 22B | 10-20 | 15.0 | | 43 | 37 | 20 | 81.2% |
| 22B | 20-30 | 21.0 | | 55 | 32 | 13 | 60.0% |
| 22C | 0-10 | 49.0 | 21.0 | 65 | 24 | 11 | 59.8% |
| 22C | 10-20 | 19.0 | | 53 | 35 | 12 | 101.2% |
| 23A | 0-10 | 3.0 | 31.0 | 35 | 42 | 23 | |
| 23A | 10-20 | 30.0 | | 57 | 26 | 17 | 58.0% |
| 23A | 20-30 | 6.0 | | 57 | 28 | 15 | 64.4% |
| 23B | 0-10 | 5.0 | 32.0 | 34 | 40 | 26 | |
| 23B | 10-20 | 7.0 | | 47 | 32 | 21 | 75.8% |
| 23B | 20-30 | 5.0 | | 47 | 37 | 16 | 60.4% |
| 23C | 0-10 | 2.0 | 36.0 | 35 | 44 | 21 | 128.6% |
| 23C | 10-20 | 2.0 | | 50 | 29 | 21 | 77.6% |
| 23C | 20-30 | 3.0 | | 58 | 26 | 16 | 60.4% |
| 23C | 30-36 | 8.0 | | 62 | 27 | 11 | 44.8% |
| 24A | 0-10 | 2.0 | 39.0 | 62 | 26 | 12 | |
| 24A | 10-20 | 1.0 | | 30 | 53 | 17 | 110.8% |
| 24A | 20-30 | 0.0 | | 37 | 60 | 3 | 68.0% |
| 24A | 30-39 | 40.0 | | 76 | 21 | 3 | 51.2% |
| 24B | 0-10 | 2.0 | 40.0 | 56 | 32 | 12 | 109.6% |
| 24B | 10-20 | 1.0 | | 35 | 49 | 16 | 103.0% |
| 24B | 20-30 | 0.0 | | 27 | 69 | 4 | 66.0% |
| 24B | 30-40 | 6.0 | | 71 | 25 | 5 | 63.2% |
| 24C | 0-10 | 2.0 | 30.0 | 66 | 33 | 1 | 104.4% |
| 24C | 10-20 | 60.0 | | 79 | 13 | 8 | 56.4% |
| 24C | 20-30 | 20.0 | | 68 | 31 | 1 | 53.6% |

Table 3-1. (cont.)

| Soil Sample | Depth | Coarse Fragments | Profile Depth | Sand | Silt | Clay | Saturation Percent |
|---|---|---|---|---|---|---|---|
| | cm | % | cm | | % | | |
| | | | Lithic Cryumbrept (LcF-R) Ridge | | | | |
| 411 | 0-10 | 49.5% | 39.0 | | | | 36.0% |
| 412 | 10-20 | 46.2% | | | | | 29.2% |
| 413 | 20-30 | 42.3% | | | | | 30.8% |
| 414 | 30-40 | 43.3% | | | | | 26.0% |
| 421 | 0-10 | 43.3% | 34.0 | | | | 36.8% |
| 422 | 10-20 | 41.3% | | | | | 34.0% |
| 423 | 20-30 | 51.3% | | | | | 32.4% |
| 424 | 30-40 | 60.1% | | | | | 30.0% |
| 431 | 0-10 | 46.5% | 28.0 | | | | 34.8% |
| 432 | 10-20 | 42.1% | | | | | 34.8% |
| 433 | 20-30 | 53.7% | | | | | 30.4% |
| | | | Typic Cryorthent (TsD) Alta Cirque | | | | |
| 811 | 0-10 | 47.0% | 29.1 | | | | 63.2% |
| 812 | 10-20 | 23.4% | | | | | 58.4% |
| 813 | 20-30 | 40.7% | | | | | 60.8% |
| 821 | 0-10 | 48.8% | 22.0 | | | | 34.8% |
| 823 | 20-30 | 56.9% | | | | | 32.4% |
| 831 | 0-10 | 41.3% | 17.5 | | | | 27.2% |
| 832 | 10-20 | 49.4% | | | | | 27.2% |
| 841 | 0-15 | 25.1% | 31.1 | | | | 58.4% |
| 842 | 15-30 | 45.1% | | | | | 39.2% |

Table 3-2. Mean depths of soil map units in ELW.

| Map Unit | Sample Series | Mean Depth | SE | Number of Sites |
|---|---|---|---|---|
| | | m | m | |
| EaD | 0,6 | 0.373 | 0.059 | 12 |
| LcF-R | 4 | 0.337 | 0.026 | 3 |
| LeC-R | 2,7 | 0.237 | 0.033 | 14 |
| TdoF-R | 1,5 | 0.326 | 0.037 | 18 |
| TsD | 8 | 0.249 | 0.027 | 4 |

Table 3-3. Bulk densities for ELW soils.

| Core Site | Bulk Density | | | | |
|---|---|---|---|---|---|
| | g/cm$^3$ | | | | |
| Depth (cm) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Entic Cryumbrept (EaD) Bench Meadow | | | | | |
| 6-1 | 1.31 | 1.64 | 1.38 | 1.71 | |
| 6-2 | 0.76 | 1.12 | 1.17 | 0.87 | 0.97 |
| 6-3 | 1.06 | 1.24 | 1.35 | 1.42 | 1.68 |
| 6-4 | 1.91 | 1.64 | 1.76 | 1.75 | |
| 6-5 | 1.12 | 1.35 | 1.13 | 1.37 | |
| Typic Cryorthent (TsD) Alta Cirque | | | | | |
| 8-1 | 1.16 | 1.30 | | | |
| 8-2 | 1.45 | 1.69 | 1.72 | | |
| 8-3 | 1.26 | 1.32 | | | |
| 8-4 | 1.33 | 1.55 | | | |
| 8-5 | 1.01 | 0.71 | 0.82 | 0.75 | 0.81 |
| Lithic Cryumbrept (LeC-R) Inlet Meadow | | | | | |
| 7-1 | 0.72 | 0.96 | | | |
| 7-2 | 0.95 | 0.96 | 1.45 | 1.47 | |
| 7-3 | 0.64 | | | | |
| 7-4 | 1.00 | 0.99 | | | |
| Typic Cryorthod-Lithic Cryorthent (TdoF-R) Pimo Stand | | | | | |
| 5-1 | 1.41 | 1.35 | 1.43 | | |
| 5-2 | 1.35 | 1.41 | 1.37 | | |
| 5-3 | 1.39 | 1.24 | 1.41 | 1.44 | |
| 5-4 | 0.79 | 1.14 | 1.45 | 1.49 | |
| 5-5 | 1.41 | 1.40 | 1.37 | 1.53 | |
| 5-6 | 1.23 | 1.40 | 1.34 | 1.19 | 1.42 |
| Lithic Cryumbrept (LcF-R) Ridge | | | | | |
| 4-1 | 1.43 | 1.26 | 1.61 | | |
| 4-2 | 1.33 | 1.25 | 1.30 | | |
| 4-3 | | 1.35 | 1.72 | | |
| 4-4 | 1.61 | 1.34 | | | |
| 4-5 | 1.67 | 1.23 | 1.11 | 1.38 | 1.43 |

Table 3-4. Soil bulk density by layer.

| | Soil/Vegetation Subunits | | |
|---|---|---|---|
| | Pimo | Salix | Wet Meadow |
| Map Unit: | TdoF-R | LeC-R | EaD |
| Depth | Bulk Density | | |
| cm | ---------$\mathrm{Mg/m^3}$--------- | | |
| 0-10 | 1.26 | 0.83 | 1.23 |
| | 0.09 | 0.08 | 0.17 |
| 10-20 | 1.32 | 0.97 | 1.40 |
| | 0.04 | 0.01 | 0.09 |
| 20-30 | 1.39 | 1.45 | 1.36 |
| | 0.01 | | 0.10 |
| 30-40 | 1.41 | 1.47 | 1.42 |
| | 0.07 | | 0.14 |
| 40-50 | 1.42 | | 1.32 |
| | | | 0.25 |

Table 3-5a. Moisture release data for Entic Cryumbrept (EaD) map unit ELW bench meadow.

| | Matric Potential | Volumetric Water Content | | | | |
|---|---|---|---|---|---|---|
| | kPa | $m^3/m^3$ | | | | |
| Depth (cm) | | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Site 1 | -30 | 0.186 | 0.153 | 0.194 | 0.115 | |
| | -60 | 0.155 | 0.129 | 0.164 | 0.105 | |
| | -90 | 0.154 | 0.114 | 0.148 | 0.091 | |
| | -300 | 0.091 | 0.084 | 0.090 | 0.037 | |
| | -900 | 0.068 | 0.062 | 0.065 | 0.038 | |
| | -1500 | 0.062 | 0.056 | 0.059 | 0.037 | |
| Site 2 | -30 | 0.466 | 0.275 | 0.257 | 0.363 | 0.398 |
| | -60 | 0.425 | 0.246 | 0.231 | 0.333 | 0.383 |
| | -90 | 0.401 | 0.227 | 0.212 | 0.312 | 0.361 |
| | -300 | 0.272 | 0.165 | 0.141 | 0.215 | 0.284 |
| | -900 | 0.214 | 0.134 | 0.117 | 0.176 | 0.180 |
| | -1500 | 0.199 | 0.125 | 0.110 | 0.163 | 0.175 |
| Site 3 | -30 | 0.203 | 0.204 | 0.230 | 0.161 | 0.135 |
| | -60 | 0.179 | 0.172 | 0.205 | 0.144 | 0.096 |
| | -90 | 0.161 | 0.166 | 0.203 | 0.134 | 0.086 |
| | -300 | 0.110 | 0.099 | 0.141 | 0.103 | 0.062 |
| | -900 | 0.083 | 0.075 | 0.116 | 0.084 | 0.034 |
| | -1500 | 0.075 | 0.068 | 0.107 | 0.079 | 0.031 |
| Site 4 | -30 | 0.056 | 0.047 | 0.044 | 0.057 | |
| | -60 | 0.047 | 0.041 | 0.040 | 0.054 | |
| | -90 | 0.041 | 0.036 | 0.035 | 0.047 | |
| | -300 | 0.031 | 0.029 | 0.029 | 0.032 | |
| | -900 | 0.020 | 0.023 | 0.023 | 0.021 | |
| | -1500 | 0.018 | 0.020 | 0.020 | 0.020 | |
| Site 5 | -30 | 0.201 | 0.153 | 0.236 | 0.206 | |
| | -60 | 0.181 | 0.139 | 0.220 | 0.185 | |
| | -90 | 0.091 | 0.082 | 0.148 | 0.126 | |
| | -300 | 0.066 | 0.061 | 0.105 | 0.091 | |
| | -900 | 0.060 | 0.057 | 0.097 | 0.084 | |
| | -1500 | 0.059 | 0.056 | 0.094 | 0.082 | |

Table 3-5b. Moisture release data for "Typic Cryorthod" and Lithic Cryorthent (TdoF-R) association map unit, ELW Pinus monticola stand.

| | Matric Potential | Volumetric Water Content | | | | |
|---|---|---|---|---|---|---|
| | kPa | $m^3/m^3$ | | | | |
| Depth (cm) | | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Site 1 | -30 | 0.109 | 0.108 | 0.118 | | |
| | -70 | 0.109 | 0.095 | 0.105 | | |
| | -90 | 0.104 | 0.082 | 0.092 | | |
| | -200 | ND | 0.069 | 0.078 | | |
| | -300 | 0.086 | 0.060 | 0.071 | | |
| | -400 | 0.061 | ND | ND | | |
| | -900 | 0.055 | 0.044 | 0.056 | | |
| | -1500 | 0.048 | 0.043 | 0.049 | | |
| Site 2 | -50 | 0.087 | 0.074 | 0.096 | | |
| | -70 | 0.092 | 0.090 | 0.091 | | |
| | -90 | 0.091 | 0.086 | 0.087 | | |
| | -300 | 0.074 | 0.074 | 0.075 | | |
| | -400 | 0.070 | 0.063 | 0.064 | | |
| | -900 | 0.051 | 0.062 | 0.071 | | |
| | -1500 | 0.050 | 0.068 | 0.068 | | |
| Site 3 | -50 | 0.121 | 0.105 | 0.091 | 0.085 | |
| | -70 | 0.117 | 0.100 | 0.088 | 0.085 | |
| | -90 | 0.110 | 0.095 | 0.084 | 0.080 | |
| | -300 | 0.091 | 0.080 | 0.069 | 0.066 | |
| | -400 | 0.071 | 0.067 | 0.060 | 0.057 | |
| | -900 | 0.059 | 0.056 | 0.058 | 0.086 | |
| | -1500 | 0.066 | 0.050 | 0.049 | 0.063 | |
| Site 4 | -30 | 0.176 | 0.126 | 0.109 | 0.110 | |
| | -60 | 0.173 | 0.114 | 0.097 | 0.100 | |
| | -90 | 0.160 | 0.116 | 0.090 | 0.088 | |
| | -300 | 0.124 | 0.071 | 0.065 | 0.066 | |
| | -900 | 0.092 | 0.049 | 0.048 | 0.046 | |
| | -1500 | 0.084 | 0.043 | 0.042 | 0.043 | |
| Site 5 | -30 | 0.123 | 0.119 | 0.125 | 0.110 | |
| | -60 | 0.108 | 0.102 | 0.110 | 0.099 | |
| | -90 | 0.106 | 0.098 | 0.104 | 0.085 | |
| | -300 | 0.065 | 0.064 | 0.075 | 0.061 | |
| | -900 | 0.046 | 0.057 | 0.067 | 0.048 | |
| | -1500 | 0.040 | 0.051 | 0.059 | 0.046 | |
| Site 6 | -30 | 0.136 | 0.132 | 0.140 | 0.113 | 0.116 |
| | -60 | 0.121 | 0.117 | 0.122 | 0.102 | 0.106 |
| | -90 | 0.119 | 0.107 | 0.126 | 0.100 | 0.100 |
| | -300 | 0.076 | 0.080 | 0.070 | 0.067 | 0.069 |
| | -900 | 0.058 | 0.068 | 0.057 | 0.055 | 0.056 |
| | -1500 | 0.049 | 0.062 | 0.049 | 0.049 | 0.051 |

Table 3-5c. Moisture release data for Lithic Cryumbrept (LeC-R) map unit, ELW inlet meadow.

| | Matric Potential | Volumetric Water Content | | | |
|---|---|---|---|---|---|
| | kPa | $m^3/m^3$ | | | |
| Depth (cm) | | 0-10 | 10-20 | 20-30 | 30-40 |
| Site 1 | -30 | 0.497 | 0.428 | | |
| | -60 | 0.471 | 0.408 | | |
| | -90 | 0.385 | 0.275 | | |
| | -300 | 0.247 | 0.194 | | |
| | -900 | 0.226 | 0.180 | | |
| | -1500 | 0.213 | 0.171 | | |
| Site 2 | -30 | 0.230 | 0.225 | 0.181 | 0.159 |
| | -60 | 0.215 | 0.209 | 0.164 | 0.137 |
| | -90 | 0.164 | 0.137 | 0.100 | 0.090 |
| | -300 | 0.108 | 0.092 | 0.073 | 0.071 |
| | -900 | 0.096 | 0.085 | 0.066 | 0.064 |
| | -1500 | 0.090 | 0.081 | 0.063 | 0.060 |
| Site 3 | -30 | 0.560 | | | |
| | -60 | 0.470 | | | |
| | -90 | 0.435 | | | |
| | -300 | 0.337 | | | |
| | -900 | 0.332 | | | |
| | -1500 | 0.286 | | | |
| Site 4 | -30 | 0.284 | 0.439 | | |
| | -60 | 0.234 | 0.366 | | |
| | -90 | 0.210 | 0.332 | | |
| | -300 | 0.168 | 0.242 | | |
| | -900 | 0.148 | 0.218 | | |
| | -1500 | 0.126 | 0.184 | | |

Table 3-5d. Moisture release data for Lithic Cryumbrept (LcF-R) map unit, ELW east ridge, near met station.

| | Matric Potential | Volumetric Water Content | | | | |
|---|---|---|---|---|---|---|
| | kPa | $m^3/m^3$ | | | | |
| Depth (cm) | | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Site 1 | -30 | 0.168 | 0.185 | 0.150 | | |
| | -70 | 0.152 | 0.159 | 0.131 | | |
| | -90 | 0.143 | 0.147 | 0.120 | | |
| | -200 | 0.130 | 0.123 | 0.098 | | |
| | -300 | 0.119 | 0.111 | 0.087 | | |
| | -900 | 0.095 | 0.085 | 0.064 | | |
| | -1500 | 0.083 | 0.073 | 0.053 | | |
| Site 2 | -50 | 0.105 | 0.091 | 0.084 | | |
| | -70 | 0.099 | 0.089 | 0.081 | | |
| | -90 | 0.095 | 0.086 | 0.078 | | |
| | -300 | 0.083 | 0.074 | 0.062 | | |
| | -400 | 0.068 | 0.066 | 0.054 | | |
| | -900 | 0.068 | 0.068 | 0.067 | | |
| | -1500 | 0.059 | 0.080 | 0.056 | | |
| Site 3 | -30 | ND | 0.149 | ND | | |
| | -50 | ND | ND | 0.124 | | |
| | -70 | ND | 0.137 | 0.123 | | |
| | -90 | ND | 0.122 | 0.117 | | |
| | -200 | ND | 0.107 | ND | | |
| | -300 | ND | 0.099 | 0.092 | | |
| | -400 | ND | ND | 0.082 | | |
| | -900 | ND | 0.078 | 0.072 | | |
| | -1500 | ND | 0.071 | 0.074 | | |
| Site 4 | -30 | 0.132 | 0.153 | 0.142 | 0.133 | 0.121 |
| | -70 | 0.131 | 0.146 | 0.132 | 0.120 | 0.108 |
| | -90 | 0.115 | 0.130 | 0.120 | 0.110 | 0.098 |
| | -200 | 0.107 | 0.118 | 0.108 | 0.090 | 0.084 |
| | -300 | 0.096 | 0.107 | 0.096 | 0.080 | 0.076 |
| | -900 | 0.077 | 0.103 | 0.074 | 0.065 | 0.061 |
| | -1500 | 0.072 | 0.090 | 0.066 | 0.057 | 0.053 |
| Site 5 | -30 | 0.115 | 0.147 | | | |
| | -60 | 0.082 | 0.114 | | | |
| | -90 | 0.074 | 0.100 | | | |
| | -300 | 0.055 | 0.068 | | | |
| | -1500 | 0.053 | 0.063 | | | |

Table 3-5e. Moisture release data for Typic Cryorthent (TsD) map unit, ELW Alta Cirque.

| | Matric Potential | Volumetric Water Content | | | | |
|---|---|---|---|---|---|---|
| | kPa | $m^3/m^3$ | | | | |
| Depth (cm) | | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Site 1 | -30 | 0.172 | 0.122 | | | |
| | -60 | 0.132 | 0.090 | | | |
| | -90 | 0.111 | 0.074 | | | |
| | -300 | 0.098 | 0.069 | | | |
| | -900 | 0.118 | 0.059 | | | |
| | -1500 | 0.087 | 0.050 | | | |
| Site 2 | -30 | 0.126 | 0.125 | 0.123 | | |
| | -60 | 0.093 | 0.095 | 0.096 | | |
| | -90 | 0.081 | 0.083 | 0.085 | | |
| | -300 | 0.083 | 0.088 | 0.086 | | |
| | -900 | 0.070 | 0.085 | 0.138 | | |
| | -1500 | 0.063 | 0.071 | 0.071 | | |
| Site 3 | -30 | 0.103 | 0.150 | | | |
| | -60 | 0.066 | 0.107 | | | |
| | -90 | 0.051 | 0.089 | | | |
| | -300 | 0.050 | 0.080 | | | |
| | -900 | 0.136 | 0.146 | | | |
| | -1500 | 0.039 | 0.072 | | | |
| Site 4 | -30 | 0.263 | 0.304 | | | |
| | -60 | 0.217 | 0.268 | | | |
| | -90 | 0.196 | 0.254 | | | |
| | -300 | 0.115 | 0.177 | | | |
| | -900 | 0.106 | 0.269 | | | |
| | -1500 | 0.086 | 0.185 | | | |
| Site 5 | -30 | 0.163 | 0.558 | 0.424 | 0.445 | 0.406 |
| | -60 | 0.151 | 0.533 | 0.403 | 0.423 | 0.393 |
| | -90 | 0.158 | 0.500 | 0.365 | 0.389 | 0.356 |
| | -300 | 0.110 | 0.365 | 0.230 | 0.295 | 0.219 |
| | -900 | 0.094 | 0.298 | 0.142 | 0.200 | 0.163 |
| | -1500 | 0.084 | 0.287 | 0.138 | 0.192 | 0.155 |

Table 3-6. Available moisture in ELW soils.

| Core Site | Available Moisture | | | | |
|---|---|---|---|---|---|
| | | | $m^3/m^3$ | | |
| Depth (cm) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Entic Cryumbrept (EaD) Bench Meadow | | | | | |
| Site 1 | 0.125 | 0.097 | 0.136 | 0.078 | |
| Site 2 | 0.267 | 0.151 | 0.146 | 0.201 | 0.222 |
| Site 3 | 0.128 | 0.136 | 0.123 | 0.083 | 0.104 |
| Site 4 | 0.038 | 0.027 | 0.024 | 0.037 | |
| Site 5 | 0.143 | 0.097 | 0.142 | 0.124 | |
| Typic Cryorthod-Lithic Cryorthent (TdoF-R) Pine Stand | | | | | |
| Site 1 | 0.060 | 0.066 | 0.069 | | |
| Site 2 | 0.037 | 0.007 | 0.029 | | estim. |
| Site 3 | 0.055 | 0.054 | 0.041 | 0.022 | estim. |
| Site 4 | 0.092 | 0.084 | 0.066 | 0.068 | |
| Site 5 | 0.083 | 0.068 | 0.066 | 0.064 | |
| Site 6 | 0.086 | 0.070 | 0.091 | 0.063 | 0.065 |
| Lithic Cryumbrept (LeC-R) Inlet Meadow | | | | | |
| Site 1 | 0.284 | 0.257 | | | |
| Site 2 | 0.140 | 0.143 | 0.118 | 0.099 | |
| Site 3 | 0.274 | | | | |
| Site 4 | 0.159 | 0.255 | | | |
| Lithic Cryumbrept (LcF-R) Ridge | | | | | |
| Site 1 | 0.085 | 0.112 | 0.097 | | |
| Site 2 | 0.046 | 0.011 | 0.029 | estimate | |
| Site 3 | | 0.078 | 0.050 | #2 is est. | |
| Site 4 | 0.061 | 0.062 | 0.076 | 0.077 | 0.068 |
| Site 5 | 0.063 | 0.084 | | | |
| Typic Cryorthent (TsD) Alta Cirque | | | | | |
| Site 1 | 0.085 | 0.072 | | | |
| Site 2 | 0.063 | 0.054 | 0.053 | | |
| Site 3 | 0.064 | 0.077 | | | |
| Site 4 | 0.177 | 0.118 | | | |
| Site 5 | 0.079 | 0.271 | 0.286 | 0.253 | 0.251 |

Table 3-7. Mean saturated hydraulic conductivities for soil cores from ELW.

| | Hydraulic Conductivity | | | | |
|---|---|---|---|---|---|
| | mm/s | | | | |
| Depth (cm) | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 |
| Entic Cryumbrept (EaD) Bench Meadow | | | | | |
| Site 1 | 0.0392 | 0.0113 | 0.0362 | 0.0255 | |
| Site 2 | 0.0357 | 0.0143 | 0.0168 | 0.0077 | 0.0193 |
| Site 3 | 0.0394 | 0.0561 | 0.0272 | 0.0124 | 0.0615 |
| Site 4 | 0.5751 | 0.0633 | 0.1256 | 0.7120 | |
| Site 5 | 0.0254 | 0.0267 | 0.0246 | 0.0258 | |
| Typic Cryorthod-Lithic Cryorthent (TdoF-R) Pine Stand | | | | | |
| Site 1 | 0.0846 | 0.0806 | 0.1397 | 0.1069 | |
| Site 2 | 0.0830 | 0.1813 | 0.1433 | | |
| Site 3 | 0.0981 | 0.0740 | 0.1621 | 0.1674 | |
| Site 4 | 0.1116 | 0.1219 | 0.1060 | 0.1002 | |
| Site 5 | 0.1233 | 0.1009 | 0.0684 | 0.0783 | |
| Site 6 | 0.0985 | 0.1200 | 0.0833 | 0.0552 | 0.0649 |
| Lithic Cryumbrept (LeC-R) Inlet Meadow | | | | | |
| Site 1 | 0.1389 | 0.0095 | | | |
| Site 2 | 0.0378 | 0.0643 | 0.0393 | | |
| Site 3 | 0.0066 | | | | |
| Site 4 | 0.0294 | 0.0043 | | | |
| Lithic Cryumbrept (LcF-R) Ridge | | | | | |
| Site 1 | 0.0624 | 0.0873 | 0.0574 | | |
| Site 2 | 0.0918 | 0.0839 | 0.0568 | | |
| Site 3 | 0.0691 | 0.0410 | 0.0788 | | |
| Site 4 | 0.0426 | 0.0229 | 0.0111 | | |
| Site 5 | 0.0333 | 0.0826 | 0.0366 | 0.0711 | |
| Typic Cryorthent (TsD) Alta Cirque | | | | | |
| Site 1 | 0.0207 | 0.0247 | | | |
| Site 2 | 0.0072 | 0.0110 | | | |
| Site 3 | 0.0028 | 0.0172 | | | |
| Site 4 | 0.3357 | 0.0139 | | | |
| Site 5 | 0.0049 | 0.0013 | 0.0007 | 0.0052 | |

Table 3-8. Estimates of water storage by map unit at ELW.

| Map Unit | Similar Soils | Volume | Available Water | | Free Water | |
|---|---|---|---|---|---|---|
| | | m3 x103 | m3/m3 | m3 x103 | m3/m3 | m3 x103 |
| Miscellaneous Map Units-not supporting terrestrial vegetation | | | | | | |
| Rj | Rock | 0.0 | 0.000 | 0.0 | 0.000 | 0.0 |
| T | Talus | 47.4 | 0.119 | 5.6 | 0.296 | 14.0 |
| Ru | Rock | 0.0 | 0.000 | 0.0 | 0.000 | 0.0 |
| G | Colluvium | 9.6 | 0.119 | 1.1 | 0.296 | 2.8 |
| K | Colluvium | 5.4 | 0.119 | 0.6 | 0.296 | 1.6 |
| F-K | Colluvium | 3.0 | 0.119 | 0.4 | 0.296 | 0.9 |
| Cryaquept-near pond | | | | | | |
| CqB | * Aquept | 1.3 | 0.201 | 0.3 | 0.545 | 0.7 |
| Cryofluvent-"Aplite Dike" inlet to the lake | | | | | | |
| TfB | * Fluvent | 1.0 | 0.116 | 0.1 | 0.366 | 0.4 |
| Entic Cryumbrept-bench meadow, wet | | | | | | |
| EaD | 1 Umbrept 1 | 2.2 | 0.116 | 0.3 | 0.366 | 0.8 |
| Lithic Cryumbrepts-well drained on slopes and ridges | | | | | | |
| LcF | Umbrept 2 | 0.8 | 0.067 | 0.1 | 0.247 | 0.2 |
| LcF-R | 2 Umbrept 2 | 7.1 | 0.067 | 0.5 | 0.247 | 1.8 |
| R-LcF | Umbrept 2 | 16.3 | 0.067 | 1.1 | 0.247 | 4.0 |
| R-LcE | Umbrept 2 | 1.8 | 0.067 | 0.1 | 0.247 | 0.4 |
| R-LeF | Umbrept 2 | 2.4 | 0.067 | 0.2 | 0.247 | 0.6 |
| LeD | Umbrept 2 | 1.1 | 0.067 | 0.1 | 0.247 | 0.3 |
| Lithic Cryumbrepts-wetter, along stream channels, (Salix) cover | | | | | | |
| LdF | Umbrept 3 | 9.0 | 0.201 | 1.8 | 0.545 | 4.9 |
| LdF-R | Umbrept 3 | 1.8 | 0.201 | 0.4 | 0.545 | 1.0 |
| LeC-R | 3 Umbrept 3 | 2.4 | 0.201 | 0.5 | 0.545 | 1.3 |
| LfqC | Umbrept 3 | 0.2 | 0.201 | 0.0 | 0.545 | 0.1 |
| T-LeF | Umbrept 3 | 0.5 | 0.201 | 0.1 | 0.545 | 0.3 |
| Entic Cryumbrepts-east and west of the lake, very well drained | | | | | | |
| EbF | * Umbrept 4 | 2.5 | 0.062 | 0.2 | 0.280 | 0.7 |
| EcF | * Umbrept 4 | 22.1 | 0.062 | 1.4 | 0.280 | 6.2 |
| "Cryorthod" and Cryumbrept association-Western White Pine stand | | | | | | |
| TdoF-R | 4 Orthod | 6.3 | 0.062 | 0.4 | 0.280 | 1.8 |
| Cryorthents-very well drained glacial till and colluvium | | | | | | |
| TrF | Orthent | 4.0 | 0.119 | 0.5 | 0.296 | 1.2 |
| TsD | 5 Orthent | 3.7 | 0.119 | 0.4 | 0.296 | 1.1 |
| ToF | Orthent | 1.6 | 0.119 | 0.2 | 0.296 | 0.5 |
| TpD-R | Orthent | 0.9 | 0.119 | 0.1 | 0.296 | 0.3 |
| TrF-R | Orthent | 0.3 | 0.119 | 0.0 | 0.296 | 0.1 |
| ToC | Orthent | 0.2 | 0.119 | 0.0 | 0.296 | 0.1 |

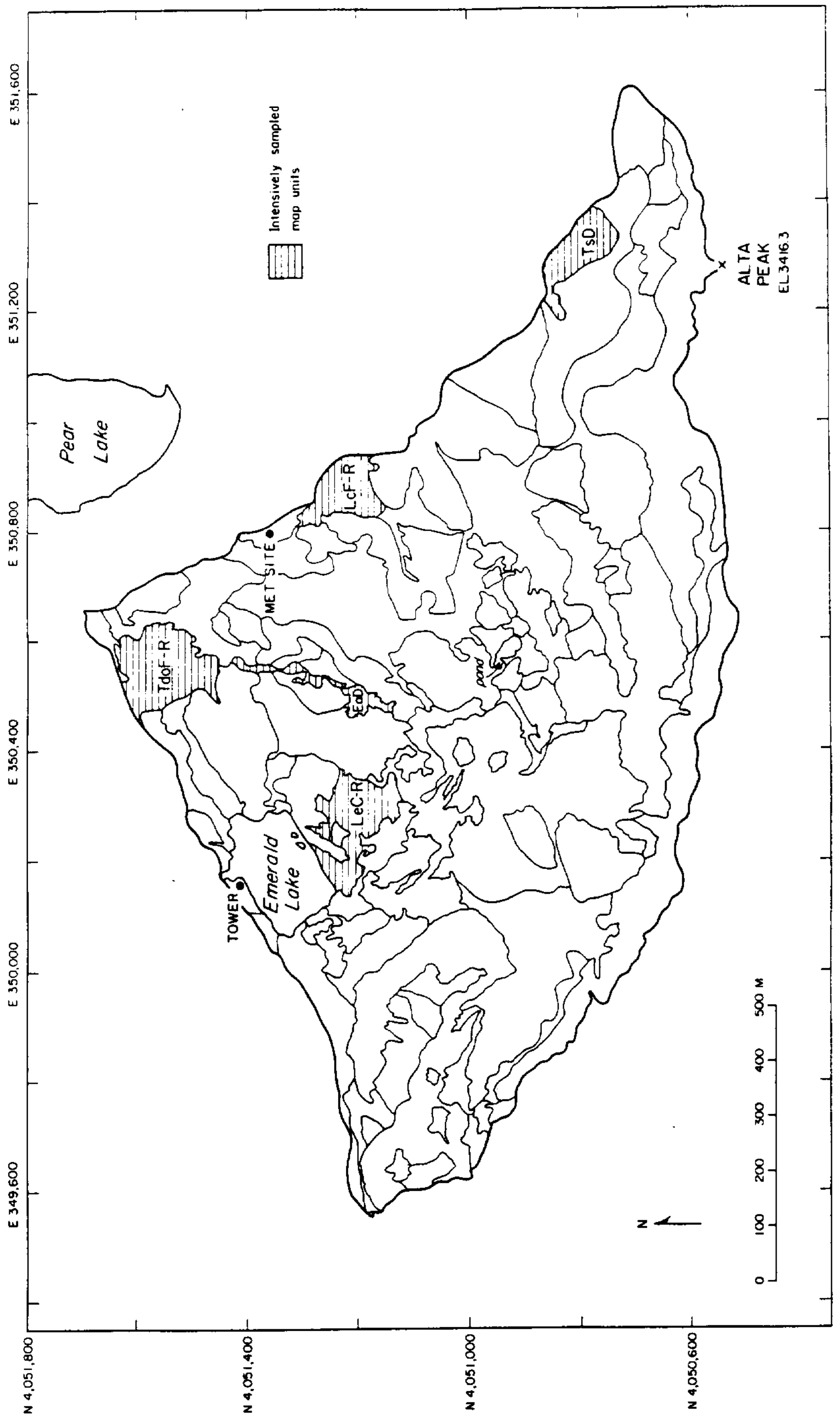


Figure 3-1. Intensively sampled map unit areas at ELW.

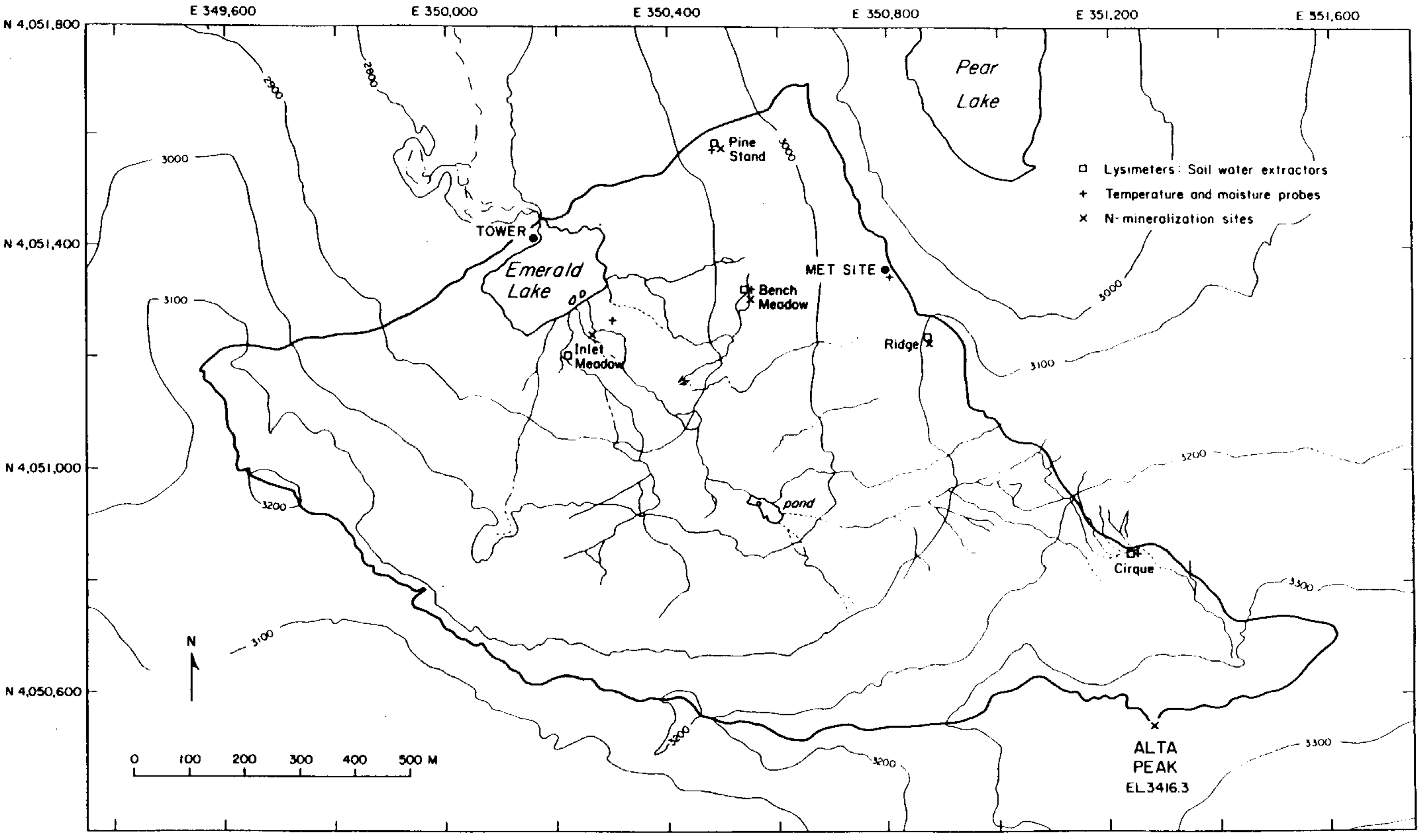


Figure 3-2. Soil temperature and moisture monitoring sites at ELW.

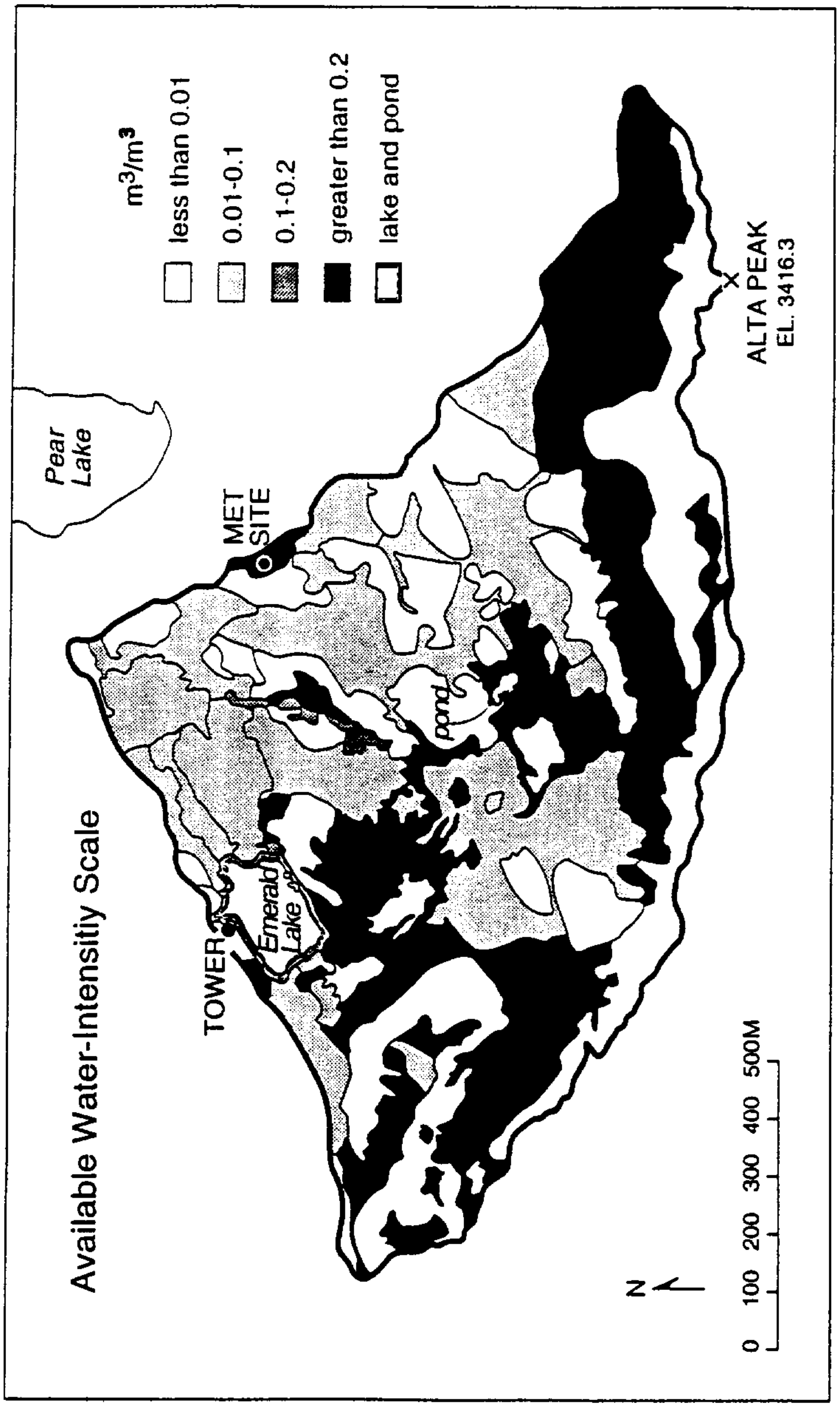


Figure 3-3. Distribution of available water capacity in ELW soil map units.

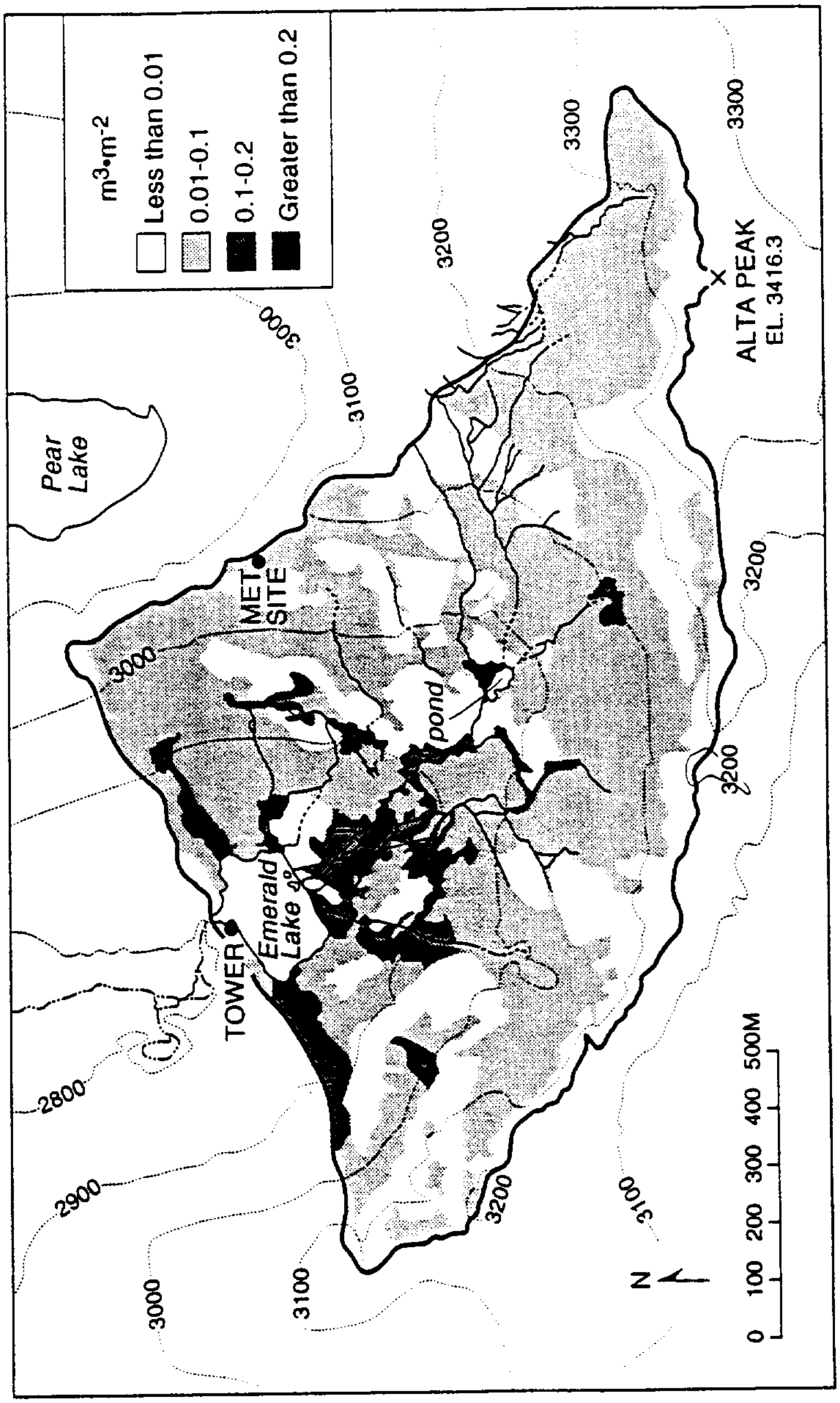
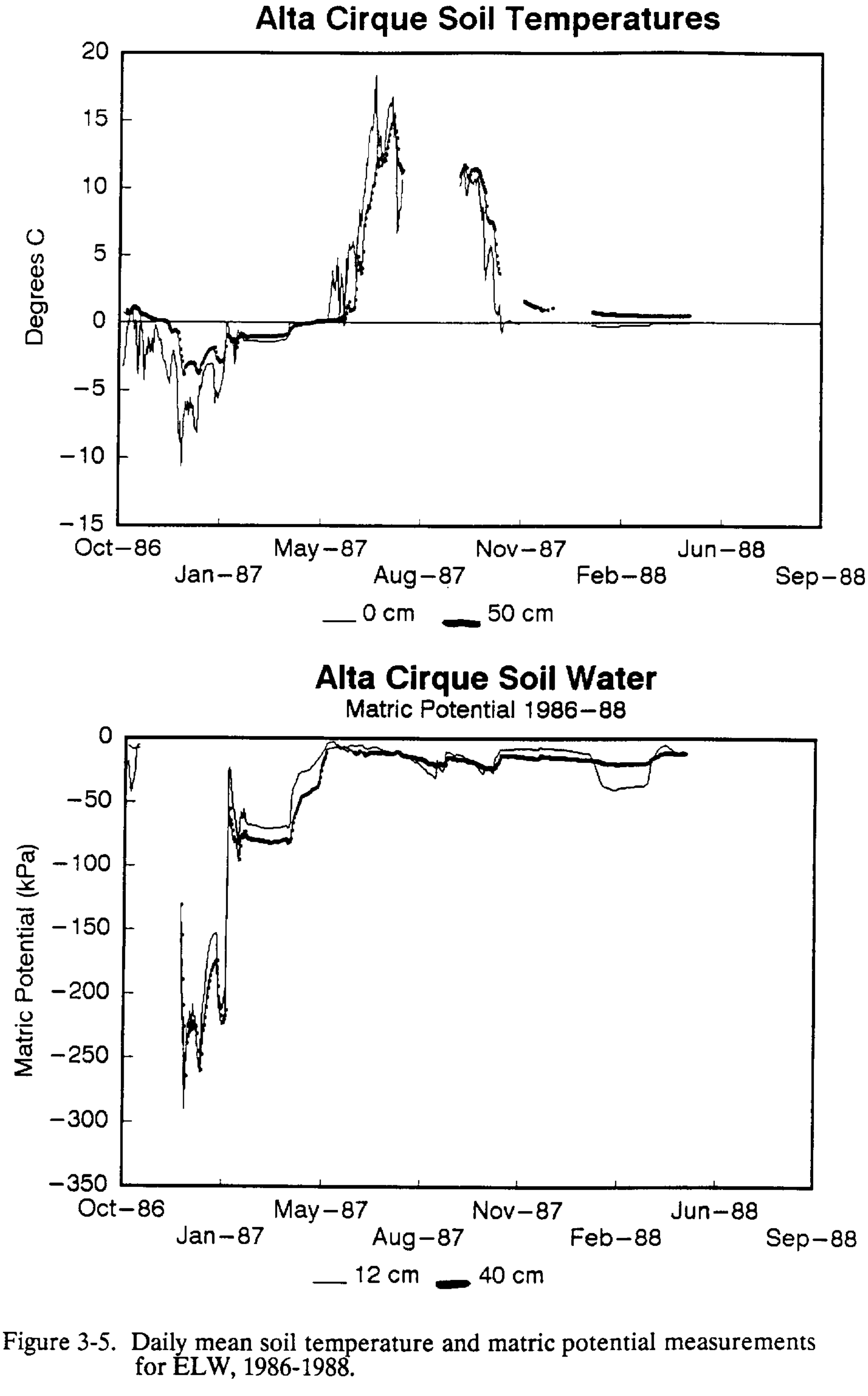


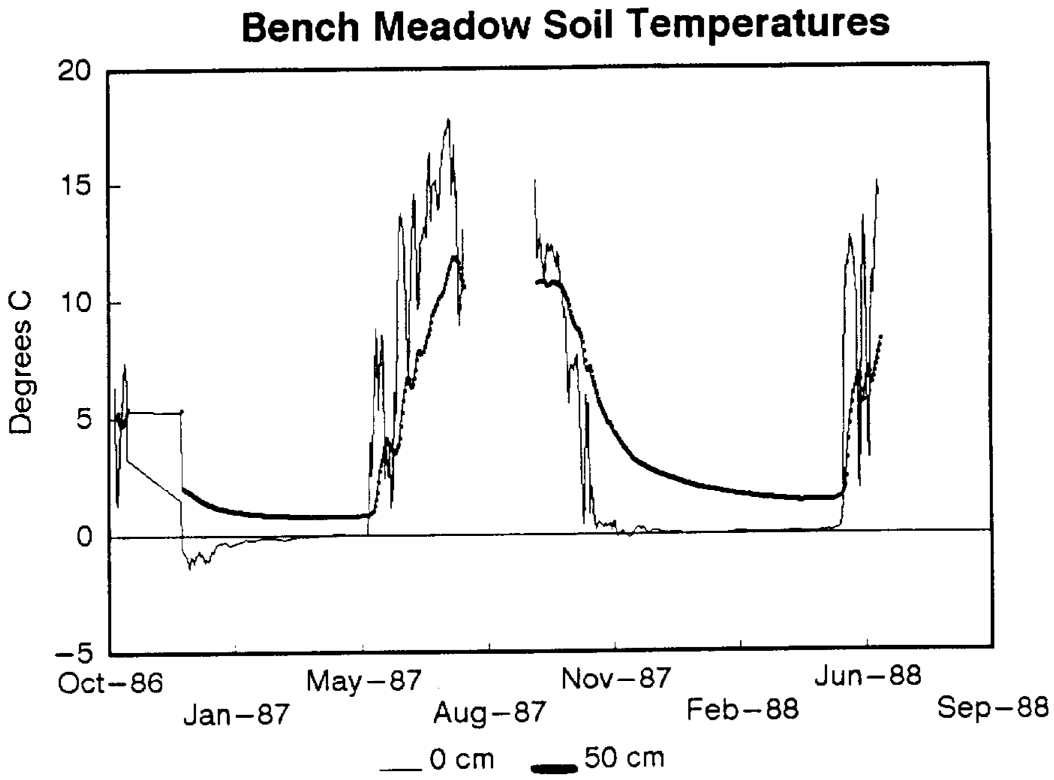
Figure 3-4. Distribution of free water capacity in ELW soil map units.


Alta Cirque Soil Temperatures

Alta Cirque Soil Water

Matric Potential 1986−88

Figure 3-5. Daily mean soil temperature and matric potential measurements for ELW, 1986-1988.



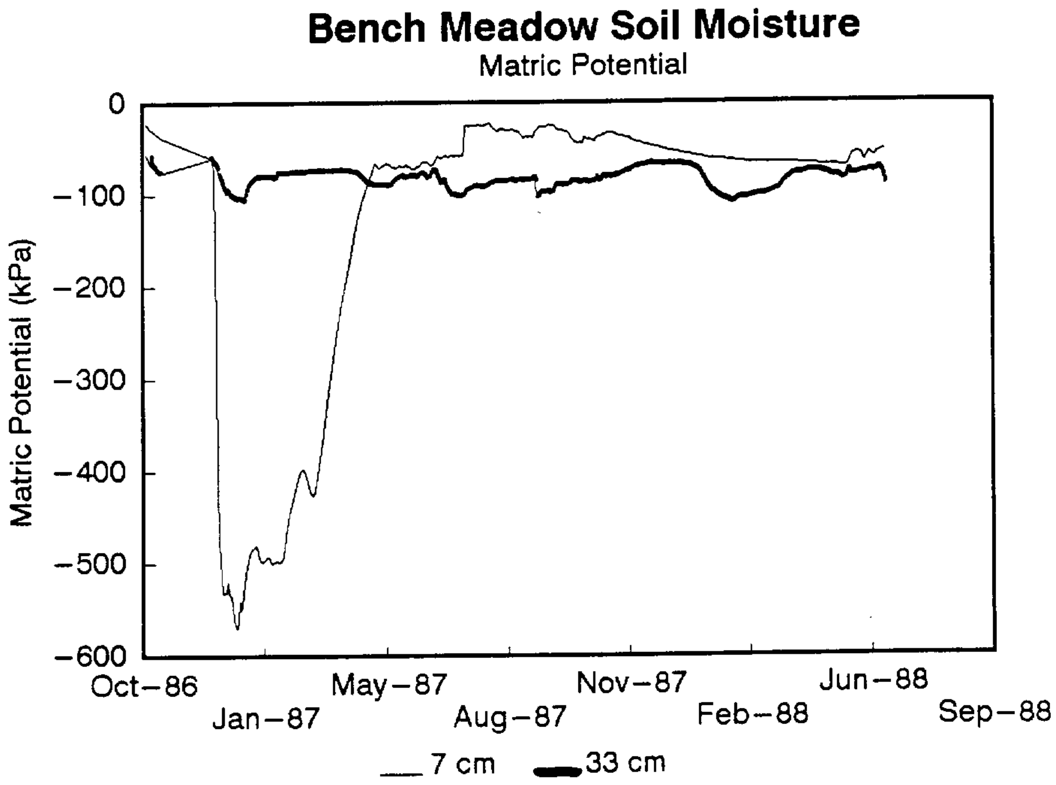
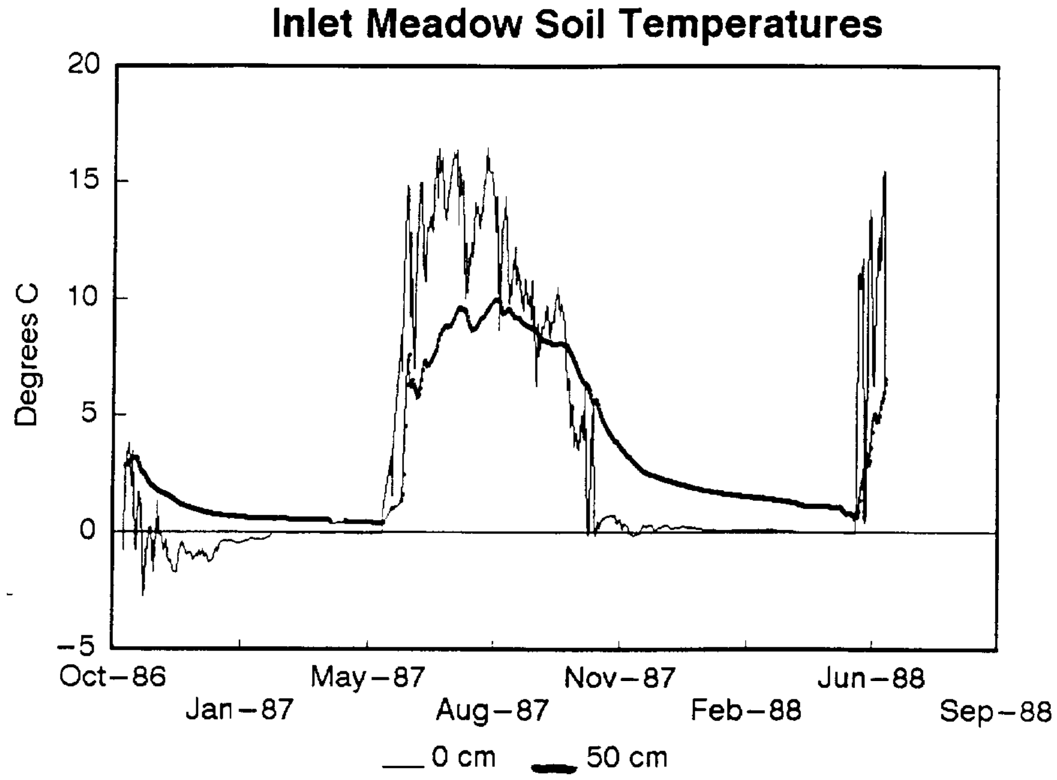


Figure 3-5. (Cont.)



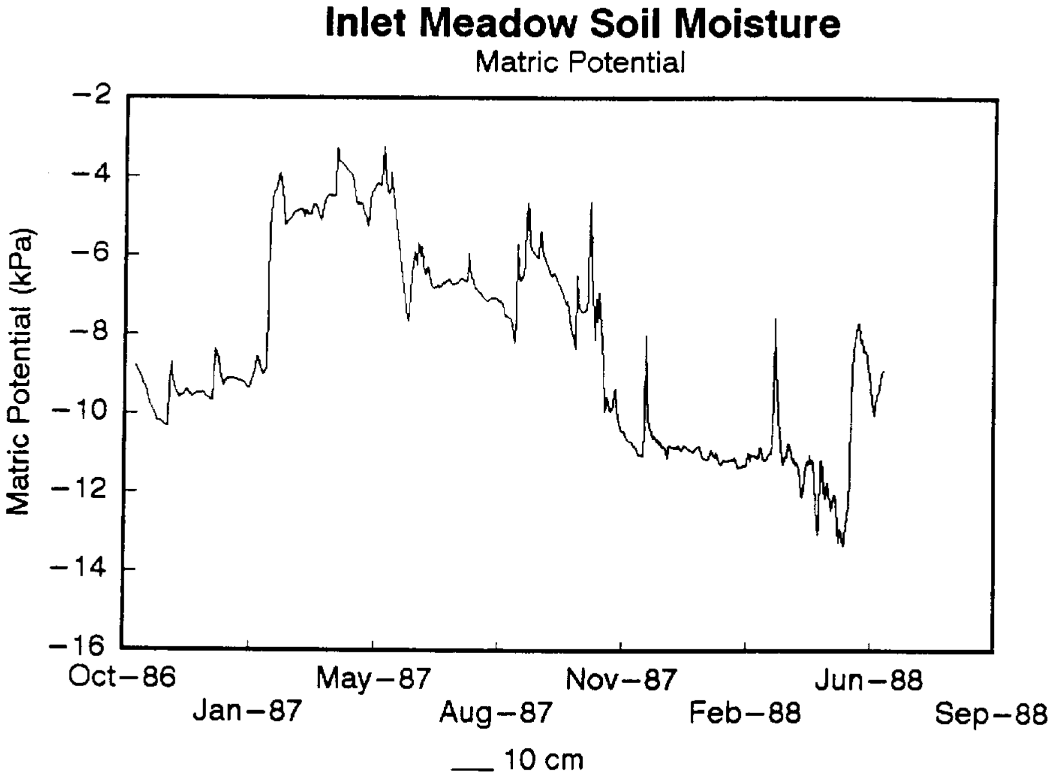
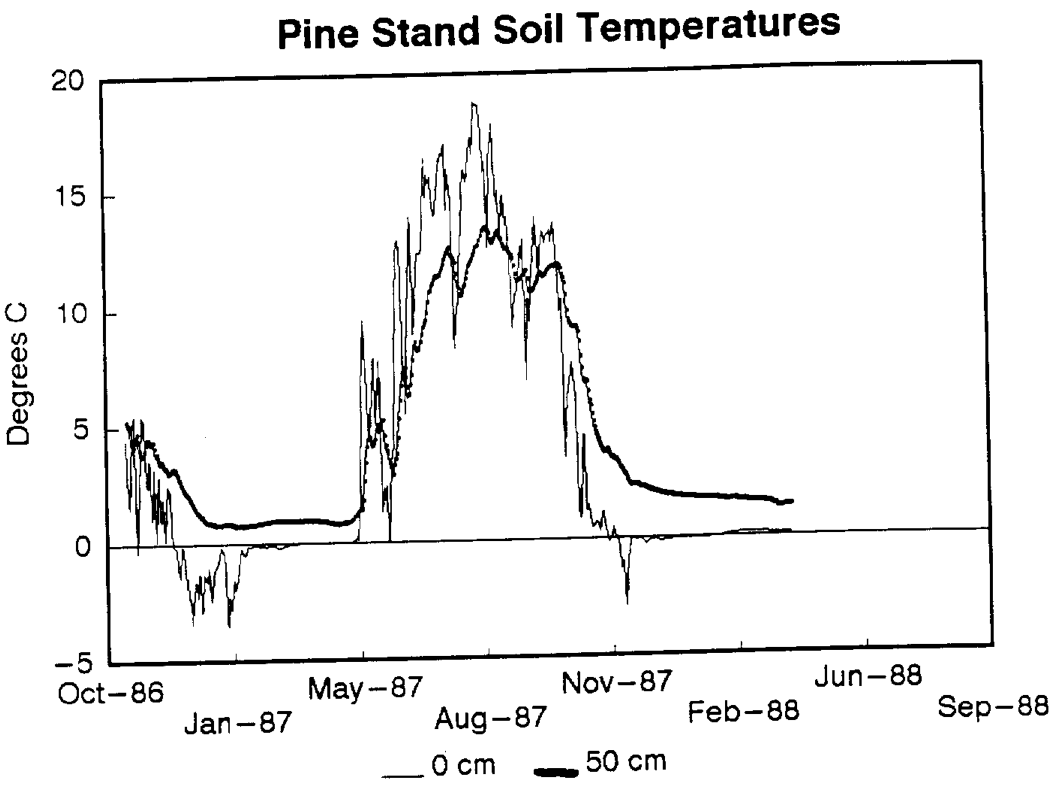


Figure 3-5. (Cont.)



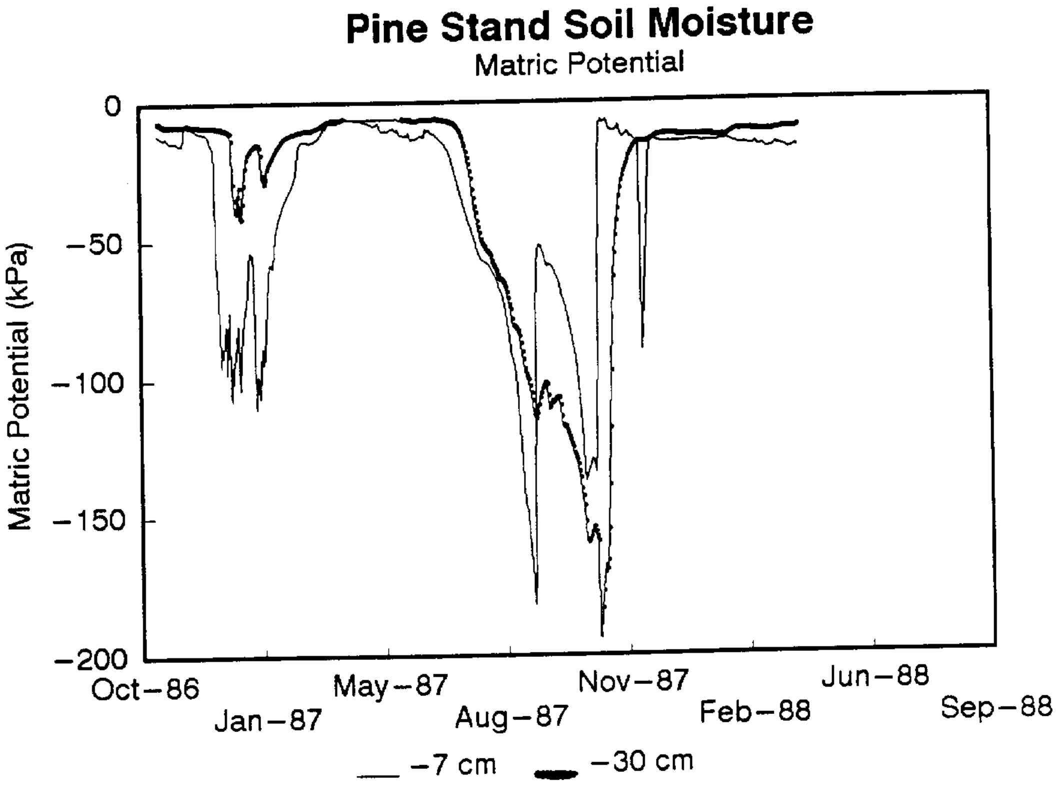
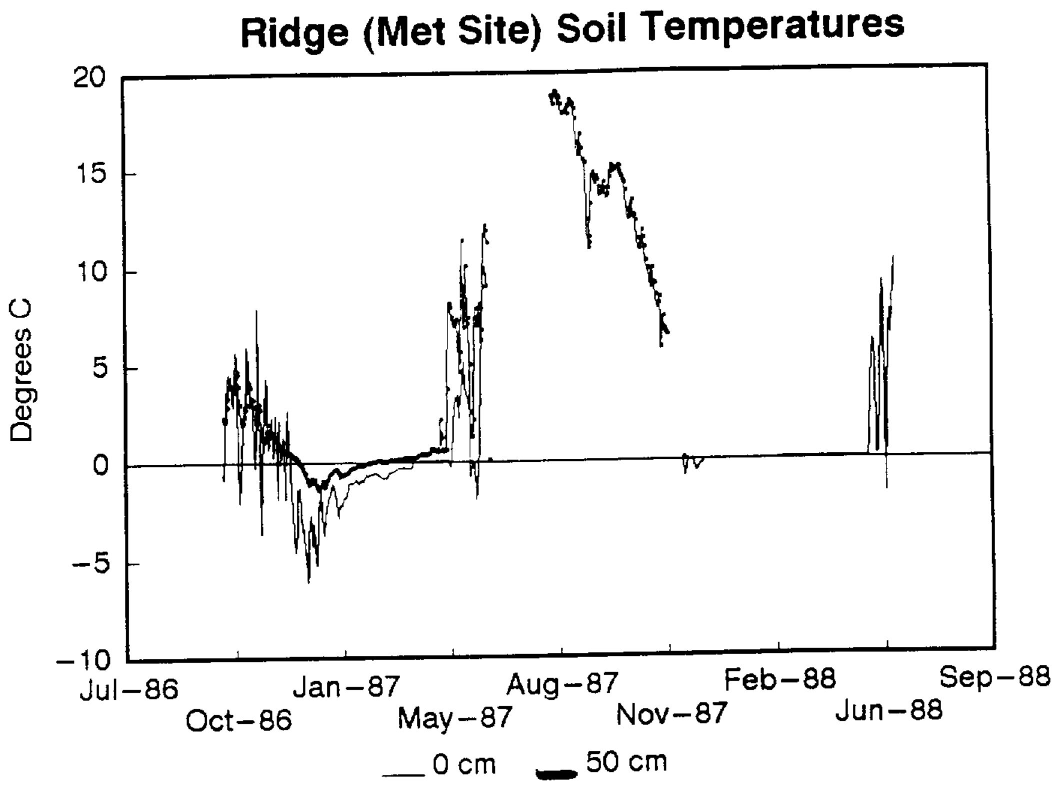


Figure 3-5. (Cont.)



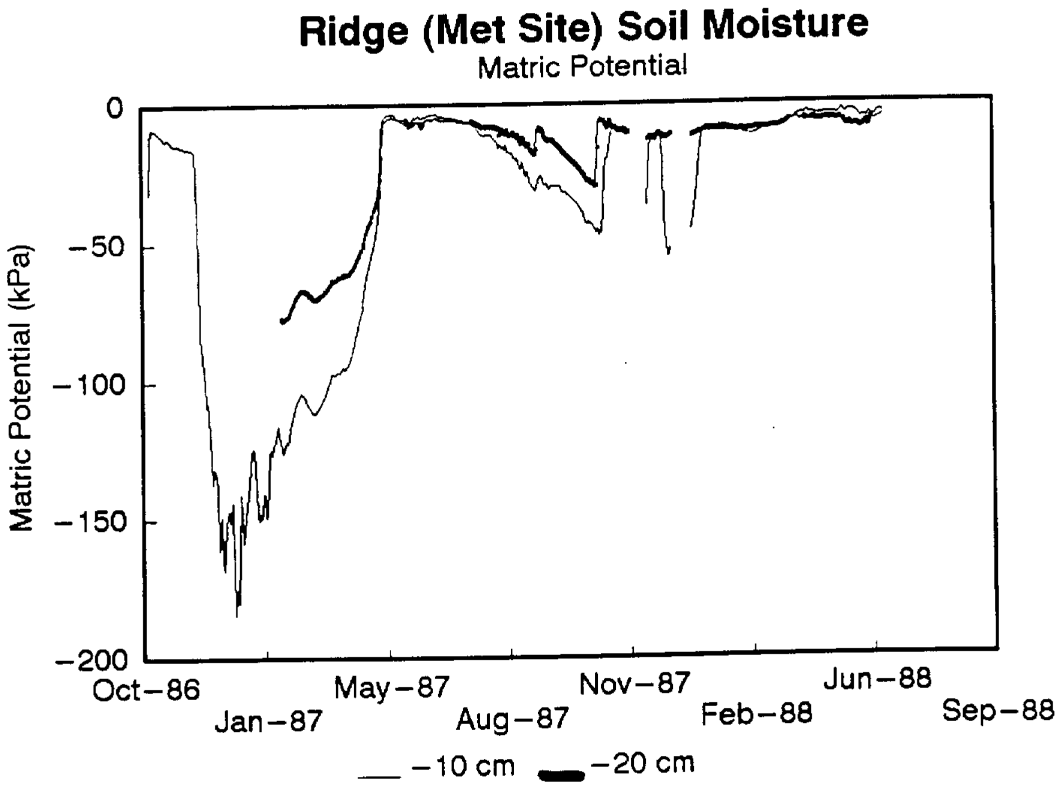


Figure 3-5. (Cont.)

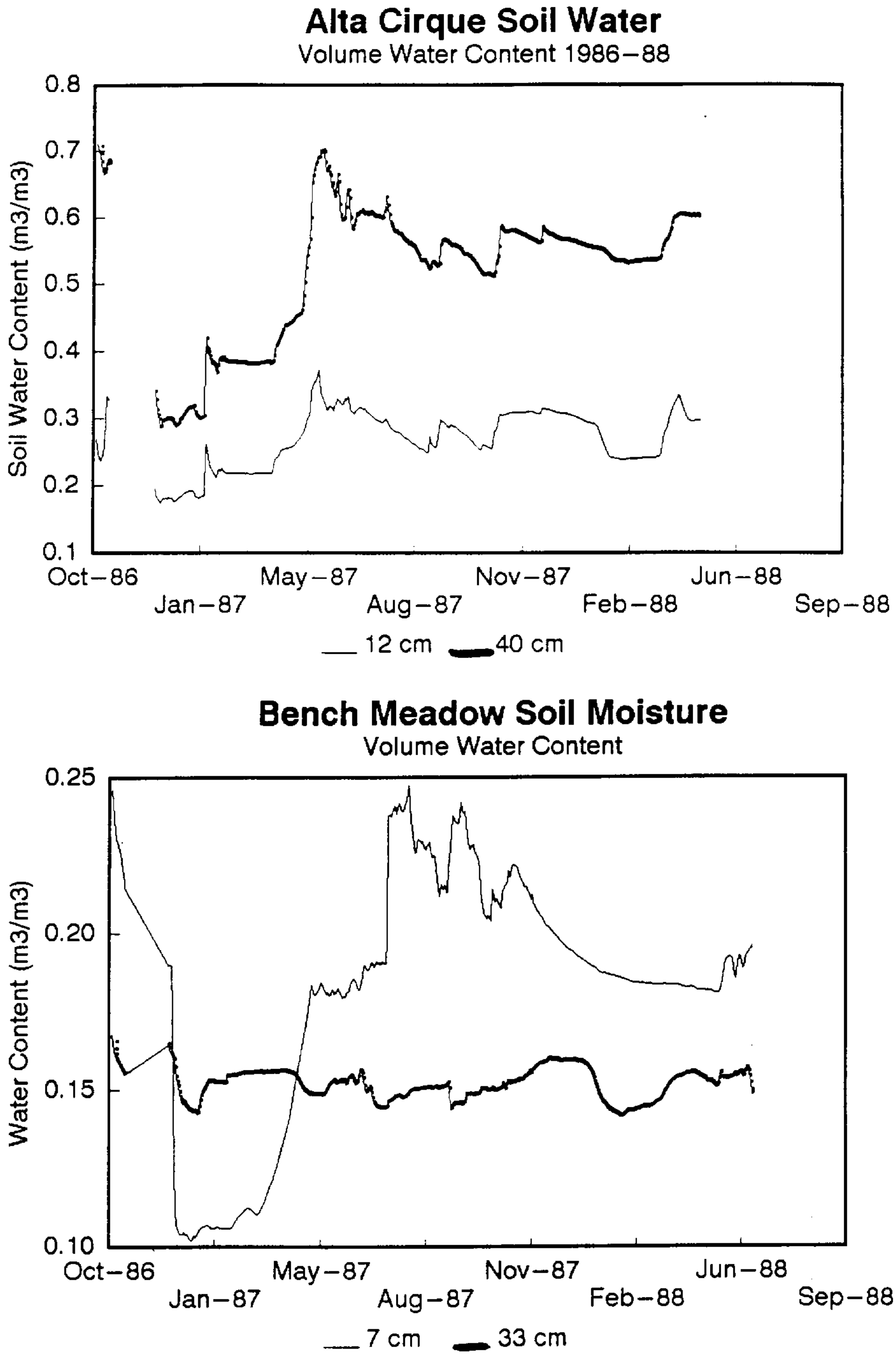
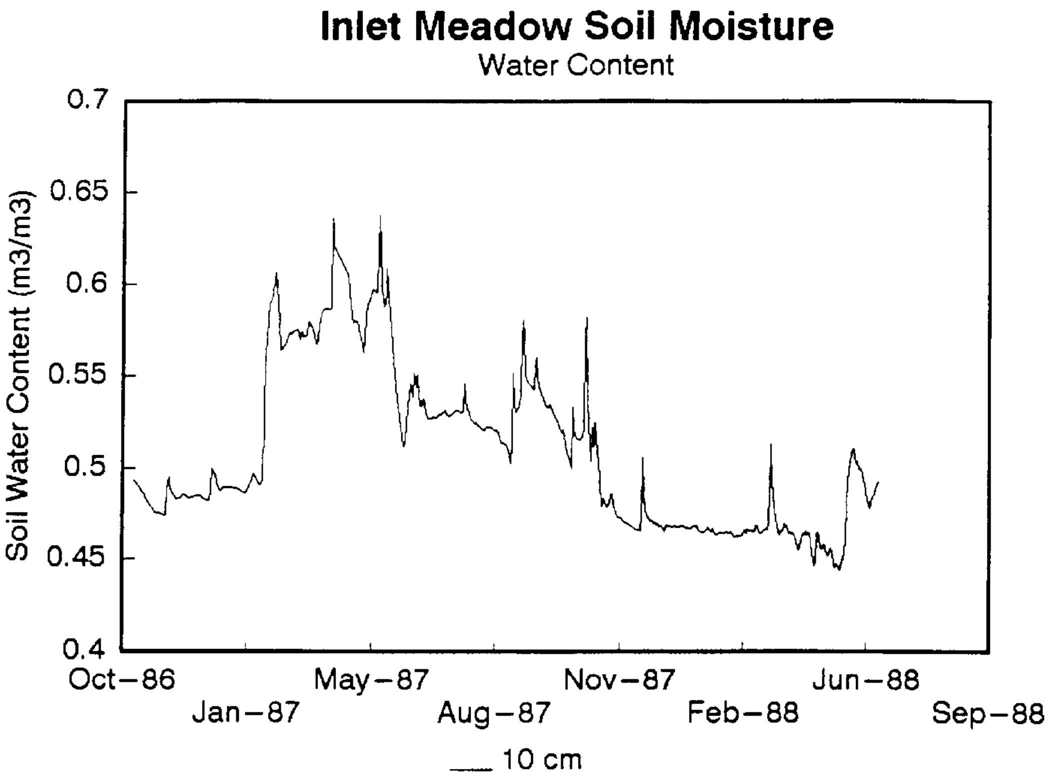


Figure 3-6. Calculated daily mean soil water content for ELW, 1986-1988.



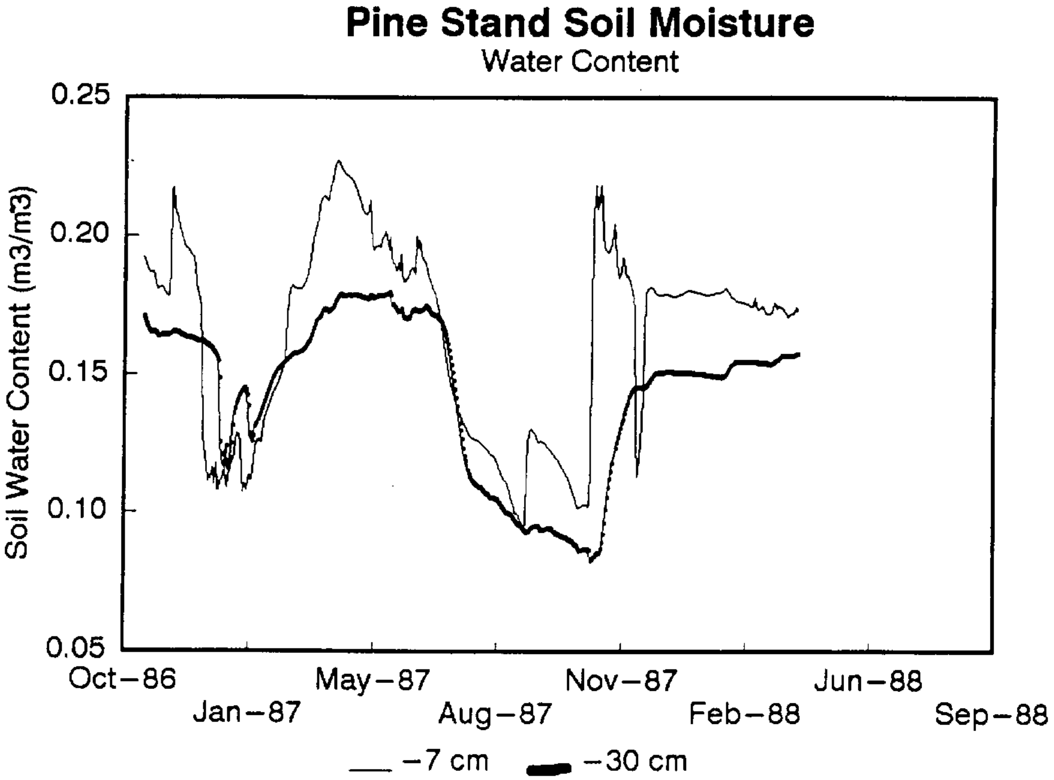


Figure 3-6. (Cont.)

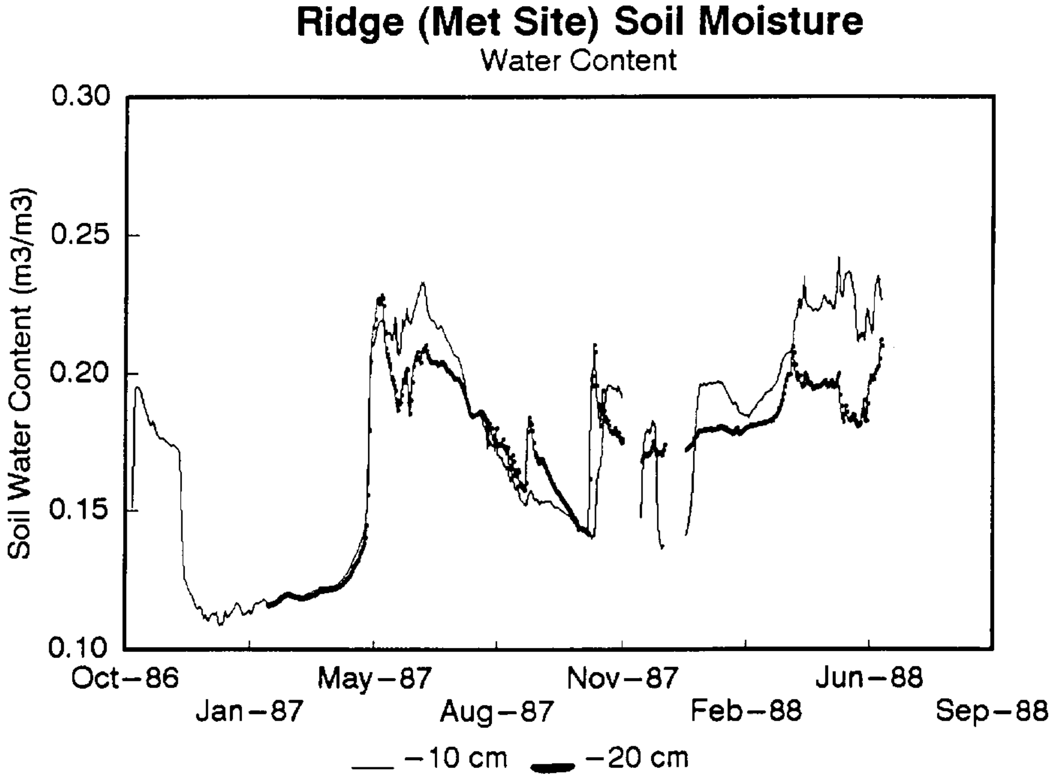


Figure 3-6. (Cont.)

# *CHAPTER 4*

# *SOIL CHEMICAL PROCESSES*

Cation exchange, mineral weathering, and sulfate adsorption are widely recognized as the critical physical chemical soil processes influencing surface water composition in response to acidic deposition (Lynch and Corbett, 1989; Swistock et al., 1989; Lawrence et al., 1988; Buell and Peters, 1988; Binkley and Richter, 1987; Reuss and Johnson, 1985; Johnson, 1984; Bache, 1983). Cation exchange at soil mineral surfaces affects the soil solution cation composition by providing a source of base cations $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, and $K^{+}$ which can rapidly neutralize solution acidity, raising the acid neutralizing capacity (ANC) of the soil solution. The capacity of the soil to neutralize $H^{+}$ is in direct proportion to the quantity of base cations present on the exchange complex. Sulfate adsorption by soil mineral surfaces also releases to the soil solution an amount of ANC equivalent to the sulfate adsorbed (Johnson, 1984; Galloway et al., 1983). Permanent changes in the ANC of the soil solution can be transferred to surface water runoff.

Most important for ELW and, by inference, Sierra watersheds in general, is that cation exchange and sulfate adsorption are processes which occur rapidly enough to influence the composition of water which has only been in contact with the soil for a very short period of time. While there is strong evidence indicating the importance of mineral weathering reactions in the control of ANC and cation flux in surface runoff of mountain watersheds on an annual time scale (Clayton, 1988; Dreever and Hurcomb, 1986; Garrels and MacKenzie, 1967), cation exchange and rapid Al dissolution reactions appear to have a greater influence on surface water composition on the scale of deposition events and snowmelt (Brown and Lund, 1990; McAvoy, 1989; Buell and Peters, 1988). These rapid reactions predominate because the silicate minerals found in granite and granodiorite have relatively slow weathering rates (Berner, 1981). Typical weathering rates ($H^{+}$ consumption rates) measured for whole watersheds are between 0.1 and 1 $Eq/m^2/yr$ (Clayton, 1988; N. Johnson, 1984).

Weathering studies of natural materials from ELW have found that cation exchange exerts a very large influence on their short-term acid neutralizing capacity (Brown and Lund, 1990; Weintraub, 1986). Another study conducted on pulverized geologic materials of ELW found $H^+$ consumption rates of 0.52-0.84 $uEq/m^2/da$ for granite and 1.1-1.9 $uEq/m^2/da$ for granodiorite (Clow, 1987), about 1-2 orders of magnitude greater than the 0.015-0.25 $uEq/m^2/da$ for soil minerals (Brown and Lund, 1990). These differences are probably related to differences in the mixtures of minerals present. Soils would tend to have a greater guantity of highly weathered and secondary minerals present resulting in a proportionately lower $H^+$ consumption rate on a mineral surface area basis.

The laboratory measurements of weathering rates appear to be lower in comparison to the rates measured for whole watersheds. This is because watershed area does not account for the roughness of the surface as pitted rock, gravel, sand, silt, etc. which was actually estimated in the laboratory experiments. The weathering rate measurements of Silver Creek watershed in the southwestern Idaho batholith (Clayton, 1988) are probably among the best for comparison with the Sierra. Rates of $H^+$ consumption measured as cation and Si export were between 150 and 170 $mEq/m^2/yr$. This would reduce to 0.41 to 0.47 $mEq/m^2/da$. This rate would be more than adequate to compensate for $H^+$ wet deposition rates measured at ELW of 6.7 (1985) and 12.8 (1986) $mEq/m^2/yr$ (Dozier et al., 1989. Accurate estimates of basin-wide weathering rates for ELW will have to wait until several more years of hydrochemical mass balance data can be evaluated. Currently, we can estimate that mineral weathering probably could compensate for current acidic deposition rates on a basin-wide annual basis.

In contrast with aluminosilicate weathering, rapid dissolution of soil $Al^{3+}$ can also act as a temporary, but important sink for $H^+$ in acidic deposition (Burns, 1989; Swistock et al., 1989; Lawrence et al., 1988). The dissolution of $Al(OH)_3$ in response to increased $H^+$ in soil solutions increases $Al^{3+}$ which may then be transported to surface waters. This results in neutralization of $H^+$ deposition in the soil component of a watershed. However, when the soil solution is transferred to the surface water component, $Al^{3+}$ precipitates again as $Al(OH)_3$ and $H^+$ is released to the stream waters as in the equation:

$$Al^{3+} + 3\,H_2O = Al(OH)_3(c) + H^+ \qquad [4\text{-}1]$$

In this way soil $Al^{3+}$, which is a sink for acidity in soils becomes a source of acidity to surface waters.

The exact source of $Al^{3+}$ in surface waters has been a subject of intense study in the past 10 years. Strong evidence exists that soil solution concentrations of $Al^{3+}$ are maintained by organic complexes in solution and exchange with soil organic matter (James and Riha, 1984; Bloom et al., 1979). Although direct runoff volumes may be great compared with the contribution of soil water to surface runoff, hydrograph separation studies have shown that soil $Al^{3+}$ has a major influence on surface water composition (Burns, 1989; Swistock et al., 1989). In some cases, equilibrium with an $Al(OH)_3$ mineral (Eq. 4-1) is sufficient to explain solution $Al^{3+}$, but in others, apparent supersaturation has to be accounted for by unmeasured organic complexes (Lawrence et al., 1988) or kinetic constraints on precipitation (Hooper and Shoemaker, 1985).

## Critical Concerns

Measurements of these soil physical chemical processes address three critical ARB concerns about the response of subalpine soils to acidic deposition. First is the capacity of high elevation soils to neutralize acidic inputs. Three mechanisms are examined here: cation exchange, sulfate adsorption, and mineral weathering. We know from previous work that these processes are all operating at ELW (Lund et al., 1987), however, data were lacking on the overall capacity of these mechanisms in the watershed. Before this project was initiated, the data on exchangeable base cations and cation exchange capacity (CEC) in ELW soils were limited to four reference pedons sampled in 1983 for the National Park Service (Huntington and Akeson, 1987). Additional sampling will provide reference values for evaluation of long-term acidification of ELW soils. Knowing more about the acid neutralizing capacity of the soils will allow some assessment of the potential for acidification of the watershed in the short-term (weeks to a few years).

Second, one of the major consequences of decreasing soil pH in response to acidic deposition is the increased solubility of amorphous $Al(OH)_3$. The $Al^{3+}$ ions released in this process are potentially toxic to fish (Baker and Schofield, 1982; Driscoll et al., 1980), a major concern for public policy on acidic deposition. The measurement of the extent of the Al pool in several ELW map units provides a basis for evaluating the reactivity of Al in response to acidification.

Third, acid neutralizing processes in soils are important in controlling the chemical composition of surface waters. Based on our assessment of the potential rate of water movement through ELW soils (this report, Chapter 3; Gupta et al., 1989), these processes are probably limited by chemical reaction rates during the critical snowmelt period. Exchange and adsorption processes are among the fastest chemical reactions in soils and may have a leading role in controlling surface water composition. Information on the capacity of ELW for acid neutralization by these mechanisms may be very useful in evaluating the potential effect of increasing rates of acidic deposition on lake watersheds in the Sierra.

## OBJECTIVES

The following objectives are addressed by this study of physical-chemical parameters of ELW soils:

1) to obtain an estimate of the total capacity of ELW to neutralize acidic deposition through cation exchange and the distribution of this capacity across the watershed.
2) to reevaluate the sulfate adsorption properties of ELW and estimate the capacity of the watershed to adsorb sulfate, and
3) to determine the content of easily dissolved fractions of Al in ELW

soils and reevaluate the role of weathering reactions in response to acidification.

## METHODS

Five soil map units within ELW were sampled to determine the magnitude and spatial variability of soil physical-chemical parameters (Figure 4-1). Three soil map units were sampled in the summer of 1986 (EaD, LeC-R, and TdoF-R) and two more were sampled in the summer of 1987 (LcF-R, TsD). The procedure for sampling soils was designed to reduce bias in site selection and sample collection. Sites were selected by assigning random numbers to a grid which was arbitrarily superimposed on the ELW soil map (Huntington and Akeson, 1987). Random selection of sample sites should assure that the means and sample errors of parameters determined will be reproducible by a similar sample survey in the future.

Bulk soil samples were collected in 10 cm depth intervals from surface to bedrock or boulder. The samples were placed in new, clean plastic bags, carried out of the watershed, and cooled to 4°C as soon as possible until they could be spread on kraft paper and dried in the UCR greenhouse. The samples were passed through a 2 mm sieve and the coarse fragments (>2 mm) were weighed and discarded. When appropriate, chemical parameters were scaled to account for the coarse fragments assuming they had no influence on anything other than the weight of the sample.

Cation exchange capacity (CEC) was determined for the three map units sampled in 1986 using a standard extraction method (NaOAc, pH 7) appropriate for soils with the pH and texture of ELW soils (Chapman, 1965). Exchangeable base cations were determined on all five map units using the standard extraction ($NH_4OAc$) method (Thomas, 1986). Cations in the extracts were measured using standard atomic absorption (Ca, Mg) and flame emission (Na, K) spectroscopy (Baker and Suhr, 1982). Standards were prepared in extractants (distilled water, $NH_4OAc$) to avoid errors due to matrix effects.

Sulfate adsorption data from a previous report (Lund et al. 1987) were used to calculate sulfate adsorption isotherms using the Langmuir equation (Kinniburgh, 1986):

$$n = KcM/(1+Kc) \qquad [4\text{-}2]$$

where n is sulfate adsorbed in mEq/kg soil, K is a distribution coefficient (L/mEq), M is the maximum sulfate adsorption for the conditions of the isotherm (pH, ionic strength), and c is the sulfate concentration in solution. The isotherm data were fitted using a non-linear least squares method.

Amorphous aluminum hydroxide ($Al(OH)_3$ amorph.) in the soils was measured by extraction with hydroxylamine hydrochloride (Barnhisel and Bertsch, 1982). Exchangeable Al was extracted using KCl (Barnhisel and Bertsch, 1982). Concentrations of Al were determined using flameless atomic absorption (Baker and Suhr, 1982). Data on four ELW soils subjected to varying concentrations of HCl in a month-long weathering experiment were used in evaluation of the solubility of $Al^{3+}$ (Brown and Lund, 1990; Lund, et al., 1987; see Appendix). The free $Al^{3+}$ and solubility of gibbsite (gamma-$Al(OH)_3$) was calculated using the solubility constants of Hodges (1987).

## RESULTS AND DISCUSSION

### Cation Exchange Properties

The maximum mean CEC's were found in the surface 10 cm of the three soil map units analyzed (Table 4-1). The CEC's decreased with depth, but this trend was least pronounced in the Typic Cryorthent, TdoF-R map unit, pine stand, and most pronounced in the Entic Cryumbrept, EaD map unit, bench meadow. The standard error (variability) of CEC was greatest in the surface 10 cm and in all layers of the Lithic Cryumbrept, LeC-R map unit, inlet meadow. This is probably related to higher organic matter content near the soil surface and in the Lithic Cryumbrept. The means and standard errors of the CEC's measured for the ELW map units are similar to data compiled for a survey of forest soils in New York and Maine (David et al., 1988). In that study, the CEC of subsurface horizons ranged from 13.7 to 1.6 mEq/100 g soil.

Of the exchangeable base cations, $Ca^{2+}$ dominates the exchange complex of ELW soils because of the relatively greater affinity of the exchange complex for $Ca^{2+}$ over $Na^+$ or $K^+$ (Table 4-2). Although the quantity of $Ca^{2+}$ retained as exchangeable is far greater than $Na^+$, the latter is more easily released in exchange for $H^+$ and is found in higher relative concentrations in the soil solution. The exchange of $H^+$ for base cations results in a decrease in solution $H^+$ and a corresponding increase in solution ANC. The decrease in exchangeable $Ca^{2+}$ with depth is probably due to uptake of $Ca^{2+}$ by plants and decomposition at the surface. Deposition of $Ca^{2+}$ in rain and dust may also have an effect.

The sum of the base cations amounts to a pool of from about 0.13 $Eq/m^2$-10cm of a typical ELW Entisol to 1.2-12 $Eq/m^2$-10cm of an Inceptisol. Exchangeable base cations from Table 4-2 and from earlier reports (Huntington and Akeson, 1987) and dimensional data on soil map units (this report, Chapter 3) were used to calculate the spatial distribution of the exchangeable base pool for ELW (Table 4-3). We assumed that talus and colluvium were similar to soil map unit TsD, near Alta Peak, because of the similarity in elevation, aspect, and geological material to the T, K, and F map units. Depth-weighted averages were used in the calculation. These calculations indicate that over half of the $1.4 \times 10^6$ Eq of exchangeable base cations in the watershed are concentrated in the wet Lithic Cryumbrepts, which cover less than 10% of the watershed area.

A map of the distribution of exchangeable bases ($Eq/m^2$) illustrates the fact that they decrease as elevation increases (Figure 4-2). Rock outcrops were assumed to have exchangeable base cations less than 0.1 $Eq/m^2$. This estimate is based on data from experiments in which artificial rain was applied to barren granite surfaces (Abrahamsen et al. 1979). Using data from the only two of eight of those experiments in which $H^+$ was consumed (both for application of pH 3.6 water), we calculated consumption rates of 0.003 and 0.180 Eq/m$^2$, apparently accounted for by cation exchange and Al release. Most ELW soils fall in the range 0.1-1 Eq/m$^2$ exchangeable base cations.

The proportion of exchangeable base cations have been shown to be an important factor in maintaining a positive alkalinity in soil solutions (David et al., 1988). Since ANC is conserved when soil solution emerges into surface waters, exchangeable base cations are a critical indication of the ability of a soil to neutralize acidic inputs. If the capacity for exchangeable bases to neutralize solution acidity is exceeded, surface water ANC can fall below 0 mEq/L. Wet deposition of $H^+$ at ELW in water year 1985 was 0.0067 and in 1986, 0.0128 Eq/m$^2$. These deposition rates are at most 10% of the sum of base cations stored in the full depth of the high elevation Entisol map units. Under these conditions and based on current understanding of the influence of exchangeable bases on acidic deposition, we expect that during a given snowmelt event, soil solution ANC could become negative (David et al., 1988).

On a mass balance basis, we expect that mineral weathering would replace base cations at an annual rate sufficient to replace those exported. If they were not replaced, $H^+$ deposition of 0.01 Eq/m$^2$/yr would deplete 0.1 Eq/m$^2$ exchangeable bases in soils by exchange for $H^+$ in a matter of a decade. This was the rate of deposition in 1986, $H^+$ deposition in 1985 was one-half this. Exchangeable bases of 1.0 Eq/m$^2$ would require 100 years for depletion, in the absence of other reactions. The map area falling within this range of exchangeable base cations is illustrated in Figure 4-2. Because nearly all ELW soils fall in the range of 0.1 to 1.0 Eq exchangeable bases/m$^2$, soils may be depleted in exchangeable bases in a period of time between 10-100 years if **no** reactions other than cation exchange are occurring.

## Sulfate Adsorption

In earlier work we concluded that the sulfate adsorption capacity of ELW soils is low compared with other areas impacted by acidic deposition (Lund et al., 1987). Basin-wide estimates of adsorption capacity were not possible at that time, however. In the 1985, 1986, and 1987 water years it has been observed that sulfate concentrations in ELW soil solutions and surface waters do not change as rapidly as the concentrations in snowmelt (Dozier et al., 1987; Mark Williams, pers. com.). A sign that sulfate retention is occurring in the system is that peaks in sulfate concentration appear to lag behind peaks in nitrate concentrations (Lynch and Corbett, 1989; Johnson and Henderson, 1979). The adsorption of $SO_4^{2-}$ on the surfaces of variable charge minerals such as kaolinite and gibbsite may account for this phenomenon.

Adsorption data collected for 0-15 cm in two Cryumbrepts at 4 pH levels (Lund, et al., 1987) were reanalyzed using the Langmuir adsorption isotherm Eq. 4-2 (Figure 4-3). Separate isotherms were fitted to adsorption data for each treatment (Table 4-4). Values of the parameters in these isotherms are comparable to similar data for other soils (Singh, 1984; Gebhart and Coleman, 1974). Values for M are slightly low (0.4-5 mEq/kg) compared with literature values (17-21 mEq/kg) for some Norwegian Spodosols. Values for K are quite high (5-16 L/mEq) in comparison with the same study (0.02-0.2). This may be a result of a greater affinity of the adsorbing surfaces for sulfate at the low concentrations of adsorbate used to generate the data (Lund et al., 1987). Because of the increase in positive charge developed on mineral surfaces with decreasing pH (Parfitt, 1978), estimates of M increased as the ($H^+$) of the soil solution increased for both soils (Figure 4-4a). The distribution coefficient (K) for sulfate adsorption increased with ($H^+$) up to $10^{-3.8}$, then declined (Figure 4-4b). This is probably due to effects of dissolution of the mineral surfaces responsible for sulfate adsorption.

There is considerable difference of opinion about the most desirable equation for description of adsorption isotherms (Parfitt, 1978). We chose to use the Langmuir isotherm for these calculations because it is a widely known convention and can be used to calculate a theoretical maximum adsorption (M). Caution needs to be used in applying these isotherm parameters to conditions where pH or solution sulfate concentrations are outside the range of the data. Under the conditions of our calculations the sulfate adsorption capacity may be overestimated by as much as 50% (Harter, 1984). It is possible that better estimates of capacity may be obtained by adsorption experiments at higher sulfate concentrations. On the other hand, the high affinity of the ELW soil adsorbent for sulfate implied by the K parameter may be an important result of using low sulfate concentrations. These conditions may be more representative of nature.

Using the data in Figure 4-4, the M and K parameters were estimated for each soil (Lithic Cryumbrept (R-LcF), K = 10.4, M = 0.75; Entic Cryumbrept (EcF), K = 9.1, M = 0.48) assuming a soil solution pH of 5.4, the mean pH of snowmelt (Figure 4-5). This figure provides an estimate of the amount of sulfate adsorbed by a volume of soil 10 cm x $m^2$ at sulfate concentrations commonly measured in ELW soil solution samples (cf. D.W. Johnson, 1984). For example, the amount of sulfate adsorbed by the surface 10 cm of soil in order for the solution concentration to increase from 20 to 40 uEq/L is 9.4 mEq/$m^2$ for the Lithic Cryumbrept and 5.0 mEq/$m^2$ for the Entic Cryumbrept.

Basin-wide adsorption capacity of the surface 10 cm at pH 5.4 was estimated using Figure 4-5, soil areas from the ELW survey, and assuming the Cryorthents, Cryorthod association, well-drained Cryumbrepts, colluvium, and talus were more similar to the Lithic Cryumbrept while the Aquept, Fluvent, and wet Cryumbrepts were similar to the Entic Cryumbrepts (Table 4-5). By multiplying area by the appropriate adsorption capacity (M), the total sulfate adsorption capacity for the surface 10 cm of the watershed is approximately 32 kEq at an average soil solution pH of 5.4. Adsorption capacity of the surface 10 cm of the well drained Cryumbrepts is approximately 77 mEq/$m^2$ and the wet Cryumbrepts only 35 mEq/$m^2$. Wet deposition rates for sulfate were 4.3 and 8.5 mEq/$m^2$ in water years 1985 and 1986, respectively (Dozier et al., 1987). Therefore, annual sulfate deposition rates range from 5 to 24% of the estimated adsorption capacity for the surface 10 cm of soil. Under these conditions, including an assumed pH of the soil solution, sulfate saturation would occur within 4-20 years.

While ELW soils may have the capacity to adsorb 4-9 $mEq/m^2$ sulfate annually, it appears that they may be close to capacity already. Mass balance of sulfate inputs and outputs to ELW will support this if there does not appear to be net adsorption. The influence of sulfate adsorption on surface water concentrations in ELW is to delay the transport of sulfate relative to water inputs. This may or may not produce a sufficient temporary increase in ANC to reduce the effects of acidic snowmelt or rain event on ELW soils and streams.

Weathering Reactions: Soil Aluminum

Standing pools of soil Al were estimated for three map units (EaD, TdoF-R, LeC-R) assuming amorphous $Al(OH)_3$ is the solid phase most likely to release $Al^{3+}$ to the soil solution (Table 4-6). Depth profiles show that in the Cryorthod association (TdoF-R) and the wet Lithic Cryumbrept (LeC-R) soil Al content is higher below the 20 cm (Figure 4-6). This indicates that Al has probably been leached from the surface horizon and either lost to runoff or redeposited in deeper soil layers. The Cryorthod association corresponds to the area mapped as till from the Tioga glaciation over 10,000 years ago (Moore and Wahrhaftig, 1984). Therefore, this material would have been subjected to the longest period of soil formation in ELW and Al should be depleted at the surface and deposited at depth (Jenny, 1980). The $Al(OH)_3$ content more than doubles between 5 and 45 cm. Comparison of measurements of amorphous $Al(OH)_3$ in soils with standing biomass found that this is the largest Al-pool in each watershed community (Herman et al., 1989).

Exchangeable $Al^{3+}$ is estimated based on the KCl extracts of soils from the same three map units (EaD, TdoF-R, LeC-R) (Table 4-7). Depth profiles show that in contrast to amorphous $Al(OH)_3$, there is little difference in exchangeable $Al^{3+}$ with depth in the Cryorthod association (Figure

4-7). Exchangeable $Al^{3+}$ is highest in the wet Lithic Cryumbrept. This is probably a result of the high organic matter contents (Bloom et al., 1989). The values for exchangeable $Al^{3+}$ measured in this soil is similar to the levels found in the soils associated with West Wachusetts Brook (2-6 mEq/100g) where release of exchangeable $Al^{3+}$ was found to have a severe impact on stream water quality (McAvoy, 1989).

Free-$Al^{3+}$ in the ELW soil solution is controlled by at least two weathering/release reactions (Brown and Lund, 1990, see Appendix). One reaction is quite rapid, accounting for at least 90% of acid neutralization in the laboratory study. In this reaction $Al^{3+}$ is released in a ratio of 3 moles $H^+$ per mole of $Al^{3+}$ (Figure 4-8). Solubility calculations indicate that the mineral involved is probably gibbsite (gamma-$Al(OH)_3$). This mineral has not been identified in all soils in the watershed. One explanation is that the source of the $Al^{3+}$ may be aluminum hydroxide ($Al(OH)_3$, amorphous) trapped in hydroxyinterlayered vermiculite, a clay mineral which is ubiquitous in ELW soils. Another explanation is that at sufficiently acidic pH, $Al^{3+}$ associated with organic matter in soils will behave in a manner similar to amorphous $Al(OH)_3$ (Bloom et al., 1979).

The second weathering reaction which can release $Al^{3+}$ involves the decomposition of minerals derived from granite or granodiorite bedrock including feldspars, hornblende, and biotite. While base cations are released in this reaction, $Al^{3+}$ and $Si^{4+}$ are also released and, in part, recombine to form kaolinite (Brown and Lund, 1990; Appendix). The formation of kaolinite and under certain conditions gibbsite, makes Al a conservative element in ELW soils.

At the present time, $Al^{3+}$ concentrations in ELW surface waters have not been observed to reach toxic levels (Lund et al., 1987). Concentrations are, in general, consistent with gibbsite saturation. Based on other studies of streams in mountainous terrain, the reaches of the streams feeding Emerald Lake which are most likely to release high levels of the toxic form of $Al^{3+}$, inorganic monomeric $Al^{3+}$ (Driscoll et al., 1980), are the sections which drain soils high in organic matter. This mainly involves the section of the inlet streams coursing through Lithic Cryumbrepts between the pond and Emerald Lake. In these sections, acidic snowmelt or storm flow could displace exchangeable $Al^{3+}$, which could reach levels in excess of $Al(OH)_3$ saturation. If the pH of the runoff were sufficiently low $Al^{3+}$ might reach toxic levels. Fish kill was observed in the upper reaches of West Wachusett Brook when stream pH dropped to 4.16 and inorganic monomeric $Al^{3+}$ exceeded 10 umol/L (McAvoy, 1989). High $Al^{3+}$ levels in this case were attributable to exchangeable $Al^{3+}$ in the soil. For the rest of ELW, soil solution and surface water Al concentrations will continue to be controlled by a combination of $Al(OH)_3$ dissolution and $Al^{3+}$ exchange.

## CONCLUSIONS

Annual $H^+$ deposition rates at ELW are at most 10% of the sum of base cations stored in the full depth of the high elevation map units with exchangeable cations in the range 0.1 to 1.0 $mEq/m^2$. Under these conditions and based on current understanding of the influence of exchangeable bases on acidic deposition, we expect that during a given snowmelt event, soil solution ANC could become negative. This would result in a negative ANC in surface water drainage from these soils. Mineral weathering should replace base cations at an annual rate sufficient to replace those exported. If they were not replaced rapidly enough, $H^+$ deposition of 0.01 $Eq/m^2/yr$ could deplete exchangeable bases within 10 to 100 years in nearly all of ELW.

Annual sulfate deposition rates range from 5 to 24% of the estimated adsorption capacity for the surface 10 cm of soil. Under these conditions sulfate saturation could occur within 4-20 years. While ELW soils may have the capacity to adsorb 4-9 $mEq/m^2$ sulfate annually, it appears that they may be close to capacity already. The influence of sulfate adsorption on surface water concentrations in ELW is to delay the transport of sulfate relative to water inputs. This may or may not produce a sufficient temporary increase in ANC to reduce the effects of acidic snowmelt or rain event on ELW soils and streams.

Based on other studies of streams in mountainous terrain, the reaches of the streams feeding Emerald Lake which are most likely release high levels of the toxic form of $Al^{3+}$ are the sections which drain soils high in organic matter. This mainly involves the section of the inlet streams coursing through Lithic Cryumbrepts between the pond and Emerald Lake. In these sections, acidic snowmelt or storm flow could displace exchangeable $Al^{3+}$, which could reach levels in excess of $Al(OH)_3$ saturation. If the pH of the runoff were sufficiently low $Al^{3+}$ might reach toxic levels. In the rest of ELW, soil solution and surface water Al concentrations are controlled by a combination of $Al(OH)_3$ (gibbsite) dissolution and $Al^{3+}$ exchange.

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Table 4-1. Cation exchange capacities of ELW soils at pH 7.

| Depth | Mean CEC | SE[1] | n[2] |
|---|---|---|---|
| | --------mEq/100g------- | | |
| | Entic Cryumbrept (EaD) Bench Meadow | | |
| 0-10 | 26.88 | 3.21 | 12 |
| 10-20 | 14.86 | 1.01 | 11 |
| 20-30 | 11.23 | 1.52 | 9 |
| 30-40 | 8.97 | 0.66 | 6 |
| 40-50 | 12.16 | 1.22 | 2 |
| 50-60 | 9.79 | 1.32 | 2 |
| 60-70 | 7.78 | | 1 |
| | Cryorthod Association (TdoF-R) Pimo Stand | | |
| 0-10 | 11.18 | 0.88 | 12 |
| 10-20 | 9.20 | 0.51 | 12 |
| 20-30 | 11.30 | 0.57 | 7 |
| 30-40 | 11.49 | | 1 |
| 40-50 | 13.86 | | 1 |
| | Lithic Cryumbrept (LeC-R) Inlet Meadow | | |
| 0-10 | 30.52 | 3.77 | 12 |
| 10-20 | 24.45 | 2.15 | 10 |
| 20-30 | 21.56 | 2.66 | 8 |
| 30-40 | 23.73 | 2.41 | 5 |

[1] Standard error
[2] Number of samples analyzed

Table 4-2. Exchangeable cations for ELW soil map units.

| Depth | XCa[1] | XMg | XNa | XK | Sum XBases | |
|---|---|---|---|---|---|---|
| cm | ---------------mEq/100g----------------- | | | | | |
| TdoF-R Cryorthod Association, Pimo Stand | | | | | | |
| 0-10 | 1.745 | 0.104 | 0.009 | 1.514 | 3.372 | Mean |
| | 0.558 | 0.042 | 0.004 | 0.247 | 0.843 | SE[2] |
| 10-20 | 0.675 | 0.052 | 0.005 | 1.173 | 1.849 | Mean |
| | 0.139 | 0.015 | 0.002 | 0.120 | 0.220 | SE |
| 20-30 | 0.878 | 0.051 | 0.003 | 1.179 | 2.111 | Mean |
| | 0.293 | 0.020 | 0.005 | 0.168 | 0.460 | SE |
| 30-40 | 0.434 | 0.013 | 0.007 | 0.508 | 0.508 | Mean |
| 40-47 | 0.753 | 0.010 | 0.007 | 0.440 | 1.209 | Mean |
| LeC-R Lithic Cryumbrept, Inlet Meadow | | | | | | |
| 0-10 | 7.648 | 0.524 | 0.014 | 4.710 | 10.003 | Mean |
| | 1.426 | 0.080 | 0.006 | 0.506 | 1.978 | SE |
| 10-20 | 2.595 | 0.150 | 0.015 | 1.759 | 4.519 | Mean |
| | 0.560 | 0.022 | 0.007 | 0.229 | 0.776 | SE |
| 20-30 | 0.709 | 0.049 | 0.016 | 0.644 | 1.418 | Mean |
| | 0.147 | 0.009 | 0.003 | 0.102 | 0.192 | SE |
| 30-40 | 0.505 | 0.031 | 0.007 | 0.267 | 0.721 | Mean |
| | 0.078 | 0.002 | 0.007 | 0.037 | 0.138 | SE |
| EaD Entic Cryumbrept, Bench Meadow | | | | | | |
| 0-10 | 4.055 | 0.309 | 0.018 | 3.777 | 8.158 | Mean |
| | 0.763 | 0.053 | 0.015 | 0.611 | 1.401 | SE |
| 10-20 | 1.891 | 0.145 | 0.004 | 2.141 | 4.181 | Mean |
| | 0.653 | 0.051 | 0.004 | 0.412 | 1.089 | SE |
| 20-30 | 0.403 | 0.026 | 0.000 | 0.924 | 1.350 | Mean |
| | 0.119 | 0.006 | 0.003 | 0.125 | 0.183 | SE |
| 30-40 | 0.431 | 0.021 | 0.004 | 0.631 | 1.087 | Mean |
| | 0.137 | 0.005 | 0.003 | 0.101 | 0.156 | SE |
| 40-50 | 0.750 | 0.026 | 0.003 | 0.608 | 1.387 | Mean |
| | 0.046 | 0.002 | 0.004 | 0.077 | 0.026 | SE |
| 50-60 | 0.656 | 0.022 | 0.000 | 0.392 | 1.054 | Mean |
| | 0.062 | 0.001 | 0.004 | 0.036 | 0.103 | SE |
| 60-70 | 0.063 | 0.000 | 0.000 | 0.149 | 0.035 | Mean |

[1] "X" denotes exchangeable in pH 7 ammonium acetate.

[2] Standard error.

Table 4-2 (cont.): Exchangeable cations for ELW soil map units.

| Depth | XCa[1] | XMg | XNa | XK | Sum XBases | |
|---|---|---|---|---|---|---|
| cm | mEq/100g | | | | | |
| | LcF-R | Lithic Cryumbrept, Ridge | | | | |
| 0-10 | 0.118 | 0.019 | 0.005 | 0.092 | 0.266 | Mean |
| | 0.026 | 0.009 | 0.001 | 0.015 | 0.042 | SE |
| 10-20 | 0.083 | 0.013 | 0.003 | 0.063 | 0.161 | Mean |
| | 0.016 | 0.005 | 0.001 | 0.014 | 0.033 | SE |
| 20-30 | 0.049 | 0.005 | 0.004 | 0.034 | 0.092 | Mean |
| | 0.004 | 0.000 | 0.000 | 0.006 | 0.011 | SE |
| 30-40 | 0.080 | 0.006 | 0.003 | 0.040 | 0.129 | Mean |
| | 0.031 | 0.002 | 0.001 | 0.011 | 0.042 | SE |
| | TsD | Typic Cryorthent, Alta Cirque | | | | |
| 0-10 | 0.130 | 0.032 | 0.008 | 0.097 | 0.267 | Mean |
| | 0.049 | 0.021 | 0.002 | 0.049 | 0.121 | SE |
| 10-20 | 0.079 | 0.015 | 0.005 | 0.054 | 0.153 | Mean |
| | 0.007 | 0.007 | 0.000 | 0.010 | 0.010 | SE |
| 20-30 | 0.082 | 0.016 | 0.006 | 0.044 | 0.147 | Mean |
| | 0.004 | 0.007 | 0.000 | 0.014 | 0.017 | SE |

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[1] "X" denotes exchangeable in pH 7 ammonium acetate.

[2] Standard error.

Table 4-3. Estimates of exchangeable cation storage by map unit.

| Map Unit | Similar Soils | Volume | Depth | Exchangeable Cations | | |
|---|---|---|---|---|---|---|
| | | $m^3x10^3$ | m | $Eq/m^3$ | $Eq/m^2$ | kEq |
| Miscellaneous Map Units-not supporting terrestrial vegetation | | | | | | |
| Rj | Rock | 0.0 | 0.000 | 0.0 | 0.0 | 0.0 |
| T | Talus | 47.4 | 0.249 | 1.8 | 0.4 | 83.8 |
| Ru | Rock | 0.0 | 0.000 | 0.0 | 0.0 | 0.0 |
| G | Colluvium | 9.6 | 0.249 | 1.8 | 0.4 | 16.9 |
| K | Colluvium | 5.4 | 0.249 | 1.8 | 0.4 | 9.6 |
| F-K | Colluvium | 3.0 | 0.249 | 1.8 | 0.4 | 5.2 |
| Cryaquept-"Parson's" Pond | | | | | | |
| CqB | * Aquept | 1.3 | 0.500 | 40.5 | 20.2 | 52.3 |
| Cryofluvent-"Aplite Dike" inlet to the lake | | | | | | |
| TfB | * Fluvent | 1.0 | 1.500 | 36.1 | 54.2 | 36.6 |
| Entic Cryumbrept-bench meadow, wet | | | | | | |
| EaD | 1 Umbrept 1 | 2.2 | 0.373 | 36.1 | 13.5 | 80.8 |
| Lithic Cryumbrepts-well drained on slopes and ridges | | | | | | |
| LcF | Umbrept 2 | 0.8 | 0.337 | 1.5 | 0.5 | 1.2 |
| LcF-R | 2 Umbrept 2 | 7.1 | 0.337 | 1.5 | 0.5 | 11.0 |
| R-LcF | Umbrept 2 | 16.3 | 0.337 | 1.5 | 0.5 | 25.0 |
| R-LcE | Umbrept 2 | 1.8 | 0.337 | 1.5 | 0.5 | 2.8 |
| R-LeF | Umbrept 2 | 2.4 | 0.337 | 1.5 | 0.5 | 3.6 |
| LeD | Umbrept 2 | 1.1 | 0.337 | 1.5 | 0.5 | 1.6 |
| Lithic Cryumbrepts-wetter, willow (Salix) cover | | | | | | |
| LdF | Umbrept 3 | 9.0 | 0.237 | 59.2 | 14.0 | 530.5 |
| LdF-R | Umbrept 3 | 1.8 | 0.237 | 59.2 | 14.0 | 104.4 |
| LeC-R | 3 Umbrept 3 | 2.4 | 0.237 | 59.2 | 14.0 | 141.2 |
| LfqC | Umbrept 3 | 0.2 | 0.237 | 59.2 | 14.0 | 14.2 |
| T-LeF | Umbrept 3 | 0.5 | 0.237 | 59.2 | 14.0 | 32.5 |
| Entic Cryumbrepts-very well drained | | | | | | |
| EbF | * Umbrept 4 | 2.5 | 0.700 | 8.5 | 6.0 | 21.3 |
| EcF | * Umbrept 4 | 22.1 | 0.700 | 8.5 | 6.0 | 189.0 |
| Cryorthod association-Western White Pine (Pimo) stand | | | | | | |
| TdoF-R | 4 Orthod | 6.3 | 0.326 | 21.8 | 7.1 | 138.5 |
| Cryorthents-very well drained glacial till and colluvium | | | | | | |
| TrF | Orthent | 4.0 | 0.249 | 1.8 | 0.4 | 7.1 |
| TsD | 5 Orthent | 3.7 | 0.249 | 1.8 | 0.4 | 6.6 |
| ToF | Orthent | 1.6 | 0.249 | 1.8 | 0.4 | 2.8 |
| TpD-R | Orthent | 0.9 | 0.249 | 1.8 | 0.4 | 1.6 |
| TrF-R | Orthent | 0.3 | 0.249 | 1.8 | 0.4 | 0.6 |
| ToC | Orthent | 0.2 | 0.249 | 1.8 | 0.4 | 0.4 |

Table 4-4. Langmuir adsorption parameters for sulfate for two representative ELW soils.

| pH | M[1] | K[2] |
|---|---|---|
| | mEq/kg | L/mEq |
| Lithic Cryumbrept (R-LcF) 0-15 cm | | |
| 5.77 | 0.54 | 9.4 |
| 4.18 | 2.37 | 10.7 |
| 3.62 | 2.56 | 16.4 |
| 3.29 | 4.86 | 8.9 |
| Entic Cryumbrept (EcF) 0-15 cm | | |
| 6.13 | 0.38 | 8.5 |
| 4.65 | 0.42 | 9.6 |
| 3.64 | 2.16 | 10.4 |
| 3.23 | 3.13 | 4.8 |

[1] Capacity term

[2] Affinity term

Table 4-5. Sulfate adsorption capacity estimates for ELW for the surface 10 cm at pH 5.4.

| Map Unit | Similar Soils | Soil Area | S-Adsorption Maximum | Maximum |
|---|---|---|---|---|
| | | ha | Eq/m$^2$10cm | kEq/10 cm |
| Miscellaneous Map Units-not supporting vegetation | | | | |
| Rj | Rock | 0 | 0 | 0 |
| T | Talus | 19.029 | 0.066 | 12.6 |
| Ru | Rock | 0 | 0 | 0 |
| G | Colluvium | 3.842 | 0.066 | 2.5 |
| K | Colluvium | 2.183 | 0.066 | 1.4 |
| F-K | Colluvium | 1.186 | 0.066 | 0.8 |
| Cryaquept-"Parson's" Pond | | | | |
| CqB | * Aquept | 0.258 | 0.059 | 0.2 |
| Cryofluvent-"Aplite Dike" inlet to the lake | | | | |
| TfB | * Fluvent | 0.068 | 0.044 | 0.0 |
| Entic Cryumbrept-bench meadow, wet | | | | |
| EaD | 1 Umbrept 1 | 0.600 | 0.043 | 0.3 |
| Lithic Cryumbrepts-well drained | | | | |
| LcF | Umbrept 2 | 0.228 | 0.077 | 0.2 |
| LcF-R | 2 Umbrept 2 | 2.118 | 0.077 | 1.6 |
| R-LcF | Umbrept 2 | 4.838 | 0.077 | 3.7 |
| R-LcE | Umbrept 2 | 0.538 | 0.077 | 0.4 |
| R-LeF | Umbrept 2 | 0.700 | 0.077 | 0.5 |
| LeD | Umbrept 2 | 0.316 | 0.077 | 0.2 |
| Lithic Cryumbrepts-wetter, along stream channels | | | | |
| LdF | Umbrept 3 | 3.779 | 0.035 | 1.3 |
| LdF-R | Umbrept 3 | 0.744 | 0.035 | 0.3 |
| LeC-R | 3 Umbrept 3 | 1.006 | 0.035 | 0.4 |
| LfqC | Umbrept 3 | 0.101 | 0.035 | 0.0 |
| T-LeF | Umbrept 3 | 0.232 | 0.035 | 0.1 |
| Entic Cryumbrepts-well drained | | | | |
| EbF | * Umbrept 4 | 0.356 | 0.044 | 0.2 |
| EcF | * Umbrept 4 | 3.160 | 0.044 | 1.4 |
| Cryorthod association-pine stand | | | | |
| TdoF-R | 4 Orthod | 1.948 | 0.069 | 1.3 |
| Cryorthents | | | | |
| TrF | Orthent | 1.619 | 0.066 | 1.1 |
| TsD | 5 Orthent | 1.502 | 0.066 | 1.0 |
| ToF | Orthent | 0.632 | 0.066 | 0.4 |
| TpD-R | Orthent | 0.364 | 0.066 | 0.2 |
| TrF-R | Orthent | 0.139 | 0.066 | 0.1 |
| ToC | Orthent | 0.091 | 0.066 | 0.1 |

Table 4-6. Mean amorphous Al content of three ELW soil map units.

| Map Unit | Amorphous Al Content | | | | | | |
|---|---|---|---|---|---|---|---|
| | g/kg | | | | | | |
| Depth: | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 |
| EaD | 11.74 | 13.68 | 15.39 | 11.75 | 14.90 | 12.34 | 12.44 |
| TdoF-R | 9.48 | 12.14 | 16.37 | 21.62 | 25.67 | | |
| LeC-R | 17.20 | 23.94 | 30.03 | 22.82 | | | |

Table 4-7. Mean K-exchangeable Al of three ELW soil map units.

| Map Unit | Exchangeable Al Content | | | | | | |
|---|---|---|---|---|---|---|---|
| | mEq/kg | | | | | | |
| Depth: | 0-10 | 10-20 | 20-30 | 30-40 | 40-50 | 50-60 | 60-70 |
| EaD | 4.99 | 3.89 | 2.70 | 1.84 | 2.24 | 2.19 | 1.15 |
| TdoF-R | 2.67 | 2.39 | 2.23 | 2.72 | 2.13 | | |
| LeC-R | 8.97 | 12.77 | 9.86 | 7.97 | | | |

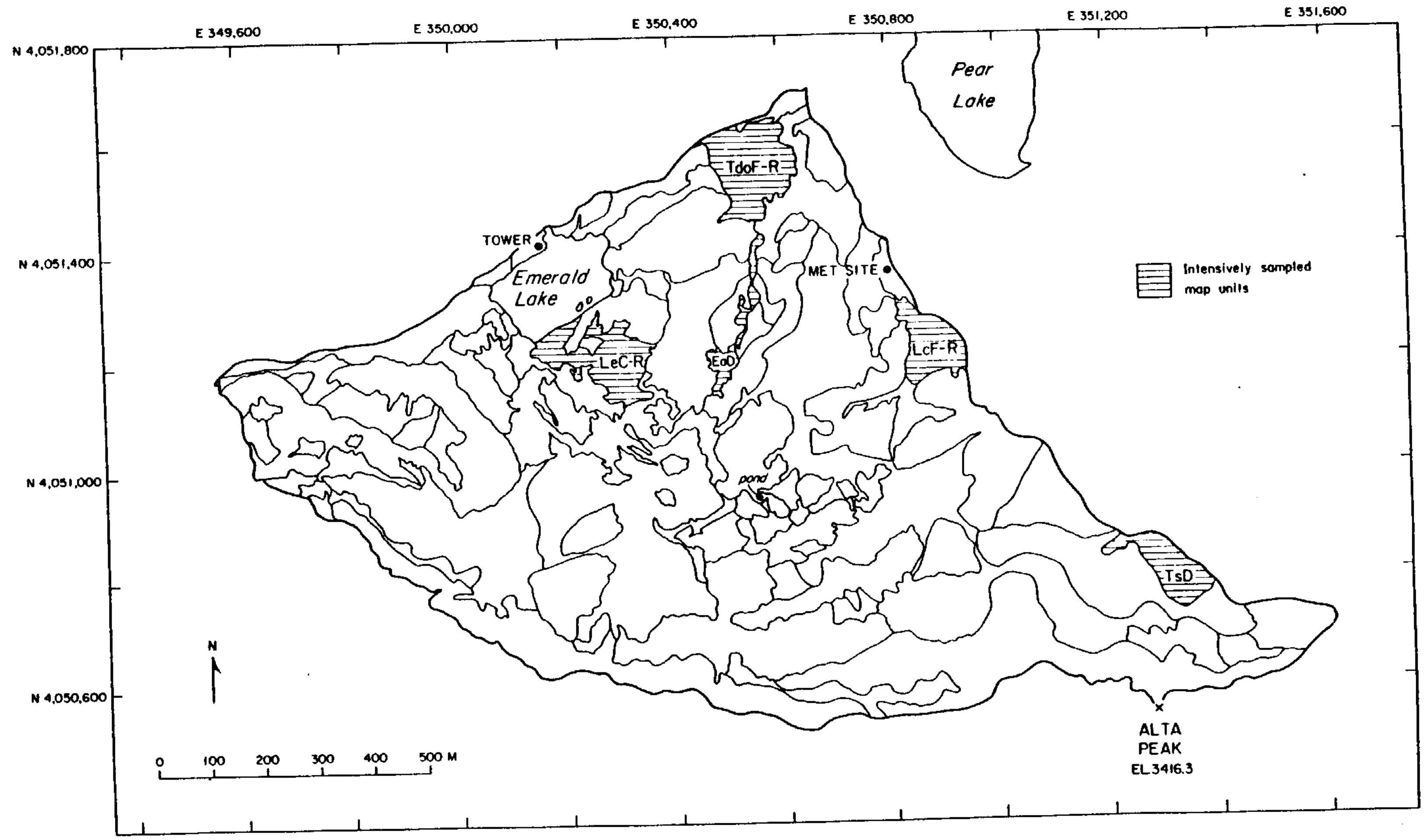

Figure 4-1. ELW intensively sampled map unit areas.

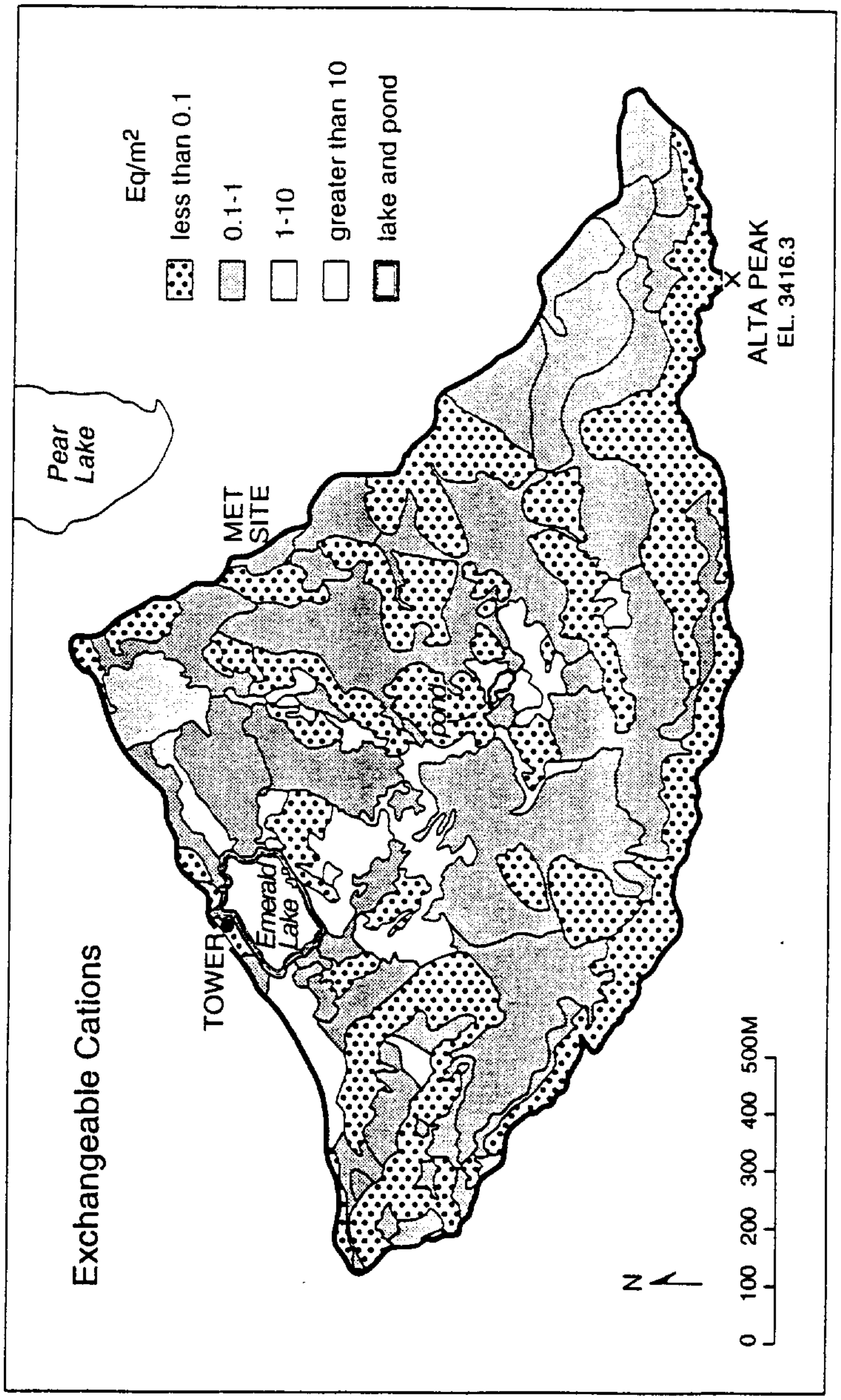

Figure 4-2. Distribution of exchangeable base cations in ELW soil map units.

Figure 4-3a.

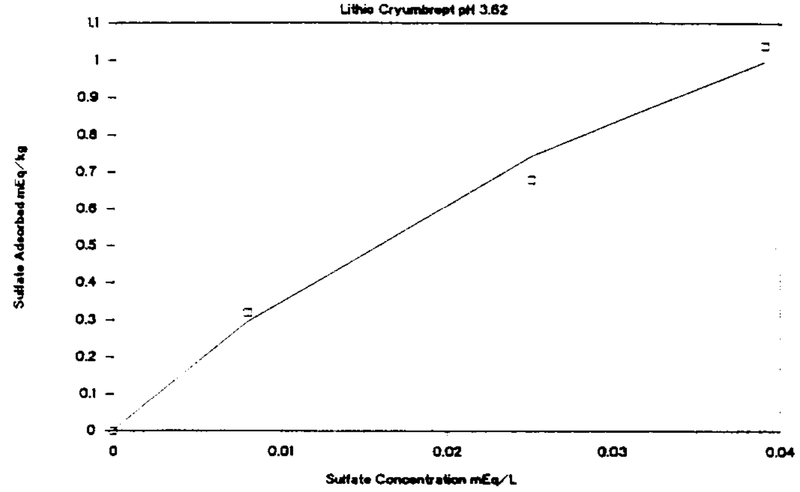
Lithic Cryumbrept pH 3.62

Figure 4-3b.

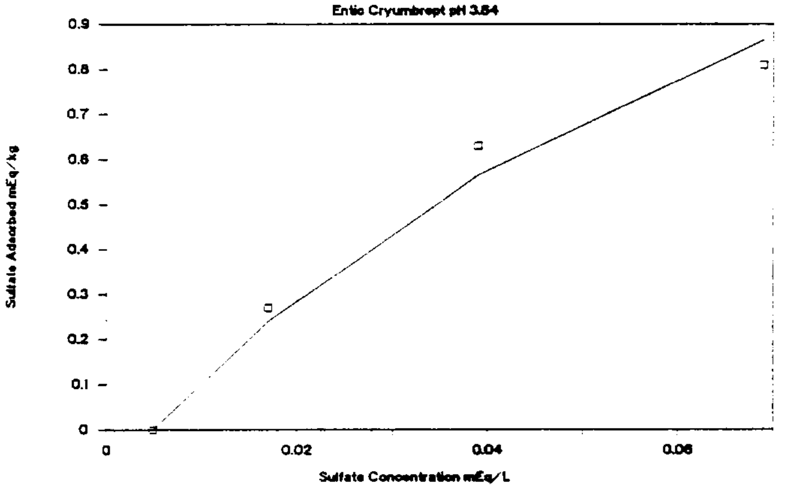
Entic Cryumbrept pH 3.84

Figure 4-3. Sulfate adsorption isotherms for two ELW surface soils at pH 3.5: a) Lithic Cryumbrept (R-LcF) 0-15 cm, b) Entic Cryumbrept (EcF) 0-15 cm.

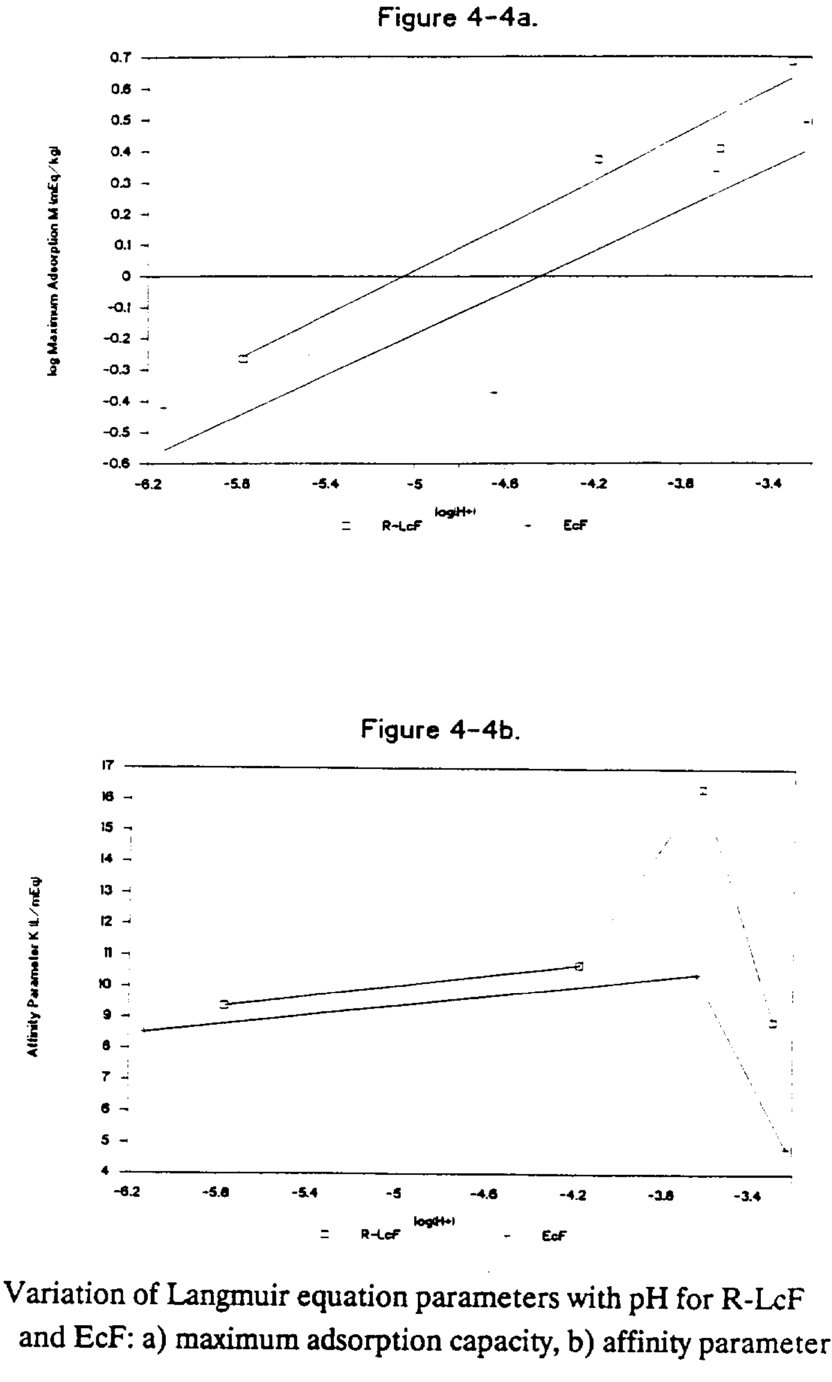

Figure 4-4a.

Figure 4-4b.

Figure 4-4. Variation of Langmuir equation parameters with pH for R-LcF and EcF: a) maximum adsorption capacity, b) affinity parameter.

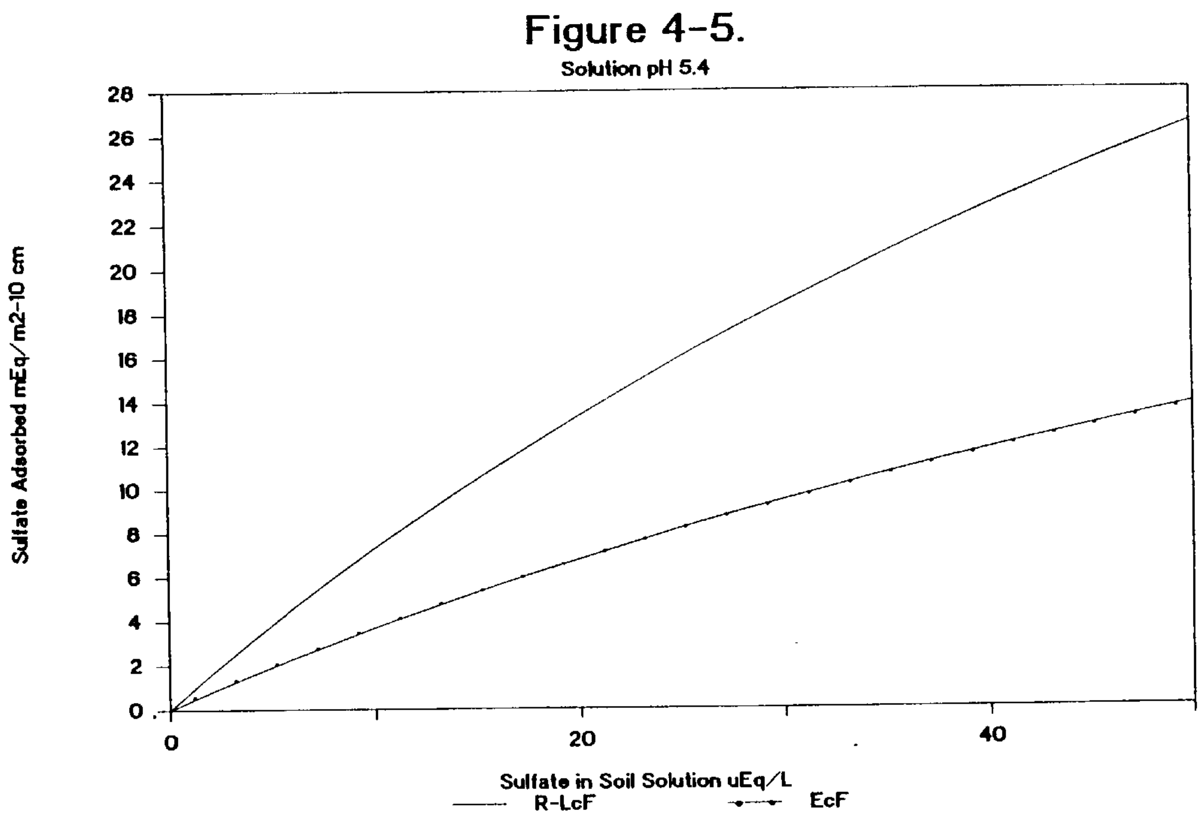

Figure 4-5. Demonstration of use of derived Langmuir isotherms for pH 5.4, R-LcF and EcF.

Figure 4-6

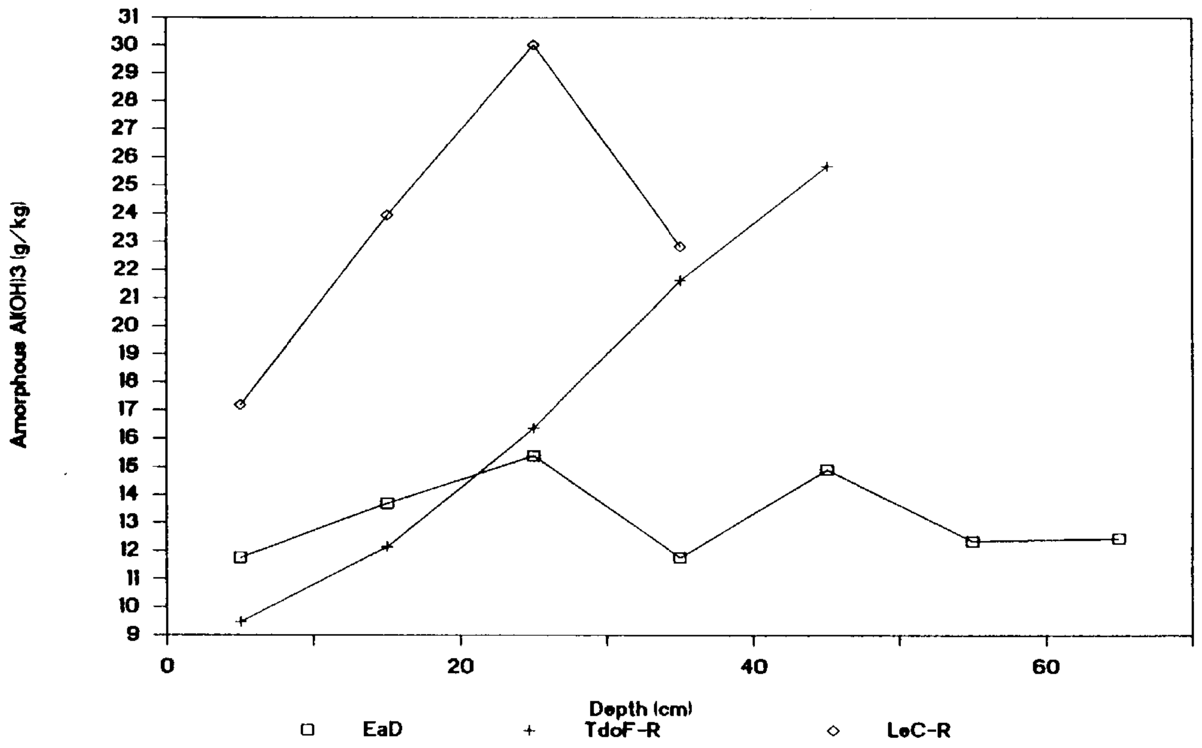

Figure 4-6. Amorphous Al depth profiles for three ELW soil map units.

Figure 4-7

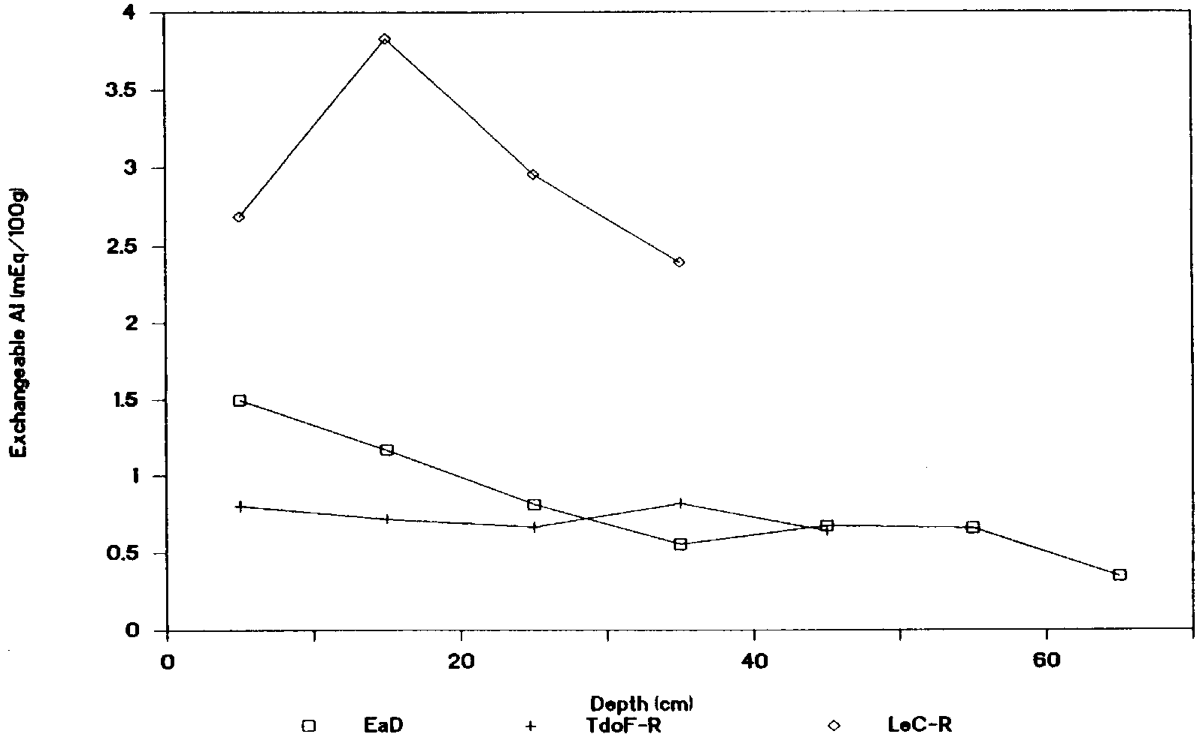

Figure 4-7. Exchangeable Al depth profiles for three ELW soil map units.

# *CHAPTER 5*

# *MINERALIZATION, NITRIFICATION AND DENITRIFICATION*

The principal form of nitrogen in most soils is as organic nitrogen (Brady, 1984). Significant proportions of soil sulfur and phosphorus are also found in the organic fractions. While they remain in the organic fraction they are relatively immobile and they are not available to be involved in soil based phenomena such as acidification of soils and waters, plant uptake, exchange reactions or mineral dissolution or precipitation reactions. In order for the California Air Resources Board to assess the potential impact of anthropogenic inputs of nitrogen and sulfur on natural ecosystems, the amounts of these materials must be placed in perspective relative to the amounts naturally present in soils and the rates at which they can be converted to more active inorganic forms through mineralization. In other words, soils have internal sources of $NH_4$-N, $NO_3$-N, and $SO_4$-S which need to be assessed. Nitrate-nitrogen can also be lost from some systems through denitrification and it is important to determine if this sink is significant in ELW.

Results of research conducted during early phases of the ELW project indicated that many soils of ELW contain large quantities of potentially mineralizable nitrogen (PMN) and sulfur. However, an *in situ* buried bag study indicated that only a very small fraction of the PMN and S was mineralized during the months of July and August, 1985. In some cases, there was even net immobilization of the inorganic N and S. Numerous factors appeared to affect the N and S mineralization processes in soils of ELW. Among the most important factors for N mineralization were soil moisture and temperature, the level of substrates (C and N) and the first order rate constant (k) for nitrogen mineralization (Lueking and Lund, 1985). Temperature and moisture also appeared to be major factors in limiting S mineralization. Additional research was conducted at ELW and in the laboratory to further elucidate the factors influencing mineralization of nitrogen and sulfur at ELW.

## OBJECTIVES

The objectives of the research related to nitrogen and sulfur at ELW were:

1) to determine effects of soil moisture and soil temperature on the mineralization and nitrification process.
2) to determine levels of potential denitrification in soils of ELW, the effects of soil temperature and moisture on denitrification, and in situ denitrification rates.

## METHODS

Buried bags (Eno, 1960) were installed at four sites on four dates (August 5, 1986; September 3, 1986; October 28, 1986; June 8, 1987) to determine "in field" N and S transformation rates for various seasons. The sites were designated as "ridge" which was located in a Lithic Cryumbrept mapping unit (LcF-R), "bench" in a Entic Cryumbrept mapping unit (EaD), "inlet meadow" in a Lithic-Histic Cryaquept mapping unit (LfqC) and "pine stand" in a Typic Cryorthod mapping unit (TdoF-R). The locations of the map delineations where the buried bag studies were carried out are shown in Figure 5-1. Bags installed during one time were removed for analysis during the next installation period. Those installed on June 8. 1987 were removed on August 27, 1987. When the soil pits were excavated for installation of the buried bags, soil samples were taken to measure soil moisture content, $NH_4$-N, $NO_3$-N, $SO_4$-S, and $PO_4$-P. Part of this sample was then placed into three plastic bags, sealed and returned to the soil pit for incubation. After the incubation period the bags were removed and the contents were analyzed for moisture content, $NH_4$-N, $NO_3$-N, $SO_4$-S, and $PO_4$-P. Nitrification was calculated as the percent of the mineralized N ($NO3^-$ and $NH4^+$) existing as $NO_3$-N. Tubes containing a buffered sucrose solution were installed with the buried bags to determine an integrated temperature for the incubation period based on sucrose inversion (Lee, 1969).

An incubation study was carried out for 16 weeks at three temperature levels that generally exist in the field (2, 15, and 25C). The samples were incubated at one moisture content and were leached with 100 mL of 0.01M KCl every two weeks (Stanford and Smith, 1972). The extracts were analyzed for $NH_4$-N and $NO_3$-N using automated colorimetric indophenol blue and cadmium reduction techniques, respectively (Keeney and Nelson, 1982). The first order rate constant for N mineralization (k) was calculated from: log(No - Nt) = No - k(t)/2.303 where No = PMN, Nt = quantity of N mineralized, and t = time (Stanford and Smith, 1972).

An incubation study was carried out for 16 weeks at a range of soil moisture contents (equal to 20, 40, 60, 80% of pore space). The samples were incubated at the optimum temperature determined by the aforementioned temperature study and leached with 100 mL of 0.01M KCl every 2 weeks. Extracts were analyzed for $NH_4$-N and $NO_3$-N as described above.

An *in situ* technique based on acetylene blockage of the conversion of $N_2O$ to $N_2$ was used to estimate denitrification in the field (Ryden et al., 1978, 1979). Small metal boxes (50x17x20 cm) inserted into the soil to a depth of 10 cm were used to trap denitrification products effluxing from the soil. A current of air was pulled through the box by a small vacuum pump connected to a port at one end of the box. A small port was open to the atmosphere at the other end of the box. Acetylene was injected into the soil through small tubes inserted up to a depth of one meter in the soil around the cover box. These small tubes had perforations along the sides to allow acetylene to enter the soil at several levels.

Nitrous oxide effluxing from the soil was swept from the cover box by the moving air and trapped on a molecular sieve placed inline. This sieve was transported to the laboratory where the $N_2O$ was displaced from the sieve with water and analyzed by gas chromatography.

## RESULTS AND DISCUSSION

Based on data obtained by the buried bag technique, the lowest daily rate of in-situ N mineralization in all four soils studied occurred over the winter months, a period of 224 days from October 28, 1986 to June 8, 1987 (Table 5-1). Mean soil temperature during this period were also the lowest (Table 5-1). These studies indicate that soil temperature is a critical factor in N mineralization in-situ.

Sulfur mineralization values were not consistently lower for this date. Soil temperature may not be the most important controlling factor for S mineralization. Phosphorus mineralization was at very low levels below our detection limits.

Nitrification was consistently highest in the ridge site during all field incubation periods (Table 5-1). The pine stand site also had high rates of nitrification for the summer 1987 incubation. Soil at the other two sites had the lowest nitrification during the 224 day winter incubation.

Mean annual soil temperatures were similar for all soils (Table 5-2). Mean annual soil moisture levels were the highest in the bench and inlet meadow soils (Table 5-2). Net N mineralization was highest in the surface horizon of the Lithic Cryorthent (pine stand) and the top 20 cm of the Lithic Histic Cryaquept (Table 5-2). Net nitrate production was the highest in the Lithic Cryumbrept (ridge). Net S mineralization was highly variable and meaningful trends were hard to assess.

In the laboratory studies, nitrogen mineralization was found to be directly related to soil incubation temperature (Table 5-3). Both the quantity of N mineralized and the estimated potentially mineralizable N (No) increased as temperature increased in all soils. The first order rate constant (k) decreased with increasing temperature in the bench and inlet meadow soils. In the pine stand soil, the lowest k value was observed at 15C.

There were no significant differences in N mineralization, No, or k due to moisture levels for any soil (Table 5-4). The laboratory study reflects the same conclusion as in-situ studies i.e. that soil temperature is the critical factor in N mineralization.

Mass balance calculations for comparison of nitrate ($NO_3^-$) and ammonium ($NH_4^+$) deposition with soil solutions show that N is accumulating in the terrestrial component of ELW. Concentrations in the soil solution are minimal during the summer months when soil temperature is highest. This is also the period when maximum plant and microbial growth would be expected.

One potential sink for N which we investigated was denitrification. In this process soil $NO_3^-$ is converted to gaseous $N_2O$ and $N_2$ and lost to the atmosphere. Rates of N loss on the order of 0.071 to 0.19 mEq($NO_3^-$)/$m^2$/da were measured in two Entisols during May and June, 1987. These values are much smaller than peak flux values of 1.7 to 7.6 mEq($NO_3$)/$m^2$/da found in some intensively managed agricultural soils of California (Ryden and Lund, 1980). Denitrification rates were near zero in July when soils were dry and at one site in May because of frozen soil (Table 5-5). These rates of denitrification measured are not insignificant compared with annual rates of $NO_3$ deposition of 4.1 mEq/$m^2$/yr (1985) and 8.1 mEq/$m^2$/yr (1986) (Dozier et al., 1987). Denitrification of the annual $NO_3$ deposition per $m^2$ would require only 22 and 43 days at the maximum rates measured. The total soil area involved only amounts to approximately 6.8 ha, however. Therefore, the net impact on the watershed is probably minimal.

## CONCLUSIONS

During the summers, mineralization (the release of N and S from organic matter by microbial activity) was measured *in situ*. Rates of N mineralization were on the order of 0.3 to 1.6 mEq(as $NH_4^+$)/$m^2$-10cm/da. Not all $NH_4^+$ produced by mineralization is converted to $NO_3^-$. About 50% was converted in the Entisol measured and less than 10% in the Inceptisols. Mineralization rates for both N and S were significant compared with the $NH_4$ deposition rates of 3.0 $mEq/m^2$ (1985) and 8.7 $mEq/m^2$ (1986) and $SO_4$ deposition rates of 4.3 $mEq/m^2$ (1985) and 6.5 $mEq/m^2$ (1986) (Dozier et al., 1987). Rates of S mineralization were on the order of 0.7 $mEq(SO_4^{2-})/m^2$-10cm/da. In many measurements N and S were consumed rather than released, resulting in a net negative mineralization rate. This is likely due to incorporation of N and S into microbial biomass on the short term and the apparent loss of these nutrients from the system.

Soil temperature was found to be more critical in affecting mineralization than was soil moisture. However, when either low temperatures or very low soil moisture contents exist, mineralization will be minimal. Likewise low soil moisture conditions will not be conducive to denitrification. Given the limited extent of soil area and limited period of waterlogged conditions, denitrification appears to have very little significance as a sink for $NO_3$ deposition at ELW.

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Table 5-1. Means for seasonal N and S mineralization, nitrification, soil temperature, and soil moisture from buried bag studies at Emerald Lake Watershed.

| Instal. Date | Depth cm | net N mineral. mg/Kg/da | net S mineral. mg/Kg/da | nitrif. % | soil temp oC | soil moist. % |
|---|---|---|---|---|---|---|
| | | | Lithic Cryumbrept (ridge) | | | |
| 8/5/86 | 0-10 | 0.626 | 0.089 | 46.4 | 15.3 | 9.2 |
| 29 d | 10-20 | 0.309 | 0.739 | 39.1 | 14.4 | 16.9 |
| | 20-30 | 0.168 | 0.393 | 16.4 | 13.2 | 14.0 |
| 9/3/86 | 0-10 | 0.215 | -0.159 | 46.5 | 5.6 | 4.0 |
| 55 d | 10-20 | 0.122 | -0.101 | 50.5 | 5.4 | 10.1 |
| | 20-30 | 0.145 | -0.086 | 34.8 | 5.5 | 14.2 |
| 10/28/86 | 0-10 | 0.014 | 0.042 | 48.2 | 0.2 | 18.1 |
| 224 d | 10-20 | 0.044 | 0.118 | 48.3 | 0.2 | 18.9 |
| | 20-30 | 0.022 | 0.008 | 38.0 | 0.2 | 15.9 |
| 6/8/87 | 0-10 | 0.020 | | 100.0 | 15.0 | 25.0 |
| 85 d | 10-20 | -0.023 | | 85.0 | 13.9 | 27.2 |
| | 20-30 | -0.022 | | 68.9 | 13.2 | 23.2 |
| | | | Entic Cryumbrept (bench) | | | |
| 8/5/86 | 0-10 | 0.118 | 0.980 | 8.0 | 14.6 | 170.0 |
| 29 d | 10-20 | 0.022 | 0.309 | 10.7 | 13.6 | 56.8 |
| | 20-30 | 0.071 | 0.686 | 8.2 | 12.5 | 39.4 |
| 9/3/86 | 0-10 | 0.378 | -0.319 | 6.8 | 8.2 | 152.0 |
| 55 d | 10-20 | 0.146 | -0.047 | 6.7 | 8.3 | 65.8 |
| | 20-30 | 0.099 | -0.071 | 8.3 | 8.3 | 47.9 |
| 10/28/86 | 0-10 | 0.037 | 0.073 | 0.6 | 2.5 | 136.0 |
| 224 d | 10-20 | 0.061 | 0.069 | 0.6 | 2.4 | 81.9 |
| | 20-30 | 0.024 | 0.055 | 1.1 | 2.5 | 55.1 |
| 6/8/87 | 0-10 | -0.267 | | 2.1 | 13.0 | 104.5 |
| 85 d | 10-20 | -0.140 | | 3.3 | 12.5 | 42.2 |
| | 20-30 | -0.034 | | 0.9 | 11.5 | 44.8 |

Table 5-1. (cont.)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Lithic-Histic Cryaquept (inlet meadow) | | | | |
| 8/5/86<br>29 d | 0-10 | 0.467 | -0.943 | 7.4 | 12.0 | 92.0 |
| | 10-20 | 0.330 | 0.713 | 10.9 | 10.4 | 53.3 |
| | 20-30 | 0.238 | 0.454 | 7.4 | 9.8 | 42.8 |
| 9/3/86<br>55 d | 0-10 | 0.085 | -0.129 | 5.7 | 5.0 | 78.6 |
| | 10-20 | 0.161 | 0.077 | 16.9 | 5.1 | 85.9 |
| | 20-30 | 0.101 | -0.057 | 17.6 | 5.2 | 54.6 |
| 10/28/86<br>224 d | 0-10 | 0.147 | 0.026 | 1.4 | 0.0 | 78.3 |
| | 10-20 | 0.075 | 0.029 | 7.9 | 0.2 | 54.3 |
| | 20-30 | 0.075 | 0.048 | 8.0 | 0.4 | 45.1 |
| 6/8/87<br>85 d | 0-10 | -0.173 | | 9.2 | 11.9 | 93.8 |
| | 10-20 | -0.001 | | 28.3 | 10.8 | 90.8 |
| | 20-30 | -0.097 | | 17.4 | 9.9 | 50.6 |
| | | Lithic Cryorthent (pine stand) | | | | |
| 8/5/86<br>29 d | 0-10 | 0.190 | 0.087 | 14.9 | 11.8 | 8.1 |
| | 10-20 | 0.045 | 0.608 | 4.9 | 11.0 | 5.6 |
| 9/3/86<br>55 d | 0-10 | 0.105 | 0.044 | 5.8 | 5.5 | 2.6 |
| | 10-20 | -0.025 | 0.173 | 6.9 | 5.5 | 4.5 |
| 10/28/86<br>224 d | 0-10 | 0.145 | 0.069 | 23.5 | 1.9 | 22.3 |
| | 10-20 | 0.039 | 0.080 | 3.2 | 1.9 | 10.3 |
| 6/8/87<br>85 d | 0-10 | -0.044 | | 38.1 | 11.1 | 18.8 |
| | 10-20 | -0.015 | | 54.8 | 10.1 | 19.3 |

Table 5-2. Net accumulation (means) of N, $NO_3$-N, and $SO_4$-S from buried bag studies. N mineralization is for period Sept. 3, 1986 to Aug. 27, 1987 (364 days) and S mineralization is for period Aug 7, 1986 to June 9, 1987 (308 days).

| Soil Depth cm | net N min mg/Kg | net $NO_3$-N mg/Kg | net S min mg/Kg | mean annual temp oC | mean annual soil mois % |
|---|---|---|---|---|---|
| Lithic Cryumbrept (ridge) | | | | | |
| 0-10 | 16.67 | 28.95 | 3.26 | 4.5 | 17.5 |
| 10-20 | 14.72 | 19.19 | 42.33 | 4.2 | 19.5 |
| 20-30 | 11.06 | 9.08 | 8.48 | 4.1 | 17.3 |
| Entic Cryumbrept (bench) | | | | | |
| 0-10 | 6.51 | -0.35 | 27.24 | 5.8 | 131.1 |
| 10-20 | 9.70 | -1.34 | 21.95 | 5.7 | 70.2 |
| 20-30 | 7.82 | -0.92 | 28.30 | 5.5 | 51.6 |
| Lithic Histic Cryaquept (inlet meadow) | | | | | |
| 0-10 | 22.83 | 2.60 | -28.70 | 3.6 | 81.9 |
| 10-20 | 25.50 | 5.44 | 31.37 | 3.4 | 67.7 |
| 20-30 | 14.07 | 2.71 | 20.72 | 3.3 | 47.9 |
| Lithic Cryorthent (pine stand) | | | | | |
| 0-10 | 34.58 | 13.76 | 20.43 | 4.6 | 18.4 |
| 10-20 | 5.95 | 5.92 | 45.01 | 4.4 | 11.5 |

Table 5-3. Mean accumulated N, potentially mineralizable N ($N_o$), and the first order rate constant (k) for laboratory incubation of three surface soils of Emerald Lake Watershed as a function of incubation temperature.

| Temp. oC | Cumulative N Mineralized mg/Kg | $N_o$ mg/Kg | k $wk^{-1}$ |
|---|---|---|---|
| | Entic Cryumbrept (bench) | | |
| 2 | 44.5 | 48.4 | 0.172 |
| 15 | 60.9 | 79.8 | 0.045 |
| 25 | 84.7 | 119.3 | 0.038 |
| | Lithic Histic Cryaquept (inlet meadow) | | |
| 2 | 257.6 | 286.3 | 0.071 |
| 15 | 358.5 | 436.0 | 0.054 |
| 25 | 548.4 | 794.5 | 0.037 |
| | Lithic Cryorthent (pine stand) | | |
| 2 | 126.4 | 141.9 | 0.069 |
| 15 | 235.8 | 479.7 | 0.022 |
| 25 | 299.8 | 477.0 | 0.037 |

Table 5-4. Nitrogen mineralization, potentially mineralizable N ($N_o$) and first order rate constant (k) for laboratory incubation of three surface soils from Emerald Lake Watershed, and moisture content during incubation.

| Water filled porespace % | Moist. content wt. % | Cumulative N Mineralized mg/Kg | $N_o$ mg/Kg | k $wk^{-1}$ |
|---|---|---|---|---|
| | | Entic Cryumbrept (bench) | | |
| 20 | 25.1 | 62.2 | 80.6 | 0.053 |
| 40 | 26.2 | 62.6 | 82.2 | 0.054 |
| 60 | 28.9 | 63.8 | 82.2 | 0.179 |
| 80 | 33.2 | 64.8 | 85.1 | 0.053 |
| | | Lithic Histic Cryaquept (inlet meadow) | | |
| 20 | 55.7 | 389.2 | 485.5 | 0.057 |
| 40 | 56.0 | 371.0 | 476.8 | 0.055 |
| 60 | 62.2 | 404.4 | 531.5 | 0.052 |
| 80 | 68.0 | 388.2 | 528.7 | 0.052 |
| | | Lithic Cryorthent (pine stand) | | |
| 20 | 44.9 | 241.2 | 404.4 | 0.042 |
| 40 | 47.7 | 239.2 | 382.9 | 0.044 |
| 60 | 55.0 | 229.2 | 384.2 | 0.042 |
| 80 | 60.7 | 173.1 | 293.4 | 0.043 |

Table 5-5. Mass balance calculations for dentrification in ELW.

| Date | Dentrification Rates<br>Denitrifying Bacteria | <br>Nitrifying Bacteria | Watershed Flux |
|---|---|---|---|
| | ---------mgN/$m^2$/da | --------- | gN/da |
| Wet Cryumbrepts and Cryaquept Map Units: 8.0 ha | | | |
| 5/1/87 | 0.0 | 0.0 | 0.0 |
| 5/1/87 | 0.0 | 0.0 | 0.0 |
| 6/11/87 | 0.0 | 1.0 | 79.0 |
| 6/11/87 | 0.9 | 1.6 | 196.4 |
| 7/22/87 | 0.0 | 0.0 | 0.0 |
| 7/22/87 | 0.4 | 0.1 | 39.9 |
| Entic Cryumbrept (EaD): 0.6 ha | | | |
| 4/30/87 | 0.0 | 0.2 | 1.2 |
| 4/30/87 | 1.8 | 0.9 | 16.0 |
| 6/10/87 | 0.0 | 0.9 | 5.3 |
| 6/10/87 | 0.0 | 0.3 | 1.7 |
| 7/23/87 | 0.0 | 0.0 | 0.0 |
| 7/23/87 | 0.0 | 0.0 | 0.0 |

# *CHAPTER 6*

# *BIOGEOCHEMICAL PROCESSES IN SOILS*

## SECTION 1: THROUGHFALL

Throughfall has received considerable attention in recent years, largely because of concern over the effects of acidic deposition on forest ecosystems. The interactions between rainfall and leaves are numerous. As precipitation passes through a vegetative canopy, its chemical composition is altered by the washoff of aerosols deposited on leaf surfaces (dry deposition) and the exchange of elements in solution with the plant tissue (canopy exchange). Canopy exchange rates are related to differences in canopy foliage such as nutrient content (Henderson et al., 1977) and shape, arrangement and surface roughness (Davidson and Elias, 1982). Dry deposition rates are proportional to aerosol concentrations in the atmosphere. Differences in canopy morphology also influence the quantity of dry deposition on leaf surfaces and the eventual washoff of those leaves by precipitation (White and Turner, 1970). Thus, different vegetative species would be expected to have different contributions to the soils on which they grow.

A major component of throughfall is water soluble organic matter. Part of this dissolved organic C (DOC) is in rainfall, including low molecular weight ( $< 100$ g/mol) organic acids such as formate and acetate (Likens, et al., 1983, and Weathers, et al., 1988). These organic acids probably originate in gaseous emissions from natural sources, since they have relatively high vapor pressures and are ubiquitous in rainfall samples. Organic acids in throughfall also originate from interaction with the leaves, resulting in mixtures of fulvates with complex acidic properties (Brown and Sposito, 1990; McDowell and Likens, 1988; Cronan and Reiners, 1983; Hoffmann, et al., 1980).

Throughfall is of interest to the CARB because of the tendency of leaves to act as receptors for airborne gasses and aerosols associated with acidic deposition. Dry deposition rates are not well known for the Sierra, and throughfall washout of deposition on leaves will be useful for comparison with other methods. Throughfall is also a measure of how acidic deposition interacts with foliage and how well it can be neutralized.

## OBJECTIVE

The objective of this research was

1) to quantitatively evaluate the sources and significance of N, S, and DOC in throughfall and compare the potential impact of throughfall DOC, nitric, and sulfuric acids with wet deposition.

## METHODS

### Throughfall Collection

Collection sites were located under or near three dominant woody vegetation types within ELW (36°35'N, 118°40'W) in Sequoia National Park: *Chrysolepsis sempervirens, Salix orestera,* and a stand of *Pinus monticola* and *Pinus contorta* dominated by *P. monticola* (Figure 6-1). There were two sites for each of the three vegetation types. Each site consisted of six collectors which were deliberately placed three underneath the canopy (throughfall collectors) and three at a distance approximately twice the height of the nearest individual away from the canopy (bulk deposition collectors). The collectors were 1-liter polyethylene bottles with 15 cm polyethylene funnels inserted in the bottle cap. A small amount of cotton was placed in the stems of the funnels to prevent leaves, insects and other debris from falling into the bottles. Throughfall collectors were surrounded by mesh hardware cloth to protect them from rodents (mainly *Marmota flaviventris*). The bulk collectors were attached to redwood stakes by pipe clamps and stood approximately 70 cm above the ground. The collectors at each site were placed 2 to 5 m away from each other as the vegetation allowed.

Samples were collected within two days after each event, chilled to less than 4°C, and filtered with glass microfiber filters (Gelman GF/F) with an effective particle retention size of 0.7 microns (1985) or 0.45 micron Nucleopore polycarbonate membrane filters (1986, 1987). Samples were stored unfrozen between 0 and 4°C. The samples were analyzed immediately for pH. Alkalinity (ANC) was determined on samples with $pH > 4.5$ by microtitration with 0.1 M HCl. Ion chromatography with a Dionex AS4A anion exchange column and $NaHCO_3/Na_2CO_3$ eluant was used for the determination of $Cl^-$, $NO_3^-$, and $SO_4^{2-}$. An automated colorimetric method (Technicon) was used for $NH_4^+$ and $NO_3^-$ analysis. Atomic absorption and flame emission spectroscopy were used to determine $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$. Dissolved organic carbon (DOC) was determined using an automated method (Dohrman) with persulfate/UV digestion and IR detection of CO2.

Recently, researchers analyzing throughfall collection networks have found that rainfall and throughfall concentration data tend to follow a log normal distribution (Kostelnik, et al., 1989; Herbert, 1988; Lewis, et al., 1984). Based on this information and examination of the ELW data, means and standard errors of deposition were calculated for each event from log transformed data. As a check on the quality of the data obtained, the number of collectors required to obtain deposition values within 10% of the mean was calculated for 5 rainfall events with depths greater than 10 mm. The Stein two-stage sample test (Steel and Torrie, 1980) was used with the log transformed data. Net throughfall deposition was calculated by subtracting the rainfall concentrations from throughfall concentrations which had been corrected for concentration by evaporation (interception).

## RESULTS AND DISCUSSION

### Interception

A fraction of the rainfall incident on the canopy may be redirected by absorption, stemflow, or evaporation. Based on observation, stemflow did not appear to be a significant path. The depth of throughfall collected at ELW was a constant fraction of rainfall depth for all three vegetative types for 1986-1987 events less than 30 mm (Figure 6-2). From a practical standpoint it was difficult to perform chemical analyses of samples from events less than about 3 mm, however, volumes were recorded for a number of low-volume events in 1987. Based on linear regressions of these data (Table 6-1) there was no significant interception threshhold (within a standard error of about 1 mm) below which rain was collected in the bulk collectors but not in the throughfall collectors. Based on these observations we conclude that evaporation was the major influence on throughfall depth.

The collection depth for throughfall collectors in rainfall events greater than 30 mm tended to be equal to and sometimes greater than the depth for the rainfall collectors. It is possible that the efficiency of the throughfall collectors was greater than the rainfall collectors during these events because of the sheltering effect of the foliage. It is also possible that cloud interception was a factor in enhancing deposition volumes under foliage during these larger storms. The calculation of net deposition rates (Lovett and Lindberg, 1984) assumes that the collection efficiencies of all collectors are equivalent. Because excess throughfall was collected for high volume events, this linear model (Lovett and Lindberg, 1984) may not be sufficient in some circumstances.

## Deposition

Deposition data were collected for 17 rainfall events in the summer months of 1985, 1986, and 1987 (Table 6-1 and Table 6-2). As a check on the quality of the data obtained, the number of collectors required to obtain deposition values within 10% of the mean was calculated for 5 rainfall events with depths greater than 10 mm (Table 6-3). Like similar data sets (Kostelnik, et al., 1989; Herbert, 1988), the number of collectors required to obtain estimates within 10% of the mean is in the hundreds for some events. A large network of collectors would be required to obtain sample means within 10% of the true mean deposition. In order to reduce the number of collectors, it has been suggested that samplers such as troughs with larger cross-sectional areas be used (Kostlenik, et al., 1989).

The period of time preceding the deposition event (antecedent period) and the depth of the event were used as predictors of net throughfall deposition (Table 6-4) in a multiple regression model (Table 6-5). The coefficient of the antecedent period is related to the dry deposition rate onto leaves and the coefficient of the rainfall depth is related to the foliar leaching or adsorption of solutes by leaf surfaces (Lovett and Lindberg, 1984). There are marked species differences for these coefficients. For example, the *P. monticola* canopy is an efficient dry deposition collector. There are significant regessions (95% level) between deposition and antecedent period for $Ca^{2+}$, $Mg^{2+}$, $K^+$, $NH_4^+$, and $NO_3^-$. On the other hand, the *S. orestera* canopy behaves as if it were a leaky sponge, exuding or exchanging some ions and absorbing others. Significant regressions of deposition against throughfall depth were determined for $K^+$, $SO_4^{2-}$, and DOC. The coefficients for the regression of $NO_3^-$ and $NH_4^+$ deposition versus depth were negative, indicating that this species consumes N in the canopy. If denitrification is taking place in the wet meadows where *S. orestera* grows, N may be lost from the soil solution before the plants have access to it. Thus, *S. orestera* may be augmenting its N requirement through foliar absorption. The correlation between depth and organic carbon deposition is statistically significant only for *S. orestera*. However, it is clear that a similar relationship is present in *C. sempervirens*. The time factor is much stronger for *P. monticola*, although it is also not statistically significant. The relationships between net N and S in *C. sempervirens* throughfall and antecedent period or depth are ambiguous.

Data from the Mt. Moosilauke region in central New Hampshire have shown that differences in bulk throughfall chemistries under different canopy types are due to differences in the amounts of base cations and weak organic acids leached from leaves (Cronan and Reiners, 1983). Throughfall from a coniferous forest was found to exhibit a lower pH and higher organic anion content relative to hardwood (deciduous) forest and bulk precipitation. Bulk precipitation pH was 4.06, under the coniferous forest, 4.00, and under the hardwoods, 4.23. The same pattern is evident in ELW throughfall samples (Table 6-4). The increased acidity of the coniferous throughfall relative to bulk precipitation may be due, in part, to the increased efficiency of pine needles for scavenging dry deposition compared with bulk collectors (Lindberg et al., 1986).

The biogeochemical significance of throughfall can best be evaluated by comparison with wet deposition measurements for ELW on a seasonal and annual basis (Dozier et al., 1987). Assuming a dry deposition season of 120 days is representative, 6.8 mmol/m$^2$ $NO_3^-$ and 1.62 mmol/m$^2$ $SO_4^{2-}$ were deposited under *P. monticola*. These figures were calculated by multiplying the dry deposition coefficient $b_1$ by 120 days. Wet deposition of $NO_3^-$ is much lower (0.6, 1985; 0.7, 1986) but $SO_4^{2-}$ is similar (1.0, 1985; 1.2, 1986) to the throughfall values. Dry deposition of $NH_4^+$ (6.09 mmol/m$^2$) as estimated by the *P. monticola* throughfall is also much higher than wet deposition for the same period. Overall, throughfall dry deposition values from *P. monticola* for a hypothetical 120 day season are similar to the annual wet deposition values for $NO_3^-$, $NH_4^+$, and $SO_4^{2-}$. In contrast, assuming summer deposition of 20 mm, rates of foliar uptake of $NO_3^-$ (-0.21 mmol/m$^2$) and $NH_4^+$ (-0.15 mmol/m$^2$) by *S. orestera* are a significant fraction of the wet deposition rates. This shrub effectively modifies acidic deposition, increasing pH and ANC.

Both *S. orestera* and *C. sempervirens* appear to contribute significant quantities of DOC to throughfall through foliar exchange or exudation. The exact composition of the DOC is unknown, however, the acidic nature of the DOC has been assessed (Brown and Sposito, 1990; see Appendix). The equivalent acidity of *S. orestera* and *C. sempervirens* is estimated as 3.35 and 7.63 mol/kgC, respectively. Assuming summer rainfall is approximately 20 mm, the foliar release of organic acids is 2.31 and 0.97 mmol/m$^2$ for *C. sempervirens* and *S. orestera*, respectively. These values were calculated by multiplying the foliar exchange coefficient $b_2$ by 0.02 m and the appropriate equivalent acidity. The wet deposition of all anions in summer rainfall was 1.4 (1985) and 1.5 mEq/m$^2$ (1986)(Dozier et al., 1987). Foliar organic anions in throughfall under these two species are in greater concentrations than any other anion. This means they will have a significant effect on throughfall pH and charge balance in summer rainfall. On an annual basis, the organic acids released in the summer only make up 5-10% of the total anion deposition.

## CONCLUSIONS

Foliage of *P. monticola* serves as an effective receptor for N and S gasses and aerosols. Dry deposition to pine needles in the summer which is washed off during rainfall events appears to be similar in quantity to annual wet-deposition of these materials. The *S. orestera* canopy apparently serves to remove N compounds from rainfall, making these shrubs an important link in the watershed N cycle.

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## SECTION 2: STREAM ACIDIFICATION EXPERIMENT

Soils are generally considered to have a large buffering capacity with respect to acidic inputs (Binkley and Richter, 1987). Processes such as cation exchange, sulfate adsorption, and mineral weathering are believed to be adequate to neutralize moderate acid loadings for all but the shallowest acidic soils. For this reason, acidified water discharged from a stream experiment on the Marble Fork of the Kaweah River, Sequoia National Park, was diverted over a small area of meadow soil before returning to the main stream channel (Melack et al., 1987).

Literature reports of controlled stream acidification experiments are limited. However, it is known that stream channel substrates are effective in neutralizing acid additions (Henriksen et al., 1988). Presumably, soil would respond similarly to acidified streamwater.

The study of soil solution response to the stream acidification experiment provides two types of useful information to CARB. First, it provides additional assurance to ARB and the National Park Service that the effects of a valuable series of stream acidification experiments on soil and surface water were temporary. Second, it provides some direct observation of the response of soil to episodic acidification which can be compared with assumptions about the effects of acidification on soils.

### OBJECTIVES

The objectives of the study of soil solutions in response to stream acidification were:

1) To monitor the impact of disposal of acidified streamwater on meadow soils adjacent to the experiment site.
2) To observe the residence time of acid anions added to the soil solution.

## METHODS

The stream acidification experiment is described in detail elsewhere (Melack et al., 1987). Twelve artificial channels were constructed and experiments consisted of combinations of parallel control and experimental channels. The effluent from the channels was mixed as it poured onto a soil-covered area. The soil was a moss-covered Lithic Cryumbrept similar to soils found in the LeC-R map unit south east of Emerald Lake. A 4 m by 4 m grid of PVC piezometer wells was installed in the soil starting 1 m below the stream channels. Tubes were inserted to bedrock to assure maximum interaction between soil and the acidified waters. Four stream water samples were also sampled at 1 m intervals downstream from the experimental channels.

The stream acidification experiments were conducted on August 20, 1986 and September 4, 1986 over a 24 hour period. Acidification for 6 hours (between 12 noon and 6 PM) was followed by 18 hours of intensive monitoring of stream recovery. Soil water samples were taken from the piezometers before acidification, then at 6 hour intervals for the duration of the experiment. Piezometers were pumped prior to sampling. Samples were filtered on site using 0.45 micron Nucleopore filters with fiberglass prefilters and stored in new polyethylene centrifuge tubes. Samples were stored unfrozen at 4°C until analyzed. Nitrate analyses were conducted using an automated colorimetric method (Technicon) and $SO_4^{2-}$ was analyzed using ion chromatography (Dionex Fast-sep anion column, $Na_2CO_3/NaHCO_3$ eluent).

## RESULTS AND DISCUSSION

Sulfate and nitrate do not appear to have been removed from the acidified stream water over the 4 m reach sampled below the channel effluent since all values are essentially the same at each sample time (Figures 6-3 and 6-4). It is possible that $SO_4^{2-}$ was removed initially during the September experiment. The 12 PM $SO_4^{2-}$ values were half of the 6 PM values (Figure 6-3b) while the $NO_3^-$ values remained constant (Figure 6-5b).

Soil solution response to $NO_3^-$ was different from response to $SO_4^{2-}$ addition. Soil solution $SO_4^{2-}$ was higher than stream concentrations at almost all sample times (Figure 6-4 cf. Figure 6-3). Sulfate was higher closer to the stream channels (Figure 6-4b) and tended to reach maximum concentrations as much as 12 hours after the end of the acidic additions. This indicates that $SO_4^{2-}$ is being retained by adsorption processes which respond to changes in solution concentrations. This is consistent with the $SO_4^{2-}$ buildup and recovery pattern in response to sulfuric acid proposed by Galloway et al. (1983). Recovery from $SO_4^{2-}$ additions to soil was quite rapid in this experiment, well within the time frame suggested as the hydrologic retention time for ELW (Gupta et al., 1989; This Report, Chapter 3). There does not appear to be any lag time between $NO_3^-$ in the soil solution and $NO_3^-$ inputs. Soil solution $NO_3^-$ recovered to preacidification values immediately following the end of acid additions. The highest $NO_3^-$ values were observed closest to the stream channels (Figure 6-6). Most soil solution $NO_3^-$ values were lower than stream values, suggesting uptake by the moss-covered soil or dilution by groundwater may have been significant. Stream macrophytes have been implicated before in the amelioration of acidic inputs by exchange mechanisms (Henriksen et al., 1988), but not for nutrient uptake.

The impact of $NO_3^-$ on soils is not clear from this experiment, since in some piezometers soil solution $NO_3^-$ was reduced or diluted and in others it was not. What is clear is that the rate of response of the soil solution is much faster to $NO_3^-$ inputs than $SO_4^{2-}$, probably due to the adsorption of $SO_4^{2-}$.

## CONCLUSIONS

The disposal of acidified streamwater on a Lithic Cryumbrept at the Marble Fork of the Kaweah River may have effectively neutralized acidity (Melack et al., 1987), however, soils appeared to have little or effect on $NO_3^-$ and $SO_4^{2-}$ concentrations over the short, 4 m reach studied. The soil solution appears to have responded quickly to $NO_3^-$ additions and some uptake or dilution appears to have occurred. Sulfate appears to be adsorbed and released, lagging behind the stream additions by at least 12 hours. This is consistent with current theory regarding the response and recovery of soils in watersheds to sulfate deposition.

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# SECTION 3:

# 1987 STREAM TRANSECT: ELW SUBBASIN ELEMENTAL FLUXES

Research on the effects of acid deposition on lake watersheds has found that hydrologic flowpaths through the terrestrial portion of the watershed control the composition of surface waters (McAvoy, 1989; Lawrence et al., 1988; Cosby et al., 1985; Reuss and Johnson, 1985). A corollary to this hypothesis is that the residence time and depth of interaction of water with soil determines the extent to which acidic deposition will be neutralized.

Among the soil processes which may influence surface water composition are concentration through evaporation or dilution by snowmelt, uptake or mineralization of soil N, $SO_4^{2-}$ adsorption, and mineral weathering. If soil solutions have a significant influence on surface water composition, evidence of these reactions should be observable along stream transects and in subbasins of ELW. Patterns in stream water composition were observed in 1985 which suggested that soils influenced N and S concentrations, and that mineral weathering had a significant influence (Lund et al., 1987). In order to address the question of how much influence soils have on surface water composition, in 1987 we cooperated with J. Melack, UCSB, to measure the flux of several elements at selected points along the stream transect monitored in 1985.

The value of these data to CARB is that stream water composition integrates the results of terrestrial processes in a way that cannot be addressed in the laboratory or in other terrestrial components. Stream monitoring data will allow some assessment of how important the various soil processes actually are in determining surface water composition, particularly with respect to N, S, and ANC.

## OBJECTIVES

The objectives of the stream transect measurements in 1987 were:

1) To measure temporal variations in streamwater composition from snowmelt through autumn rains.

2) To assess the relative contribution of terrestrial processes to surface water composition.

## METHODS

The stream transect sampled in 1987 was an abbreviated version of the transect sampled in 1985 (Lund et al., 1987). Sites sampled included site 11, 12, 13, 14, 16, 2, and 1 (Figure 6-1). Stream samples were filtered in the field with a 0.45 micron Nucleopore filter and stored unfrozen at 0-4°C in clean 125 ml polyethylene bottles. On four occasions, stream discharge was measured at 3-5 sites along the transect. At high flows, discharge was measured by the salt dilution method and during low flows, calibrated buckets and graduated cylinders were used (Dozier et al., 1987).

Solution conductivity, pH and ANC were measured within 1-2 days. Ion chromatography with a Dionex AS4A anion exchange column and $NaHCO_3/Na_2CO_3$ eluant was used for the determination of $Cl^-$, $NO_3^-$, and $SO_4^{2-}$. An automated colorimetric method (Technicon) was used for $NH_4^+$ and $NO_3^-$ analysis. Atomic absorption and flame emission spectroscopy were used to determine $Ca^{2+}$, $Mg^{2+}$, $K^+$, and $Na^+$. Dissolved organic carbon was determined using and automated persulfate/UV digestion and IR detection of $CO_2$.

The discharge data were used to calculate the flux of elements from a subbasin of ELW which drains into the pond south east of Emerald Lake. This subbasin, approximately 44.8 ha, was identified as subbasin "C + D" in Dozier et al. (1987). Flux was calculated for site 14 on an aerial basis by multiplying concentration by discharge and dividing by the area of the basin. Total transport per $m^2$ of the basin was determined by integrating over the flux values obtained for each sample date using the trapezoidal approximation (Cheney and Kincaid, 1980).

# RESULTS AND DISCUSSION

Because of many personnel changes in 1987, not all stream transect sites were sampled consistently. Discharge and chemical composition were sampled consistently for transect sites 2, on the bench meadow east of Emerald Lake, 16, on the inlet meadow southeast of the lake, and 14, at the outlet to the pond south east of the lake. Stream chemical composition was sampled 9-10 times between April 30 and October 29.

## Temporal Variations in Solute Concentrations

Stream $NO_3^-$ concentrations along the central drainage in ELW (sites 14, 16) were highest during snowmelt in the spring and were apparently influenced by rainfall events in the fall (Figure 6-7). In contrast, nitrate concentrations were very low, below 1 umol/L, at site 2 in the bench meadow from after snowmelt in mid-May through October. Low nitrate concentrations in surface waters are a consequence of hydrologic flowpaths directed through soils. During high stream discharge a portion of the rainfall or snowmelt may become surface runoff and does not come in contact with soil. Alternatively, cessation of $NO_3^-$ uptake by biota would be minimal in the spring due to cold conditions immediately after snowmelt. In the fall, plant scenesence and decomposition of plants and microbes might contribute to a release of N. In general mountain watersheds tend to be very conservative with respect to N retention (Brown et al., 1990; Buell and Peters, 1988; Knight et al., 1985). At ELW, the short growing season and thin, quickly chilled soils may contribute to the dramatic changes in $NO_3^-$ concentrations from spring through fall.

In contrast to $NO_3^-$ which varied from less than 1 to over 50 umol/L during the survey, $SO_4^{2-}$ concentrations stayed between 1 and 9 umol/L (Figure 6-8). Concentrations at sites 14 and 16 were very similar while site 2 was slightly lower for most of the season. Sulfate concentrations in surface water are almost certainly being regulated by $SO_4^{2-}$ adsorption. Calculations indicate that ELW soils are probably near capacity for $SO_4^{2-}$ adsorption (This Report, Chapter 4). The effect of this is to maintain a constant pattern of

$SO_4^{2-}$ concentrations throughout the year (Lynch and Corbett, 1989; Lewis and Grant, 1979). This contrast with well-known $SO_4^{2-}$ adsorption properties of soils in the Blue Ridge Mountains, which apparently have not reached $SO_4^{2-}$ adsorption capacity (Ryan et al., 1989; Buell and Peters, 1988). It is particularly interesting to note that in ELW, $SO_4^{2-}$ concentrations during snowmelt do not appear to be greatly different from lower flows during the summer and fall when concentrations in rainfall tend to be higher. In spite of the limited soil coverage in ELW, $SO_4^{2-}$ appears to be very effectively controlled by soil adsorption.

The ANC's of surface waters appear be inversely related to $NO_3^-$ concentrations. The stream on the bench meadow (site 2) had the highest ANC of the three sites (Figure 6-9). Concentrations were lowest in spring and fall and could be the result of dilution by snowmelt or may actually be related to nitrate uptake, which would also increase soil solution ANC. For whichever reason, this pattern of ANC regulation is common for mountain watersheds (Lewis and Grant, 1979).

ELW Subbasin Fluxes

Discharge declined for each of the four measurements made at sites along the stream transect (Figure 6-10). It is important to note that our measurements do not accurately reflect the peak discharge from the watershed in May. Discharge rates were high at the time of the April measurement, however, and may be representative for use in crude calculations of elemental flux. Nitrate flux at sites 14 and 16 does appear to increase in the fall, indicating greater deposition or N mineralization and release in the colder weeks of the season (Figure 6-11). Sulfate concentrations follow discharge very closely (Figure 6-12). The ANC of surface water declines with discharge, although it appears to be constant over part of the range of discharge (Figure 6-13).

Data for site 14 converted to an aerial basis for integration are presented in Table 6-7. The total discharge depth calculated in this manner was

0.82 m, which would represent most of the annual loading to ELW for the 1987 water year of 0.96 m water equivalent (M. Williams, personal communication). The deposition rates of $NO_3^-$, $SO_4^{2-}$, and $H^+$ for the 1987 water year were 11.4, 4.7, and 5.8 mmol/m$^2$, respectively. The calculated subbasin discharge of 4.2 mmol/m$^2$ $SO_4^{2-}$ balances quite well with the annual deposition rate. This lends credibility to the argument that sulfate adsorption capacity has been reached at least in the higher elevation region of ELW. The calculated 13.8 mmol/m$^2$ $NO_3^-$ discharged from the basin is greater than deposition, however, this might be expected because of the oxidation of $NH_4^+$ which also was deposited. The flux of alkalinity was most interesting, since 19.9 mmol/m$^2$ exceeded $H^+$ wet deposition by a factor of 3 for the water year. Significant alkalinity forming processes must be active in the watershed, particularly weathering and $NO_3^-$ immobilization.

## CONCLUSIONS

Sulfate concentrations in ELW surface waters appear to be regulated by adsorption processes. No net accumulation of $SO_4^{2-}$ over the year is evident, hence, it is likely that adsorption is close to capacity at present. Nitrate concentrations in surface waters are reduced by plant uptake and immobilization in soils at ELW. However, the increase in $NO_3^-$ concentrations in spring and fall indicate that either deposition rates exceed the soil capacity for immobilization and plant uptake or the cool conditions and short growing season reduce the capacity of the watershed to retain $NO_3^-$ in these seasons. The net production of nearly 20 mmol/m$^2$ ANC is interesting from the standpoint of neutralization of acidic deposition. Evidently, weathering and immobilization are sufficient to produce more than three times the ANC needed to neutralize annual $H^+$ deposition.

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## SECTION 4: RESPIRATION: $CO_2$ CONCENTRATIONS IN SOILS

The production of carbon dioxide ($CO_2$) through respiration is the final product of the decomposition of organic matter. In soils, concentrations of $CO_2$ may greatly exceed the average concentration in air because of high respiration rates and low rates of diffusion of gasses up out of the soil. The average concentration of $CO_2$ in the atmosphere is around 0.03%, while levels in the soil atmosphere are commonly in the range of 0.3 to 3% (Lindsay, 1979). Concentrations of $CO_2$ two orders of magnitude above atmospheric may have a significant influence on the acidity and composition of soil solutions and surface waters. Soil $CO_2$ concentrations are an important input parameter in hydrochemical models of watersheds (Reuss and Johnson, 1985, Cosby et al., 1985).

Data on the annual trends in $CO_2$ concentrations in soils are important for CARB because the weathering process which generates ANC in the watershed depends on the concentration of $CO_2$ dissolved in the soil solution. This will assist in determining natural levels of ANC production.

### OBJECTIVES

The objective of monitoring $CO_2$ concentrations in soil air was:

1) To obtain data for an annual cycle of $CO_2$ concentrations for comparison with soil solution data.

### METHODS

Soil carbon dioxide concentrations were monitored on a regular Soil air wells were installed in 1986 to collect larger volumes of soil gasses under water-saturated conditions. These wells consisted of 2.5 cm diameter PVC pipes placed in holes that were augered to the desired depth. Two sample tubes were placed at each depth. The pipes were capped with a rubber septum which was protected with an oversized PVC cap. The samples were collected in 10 cc syringes which were sealed with a rubber stopper. Samples were transported to lower elevations for analysis using gas chromatography. Analyses were performed as quickly as possible to minimize the opportunity for sample contamination. Certified $CO_2$-Nitrogen mixtures were used for standardization of the gas chromatograph.

Samples were collected at all five soil lysimeter sites in ELW (Figure 6-14). Sampling began in September 1986 and continued to November 1987. Samples were collected every two moths in the winter and twice a month starting in April.

## RESULTS AND DISCUSSION

Soil air samples collected through the winter of 1986-1987 showed that $CO_2$ concentrations reached 2.4% in the Entic Cryumbrept, EaD map unit, bench meadow (Figure 6-15), and 2.0% in the Lithic Cryumbrept, LeC-R map unit, inlet meadow (Figure 6-14c). Minimum concentrations measured were around 0.04%. The trend in $CO_2$ concentrations with depth varied from site to site and time of year. Concentrations tended to be elevated between January and May in the TdoF-R map unit, pine stand (Figure 6-15), and the Lithic Cryumbrept, LeC-R map unit, inlet meadow (Figure 6-15), reaching maximum concentrations in February. A second maximum is observed in the early summer months between May and July. The concentrations of $CO_2$ were low all year at the ridge (LcF-R map unit) and cirque (TsD map unit) sites (Figures 6-14d and 6-14e, respectively). These sites have almost no vegetation, therefor there were few or no roots to produce $CO_2$ in the soil.

The annual cycle of $CO_2$ concentrations in ELW soils is typical for subalpine conditions (Solomon and Cerling, 1987). The reasons for high concentrations of $CO_2$ in the soil atmosphere in the winter are not intuitively obvious. Respiration is not expected to be very rapid at low mid-winter temperatures. High soil moisture contents can decrease the rate at which $CO_2$ is released from soils (Solomon and Cerling, 1987). As a result, even low respiration rates could result in an accumulation of $CO_2$.

These results have significant implications for the geochemistry of Sierra Nevada surface waters. Soil $CO_2$ has previously been implicated as a powerful and important rock weathering agent in the Sierra (Mankiewicz and Sweeney, 1977, Feth, et al., 1964). The relative concentrations and annual patterns of aqueous $CO_2$ supplied to groundwater have never been determined before in the Sierra. These results will allow accurate modelling of the chemistry of the surface and soil solution chemistry at ELW. High soil $CO_2$ in the winter increases the ability of the soil solution to weather minerals. Significant weathering may occur in the winter as a result. In the soils (ridge and cirque sites) where $CO_2$ concentrations were not elevated, the soil solution would be expected to be a less aggressive weathering agent, resulting in production of less ANC by weathering. As a result, these soils would be less able to neutralize acidic snowmelt.

## CONCLUSIONS

Typical annual maxima in soil $CO_2$ concentrations were observed between January and May and May and July in 1986-87. Soils with elevated $CO_2$ concentrations would have soil solutions more effective in causing production of ANC through weathering reactions. Soils at two sites exhibited little or no elevation of $CO_2$ concentrations. Weathering would be naturally at a lower rate at these sites, possibly reducing the ability of soils to neutralize acidic snowmelt.

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## SECTION 5: SNOWMELT-SOIL SOLUTION INTERACTIONS

Most soils have a great capacity for the neutralization of acidic inputs (Binkley and Richter, 1987). Long term studies of soil solution composition *in situ* have found that soils have a strong influence on the composition of water which percolates into them (Sears and Langmuir, 1982). These influences are due particularly to the rapid cation exchange reactions which occur between cations by clay minerals and organic matter by electrosytatic forces and solution cations. Observations of cation concentrations in the soil solution during snowmelt at a pristine site have shown how effectively cation concentrations are buffered even under high flow conditions (Ferrier et al., 1989). The ability of soils to have an effect on surface water composition during snowmelt depends both on the hydrologic flowpaths and on the chemical and biological reactions that take place in the soils.

There are two important reasons that the CARB needs to have information on soil solution composition collected *in situ* at this subalpine to alpine site, very representative of Sierra soils. First, there is a need to evaluate the effect of acidic deposition on the soils. The best measure of the status of the soil with respect to all biological activity in it (potential or current) is to directly sample the soil solution. Second, soils can have an important influence on surface water composition. It is important to evaluate by direct measurement whether the soil solution composition is related to the composition of deposition (snowmelt) and surface water runoff.

### OBJECTIVES

The objectives of the soil solution sampling program in 1986-87 were:

1) To measure soil solution chemical composition through an entire annual cycle in soils representative of ELW.
2) To measure changes in the soil solution chemical composition during the spring snowmelt.

# METHODS

The type of lysimeter used at ELW was an active collector which exerts suction on the soil to withdraw water, properly called a soil water extractor. Both the terms lysimeter and soil water extractor are used interchangeably in this report.

These devices were described in an earlier report (Lund et al. 1987). Briefly; they consist of a 10 cm diameter base machined from solid, cylindrical PVC stock filled with a porous (35 um) polyethylene plate covered by a nylon reinforced filter membrane (0.2 um effective pore size Gelman Versapor). This membrane is rated for approximately -0.75 bars (or -11 psi) bubble pressure when moist, in excess of the -0.20 bars (-2.9 psi) vacuum used. The membrane is held over the polyethylene plate backing by a PVC ring machined to a tight fit around the PVC base. The tensiometer plate is connected to surface sample bottles via 3.18 mm (1/8 inch, outer diameter) teflon tubing. Polycarbonate collecting bottles (250 mL) were in the line between the lysimeter plates and the vacuum pump A manifold system connects four lysimeters to a single vacuum system and allows vacuum lines to be turned off individually. The vacuum system consists of a 12 V vacuum pump powered by a 90 amp-hour "deep cycle" battery which is continuously charged at a rate of about 0.5 amp·hr$^{-1}$ by a 10 watt solar cell (Kyocera). The battery power is adequate to allow weekly sampling or other periodic use for 1 to 2 months without recharging. The vacuum is regulated at -0.20 bars (-2.9 psi) by a microswitch connected to an automobile vacuum advance unit (1956 Ford).

Tension lysimeters were installed in July, 1985 at four sites in ELW: (1) the wet inlet meadow south of the lake (Lithic Cryumbrept); (2) the pine stand at the top of the joint NE of the lake (Typic Cryorthod association); (3) on a bench east of the lake (Entic Cryumbrept); and (4) in the soil of the glacial moraine along the ridge east of the lake and below Alta Peak (Typic Cryorthent). A fifth sampler was installed in the summer of 1986 at the ridge site east of the lake (Lthic Cryumbrept). These sites are detailed on a map of

ELW (Figure 6-14). Each of the soils sampled have developed two or three distinct soil horizons which are sampled separately by two lysimeter plates in each of two surface horizons. The tension lysimeters were activated manually only when there was sufficient moisture in the soil (greater than -0.20 bars tension). Usually 2 to 3 hours of operation was sufficient to obtain samples.

Anion analyses were performed by ion chromatography ($Cl^-$, $NO_3^-$ $SO_4^{2-}$) and automated colorimetric (Technicon) analysis ($NO_3^-$). Cation analyses were performed by AA spectrometry ($Ca^{2+}$, $Mg^{2+}$) emission spectrometry ($Na^+$, $K^+$) and automated colorimetric (Technicon) analyses ($NH_4^+$). Titrations for ANC were performed with dilute 0.01 M HCl under controlled conditions. Dissolved organic C was determined by an automated persulfate oxidation method (Dohrman).

## RESULTS AND DISCUSSION

The snowmelt event of the 1986-1987 water year was monitored from April through July. Equipment failures at the cirque and inlet meadow site limited our ability to collect data at these sites. Snowmelt appears to occur very rapidly at the pine stand site, also making data limited. The best time series data were collected for the bench meadow site and the ridge site.

Of particular importance is the fact that during the snowmelt event we observed a depression of pH and ANC in the soil solution (Figures 6-16 and 6-17). The Lithic Cryumbrept at the ridge site was sufficiently acidified for the ANC to drop below zero and remain below zero until moisture levels became too low for the extractors to operate successfully (Figure 6-16a). Recovery of ANC and pH to values similar to the onset of snowmelt in April was complete by fall 1987.

The ANC depression was correlated with nitrate concentrations in the soil solution (Figure 6-18) and not correlated with sulfate concentrations (Figure 6-19). This implies that nitric acid deposition was responsible for the drop in pH and ANC. These data indicate that the acid neutralization mechanisms of this soil could not respond quickly enough to compensate for this acidification episode during snowmelt. The Entic Cryumbrept at the bench meadow monitored during the same snowmelt event did not exhibit as dramatic a response (Figures 6-16, 6-17, 6-18 and 6-19).

In order to evaluate the relationship between snowmelt and soil solution composition, snowmelt data were obtained for sites adjacent to the lysimeter in the bench meadow and for a site at in the cirque, similar in elevation and exposure to the ridge site (Mark Williams, pers. communication). These data show (Figure 6-20) that there was a depression in concentrations of $NO_3^-$ and $SO_4^{2-}$ during snowmelt caused by dilution punctuated by temporary increases caused by rainfall on the snow (Mark Williams, pers. communication). Alkalinity was calculated as the difference between the strong acids and strong bases and found to vary inversely with the concentrations of $NO_3^-$ and $SO_4^{2-}$ (Figure 6-20).

Soil solution $NO_3^-$ at the ridge site followed snowmelt concentrations, while at the bench site, $NO_3^-$ appears to have been immobilized by the soil. Sulfate concentrations also tended to be higher and more similar to snowmelt at the ridge site compared with the bench. This is probably due to greater $SO_4^{2-}$ adsorption capacity at the bench site. Apparently the bench site has greater capacity for neutralizing the strong acidic anions than the ridge soil. These anions result in a negative ANC of this soil solution while the bench soil solution is buffered at a low but positive ANC, greater than the original ANC of the snowmelt. Additional acidic inputs to the ridge site soil would result in greater acidification of this soil while the same deposition on the bench meadow soil might not result in further noticeable change.

The effect of summer rainfall on soil solutions in the field is still essentially unknown. Some rainfall mixed with snowmelt in the spring 1987, but soil water would still have been dominantly from snow. Rainfall events in the summer and fall fell on soils with water contents which were too low to be extracted in the field. Other extraction methods will have to be employed in order to study rainfall-soil interactions in situ.

## CONCLUSIONS

Soil solution samples from ELW confirm the fact that soil solution ANC is adversely affected by acidic snowmelt and rainfall inputs. Samples from the high elevation, well drained ridge Lithic Cryumbrept show that this soil barely has sufficient capacity to neutralize acidic inputs at the current rates of $NO_3^-$ and $SO_4^{2-}$ deposition. This is a consequence of the low $SO_4^{2-}$ adsorption capacity and low concentration of exchangeable cations in this soil (This report, Chapter 4). This soil is representative of most of the higher elevations at ELW (Chapter 3 and 4). Soil solution ANC at slightly lower elevations at ELW (Entic Cryumbrept, bench meadow) do not appear to be lowered as much by snowmelt.

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Table 6-1. Interception of rainfall by three species in ELW.

| | Slope Thrufall/Rain | SE | Intercept | SE | r | n |
|---|---|---|---|---|---|---|
| | m/m | m/m | m | m | | |
| Chrysolepsis | 0.698 | 0.053 | 0.00008 | 0.00198 | 0.95 | 21 |
| Pinus | 0.587 | 0.083 | -0.00015 | 0.00315 | 0.85 | 21 |
| Salix | 0.885 | 0.076 | -0.00043 | 0.00243 | 0.94 | 19 |

**Table 6-2.** Logarthmically transformed mean deposition of selected elements for throughfall and rainfall in 1985-1987.

| Date | Depth | DOC | Ca | Mg | Na | K | H | NH4 | Cl | NO3 | SO4 | HCO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mm | $mg/m^2$ | | | | | $umol/m^2$ | | | | | |
| | | | | | | *Castanopsis sempervirens* | | | | | | |
| 07/23/85 | 6.3 | 833 | 805 | 75 | 715 | 908 | 365 | 336 | 722 | 406 | 184 | 0 |
| 07/27/85 | 1.4 | 275 | 186 | 69 | 327 | 433 | | 438 | 5 | 334 | 33 | 0 |
| 09/14/85 | 35.8 | 561 | 700 | 300 | 844 | 1315 | 440 | 161 | 81 | 1078 | 158 | 0 |
| 09/20/85 | 10.2 | 287 | 233 | 93 | 229 | 233 | 294 | 279 | 9 | 226 | 94 | 0 |
| 07/24/86 | 13.6 | 485 | 858 | 214 | 235 | 1013 | 79 | 39 | 360 | 493 | 376 | 132 |
| 08/21/86 | 2.2 | 208 | | | 176 | | 12 | 82 | | 490 | | 230 |
| 09/20/86 | 5.1 | 263 | 289 | 105 | 67 | 472 | 201 | 161 | 5731 | 362 | 102 | 0 |
| 10/15/86 | 53.6 | 1048 | 1424 | 222 | 238 | 963 | 1871 | 161 | 244 | 1428 | 235 | 0 |
| 06/11/87 | 16.4 | 480 | 294 | 145 | 572 | 544 | 994 | 236 | 1079 | 559 | 434 | 1 |
| 09/01/87 | 0.9 | | | | | | 72 | | 544 | 73 | 137 | |
| 09/03/87 | 7.7 | 718 | 487 | 317 | 796 | 1274 | 462 | 376 | 579 | 235 | 383 | 677 |
| 09/12/87 | 3.2 | 260 | 187 | 77 | 230 | 452 | 85 | 42 | 130 | 92 | 116 | |
| 10/22/87 | 1.7 | | | | | | 11 | | 50 | 17 | 37 | |
| 10/24/87 | 15.4 | 415 | 448 | | | 124 | 105 | 256 | 93 | 171 | 38 | |
| 10/29/87 | 13.0 | 478 | 96 | 88 | 256 | 424 | 97 | 16 | 43 | 14 | 25 | 28 |
| | | | | | | *Pinus monticola* | | | | | | |
| 07/23/85 | 2.7 | 834 | 1295 | 363 | 563 | 870 | 120 | 1510 | 504 | 634 | 406 | 0 |
| 07/27/85 | 0.5 | 50 | 62 | 18 | 152 | 95 | | 99 | 54 | 136 | 40 | 0 |
| 09/14/85 | 36.7 | 1446 | 2951 | 1025 | 1268 | 2286 | 923 | 3873 | 55 | 8458 | 951 | 0 |
| 09/20/85 | 7.5 | 173 | 218 | 92 | 713 | 257 | 59 | 345 | 107 | 409 | 103 | 6 |
| 07/24/86 | 15.9 | 578 | 1194 | 234 | 209 | 584 | 59 | 2045 | 739 | 3173 | 504 | 1247 |
| 08/21/86 | 1.3 | 143 | | | 731 | | 3 | 1636 | | 448 | | 87 |
| 09/20/86 | 5.7 | 180 | 777 | 261 | 185 | 633 | 36 | 1566 | | 2219 | | 61 |
| 10/15/86 | 40.7 | 257 | 1222 | 249 | 661 | 625 | 238 | 1810 | 623 | 2084 | 395 | 174 |
| 06/11/87 | 10.2 | 236 | 388 | 128 | 432 | 310 | 250 | 1231 | 900 | 1557 | 666 | 14 |
| 09/03/87 | 4.5 | 377 | 1312 | 362 | 823 | 831 | 82 | 3051 | 639 | 3718 | 819 | |
| 09/12/87 | 3.0 | 242 | 344 | 88 | 222 | 380 | 72 | 411 | 176 | 1059 | 178 | |
| 10/22/87 | 1.3 | | | | | | 4 | | 170 | 1905 | 202 | |
| 10/24/87 | 11.4 | 1089 | 495 | 159 | | | 81 | 1268 | 407 | 1277 | 321 | 363 |
| 10/29/87 | 9.2 | 737 | 331 | 117 | 223 | 267 | 100 | 358 | 216 | 593 | 131 | 5 |

Table 6-2. Continued.

| Date | Depth | DOC | Ca | Mg | Na | K | H | NH4 | Cl | NO3 | SO4 | HCO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mm | $mg/m^2$ | | | | | $umol/m^2$ | | | | | |
| | | | | | | *Salix orestera* | | | | | | |
| 07/23/85 | 2.0 | 99 | 210 | 133 | 412 | 386 | | 25 | 500 | 7 | 48 | 0 |
| 07/27/85 | 0.8 | 45 | 64 | 50 | 42 | 182 | | 3 | 6 | 6 | 24 | 0 |
| 09/14/85 | 43.5 | 539 | 806 | 550 | 590 | 1571 | 77 | 32 | 186 | 51 | 327 | 807 |
| 09/20/85 | 13.1 | 88 | 232 | 145 | 281 | 472 | 18 | 126 | 110 | 54 | 133 | 1104 |
| 08/21/86 | 2.3 | 77 | | | 269 | 99 | 0 | 13 | | 46 | | 426 |
| 09/20/86 | 5.3 | 94 | 374 | 158 | 64 | 523 | 3 | 0 | 106 | 131 | 53 | 864 |
| 10/15/86 | 50.3 | 535 | 1909 | 620 | 869 | 1563 | 87 | 32 | 333 | 135 | 313 | 2562 |
| 09/01/87 | 1.8 | | | | | | 6 | | 167 | 382 | 259 | |
| 09/03/87 | 10.8 | 179 | 553 | 266 | 1061 | 581 | 87 | 832 | 879 | 701 | 393 | 181 |
| 09/12/87 | 4.4 | 247 | 284 | 115 | | | 34 | 84 | 151 | 279 | 121 | |
| 10/22/87 | 3.8 | | | | | | 7 | | 250 | 1 | 155 | |
| 10/24/87 | 15.0 | 1546 | 1697 | 904 | | | 267 | 90 | 531 | 45 | 232 | 93 |
| 10/29/87 | 23.7 | 882 | 2120 | 1197 | 436 | 1010 | 173 | 39 | 317 | 104 | 150 | 264 |
| | | | | | | Bulk Deposition | | | | | | |
| 07/23/85 | 5.8 | 27 | 82 | 27 | 330 | 104 | 30 | 209 | 328 | 162 | 76 | 2 |
| 07/27/85 | 2.8 | 17 | 50 | 10 | 89 | 141 | 17 | 270 | 34 | 197 | 48 | 2 |
| 09/14/85 | 33.4 | 56 | 218 | 65 | 483 | 173 | 308 | 414 | 3 | 748 | 289 | 1 |
| 09/20/85 | 13.9 | 20 | 44 | 17 | 381 | 28 | 80 | 276 | 11 | 267 | 116 | 6 |
| 07/24/86 | 23.8 | 62 | 613 | 63 | 163 | 171 | 668 | 519 | 121 | 851 | 959 | 23 |
| 08/21/86 | 4.4 | 21 | 168 | 40 | 294 | 121 | 13 | 92 | 52 | 268 | 133 | 63 |
| 09/20/86 | 7.4 | 11 | 184 | 21 | 37 | 57 | 29 | 57 | 196 | 136 | 47 | 12 |
| 10/15/86 | 36.0 | 47 | 756 | 38 | 162 | 108 | 110 | 1011 | 116 | 966 | 186 | 34 |
| 06/11/87 | 21.2 | 41 | 110 | 44 | 253 | 118 | 447 | 1305 | 544 | 947 | 510 | 58 |
| 09/01/87 | 2.0 | | | | | | 5 | | 127 | 273 | 199 | |
| 09/03/87 | 11.0 | 49 | 225 | 62 | 338 | 145 | 17 | 1279 | 134 | 856 | 424 | 522 |
| 09/12/87 | 5.0 | 27 | 110 | 20 | 108 | 55 | 48 | 135 | 52 | 263 | 101 | |
| 10/22/87 | 3.9 | | | | | | 5 | | 26 | 161 | 59 | |
| 10/24/87 | 14.8 | 17 | 41 | 10 | | | 24 | 144 | 33 | 112 | 34 | 2 |
| 10/29/87 | 20.2 | 34 | 39 | 12 | 139 | 30 | 104 | 95 | 24 | 159 | 43 | 17 |
| 10/24/87 | 15.8 | 16 | 24 | 2 | | | 44 | 135 | 51 | 146 | 31 | 0 |
| 09/03/87 | 11.0 | 75 | 383 | 85 | 315 | 207 | 26 | 1653 | 302 | 882 | 433 | 1044 |

Table 6-3. Standard deviation of depths and log standard deviations from the log mean deposition for selected elements for throughfall and rainfall in 1985-1987.

| Date | Depth | DOC | Ca | Mg | Na | K | H | NH4 | Cl | NO3 | SO4 | HCO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | mm | mg/$m^2$ | umol/$m^2$ | | | | | | | | | |
| *Castanopsis sempervirens* | | | | | | | | | | | | |
| 07/23/85 | 6.0 | 0.37 | 0.34 | 0.33 | 0.34 | 0.38 | 0.39 | 0.19 | 0.39 | 0.18 | 0.28 | 0.00 |
| 07/27/85 | 0.5 | 0.35 | 0.42 | 0.42 | 0.31 | 0.28 | nss | 0.47 | 1.18 | 0.56 | 0.79 | 0.00 |
| 09/14/85 | 17.8 | 0.83 | 0.84 | 0.82 | 0.72 | 0.84 | 0.60 | 1.08 | 1.48 | 0.60 | 1.06 | 0.00 |
| 09/20/85 | 2.7 | 0.28 | 0.22 | 0.22 | 0.23 | 0.29 | 0.13 | 0.18 | 0.99 | 0.25 | 0.13 | 0.00 |
| 07/24/86 | 4.5 | 0.22 | 0.14 | 0.39 | 0.27 | 0.11 | 0.29 | 1.17 | 0.10 | 0.24 | 0.21 | 0.98 |
| 08/21/86 | 0.7 | 0.09 | nss | nss | 0.00 | nss | 0.39 | 0.64 | nss | 0.11 | nss | 0.00 |
| 09/20/86 | 1.7 | 0.15 | 0.11 | 0.11 | 0.21 | 0.12 | 0.72 | 0.47 | 0.00 | 0.31 | nss | 0.00 |
| 10/15/86 | 9.3 | 0.26 | 0.10 | 0.20 | 0.08 | 0.23 | 0.22 | 1.02 | 0.17 | 0.07 | 0.14 | 0.00 |
| 06/11/87 | 3.3 | 0.20 | 0.16 | 0.26 | 0.26 | 0.22 | 0.14 | 0.22 | 0.23 | 0.34 | 0.06 | 0.51 |
| 09/01/87 | 0.2 | nss | nss | nss | nss | nss | 0.09 | nss | 0.11 | 0.39 | 0.04 | nss |
| 09/03/87 | 1.1 | 0.21 | 0.21 | 0.29 | 0.33 | 0.48 | 0.83 | 0.19 | 0.35 | 0.43 | 0.15 | nss |
| 09/12/87 | 0.8 | 0.21 | 0.12 | 0.34 | 0.25 | 0.28 | 0.38 | 0.46 | 0.16 | 0.68 | 0.10 | nss |
| 10/22/87 | 0.7 | nss | nss | nss | nss | nss | 0.02 | nss | 0.09 | 0.94 | 0.03 | nss |
| 10/24/87 | 0.2 | 0.20 | 0.27 | nss | nss | 0.90 | 0.09 | 0.01 | 0.69 | 0.06 | 1.59 | 756 |
| 10/29/87 | 5.4 | 0.50 | 0.30 | 0.40 | 0.30 | 0.44 | 0.27 | 0.21 | 0.32 | 0.38 | 0.75 | 1.04 |
| *Pinus monticola* | | | | | | | | | | | | |
| 07/23/85 | 1.9 | 0.12 | 0.26 | 0.19 | 0.23 | 0.18 | 0.34 | 0.33 | 0.46 | 0.40 | 0.25 | 0.00 |
| 07/27/85 | 0.2 | 0.07 | 0.11 | 0.18 | 0.14 | 0.13 | nss | 0.17 | 0.20 | 0.14 | 0.26 | 0.00 |
| 09/14/85 | 12.1 | 0.25 | 0.19 | 0.25 | 0.29 | 0.30 | 0.22 | 0.54 | 1.31 | 0.23 | 0.30 | 0.00 |
| 09/20/85 | 3.0 | 0.20 | 0.18 | 0.23 | 0.15 | 0.22 | 0.29 | 0.44 | 0.92 | 0.34 | 0.33 | 1.22 |
| 07/24/86 | 1.1 | 0.14 | 0.36 | 0.66 | 0.44 | 0.76 | 0.11 | 0.25 | 0.18 | 0.13 | 0.09 | 0.14 |
| 08/21/86 | 1.1 | 0.21 | nss | nss | 0.18 | nss | 0.34 | 0.27 | nss | 0.48 | nss | 0.00 |
| 09/20/86 | 1.6 | 0.33 | 0.23 | 0.29 | 0.32 | 0.25 | 0.74 | 0.39 | nss | 0.33 | nss | 1.07 |
| 10/15/86 | 10.7 | 0.11 | 0.13 | 0.14 | 0.24 | 0.14 | 0.59 | 0.14 | 0.05 | 0.05 | 0.10 | 1.32 |
| 06/11/87 | 6.6 | 0.18 | 0.38 | 0.38 | 0.48 | 0.39 | 0.57 | 0.24 | 0.14 | 0.19 | 0.08 | 0.99 |
| 09/03/87 | 2.8 | 0.09 | 0.10 | 0.09 | 0.23 | 0.40 | 0.15 | 0.21 | 0.14 | 0.22 | 0.13 | nss |
| 09/12/87 | 1.1 | 0.20 | 0.14 | 0.23 | 0.09 | 0.15 | 0.38 | 0.41 | 0.08 | 0.25 | 0.19 | nss |
| 10/22/87 | 1.5 | nss | nss | nss | nss | nss | 0.23 | nss | nss | 0.00 | 0.00 | nss |
| 10/24/87 | 4.7 | 0.35 | 0.35 | 0.36 | nss | nss | 0.24 | 0.32 | 0.32 | 0.36 | 0.36 | 0.44 |
| 10/29/87 | 5.9 | 0.49 | 0.11 | 0.17 | 0.43 | 0.54 | 0.35 | 0.44 | 0.19 | 0.28 | 0.14 | 0.71 |

Table 6-3. Continued.

| Date | Depth | DOC | Ca | Mg | Na | K | H | NH4 | Cl | NO3 | SO4 | HCO3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | mm | $mg/m^2$ |  |  |  |  | $umol/m^2$ |  |  |  |  |  |
| *Salix orestera* |  |  |  |  |  |  |  |  |  |  |  |  |
| 07/23/85 | 1.8 | 0.47 | 0.57 | 0.54 | 0.34 | 0.58 | nss | 1.16 | 0.49 | 0.69 | 0.93 | 0.00 |
| 07/27/85 | 0.5 | 0.12 | 0.27 | 0.30 | 1.19 | 0.23 | nss | 0.49 | 0.57 | 0.79 | 0.45 | 0.00 |
| 09/14/85 | 23.4 | 0.53 | 0.68 | 0.73 | 0.77 | 0.74 | 0.95 | 1.09 | 1.31 | 0.96 | 0.34 | 0.97 |
| 09/20/85 | 3.1 | 0.37 | 0.28 | 0.26 | 0.30 | 0.31 | 0.26 | 0.58 | 0.98 | 0.70 | 0.14 | 0.23 |
| 08/21/86 | 0.9 | 0.27 | nss | nss | nss | 0.00 | 0.03 | 0.69 | nss | 0.49 | nss | 0.03 |
| 09/20/86 | 3.3 | 0.09 | 0.02 | 0.05 | 0.18 | 0.16 | 0.22 | 0.32 | 0.00 | 0.24 | 0.00 | 0.35 |
| 10/15/86 | 7.7 | 0.36 | 0.12 | 0.20 | 0.05 | 0.32 | 0.38 | 0.79 | 0.32 | 0.47 | 0.08 | 0.57 |
| 09/01/87 | 0.3 | nss | nss | nss | nss | nss | 0.43 | nss | 0.04 | 0.24 | 0.10 | nss |
| 09/03/87 | 2.6 | 0.13 | 0.12 | 0.19 | 0.10 | 0.21 | 0.44 | 0.28 | 0.58 | 0.14 | 0.04 | 1.16 |
| 09/12/87 | 1.2 | 0.56 | 0.21 | 0.29 | nss | nss | 0.30 | 0.24 | 0.21 | 0.12 | 0.14 | nss |
| 10/22/87 | 0.6 | nss | nss | nss | nss | nss | 0.43 | nss | 0.28 | 0.88 | 0.18 | nss |
| 10/24/87 | 0.3 | 0.60 | 0.32 | 0.25 | nss | nss | 0.40 | 0.12 | 0.35 | 0.37 | 0.24 | 1.63 |
| 10/29/87 | 4.2 | 0.40 | 0.41 | 0.37 | 0.26 | 0.36 | 0.33 | 0.18 | 0.76 | 0.32 | 0.37 | 1.12 |
| *Bulk Deposition* |  |  |  |  |  |  |  |  |  |  |  |  |
| 07/23/85 | 2.2 | 0.20 | 0.27 | 0.55 | 0.27 | 0.15 | 0.41 | 0.30 | 0.43 | 0.36 | 0.57 | 0.88 |
| 07/27/85 | 0.3 | 0.17 | 0.08 | 0.08 | 1.07 | 0.77 | 0.34 | 0.09 | 0.86 | 0.08 | 0.52 | 0.72 |
| 09/14/85 | 1.8 | 0.24 | 0.17 | 0.20 | 0.12 | 0.58 | 0.19 | 0.68 | 1.00 | 0.37 | 0.18 | 0.93 |
| 09/20/85 | 1.4 | 0.23 | 0.18 | 0.31 | 0.31 | 0.66 | 0.30 | 0.63 | 1.08 | 0.47 | 0.16 | 0.85 |
| 07/24/86 | 0.9 | 0.13 | 0.03 | 0.09 | 0.05 | 0.15 | 0.80 | 0.80 | 0.08 | 0.17 | 0.46 | 1.23 |
| 08/21/86 | 1.0 | 0.27 | 0.21 | 0.35 | 0.43 | 0.47 | 0.68 | 0.70 | 0.11 | 0.22 | 0.16 | 1.01 |
| 09/20/86 | 3.0 | 0.24 | 0.14 | 0.22 | 0.22 | 0.26 | 0.47 | 0.52 | 0.76 | 0.16 | 0.18 | 1.13 |
| 10/15/86 | 5.6 | 0.09 | 0.08 | 0.19 | 0.46 | 0.16 | 0.22 | 0.09 | 0.18 | 0.09 | 0.12 | 1.16 |
| 06/11/87 | 2.5 | 0.08 | 0.07 | 0.07 | 0.27 | 0.15 | 0.25 | 0.07 | 0.18 | 0.06 | 0.06 | 1.11 |
| 09/01/87 | 0.3 | nss | nss | nss | nss | nss | 0.27 | nss | 0.16 | 0.05 | 0.07 | nss |
| 09/03/87 | 1.5 | 0.20 | 0.06 | 0.13 | 0.17 | 0.05 | 0.20 | 0.05 | 0.18 | 0.07 | 0.00 | 0.13 |
| 09/03/87 | 1.9 | 0.11 | 0.38 | 0.10 | 0.32 | 0.25 | 0.21 | 0.13 | 0.15 | 0.07 | 0.07 | 0.43 |
| 09/12/87 | 0.3 | 0.06 | 0.08 | 0.09 | 0.38 | 0.23 | 0.30 | 0.23 | 0.19 | 0.04 | 0.06 | nss |
| 10/22/87 | 0.8 | nss | nss | nss | nss | nss | 0.33 | nss | 0.30 | 0.11 | 0.31 | nss |
| 10/24/87 | 1.5 | 0.14 | 0.23 | 0.28 | nss | nss | 0.21 | 0.11 | 0.15 | 0.30 | 0.30 | 0.82 |
| 10/29/87 | 7.0 | 0.28 | 0.22 | 0.32 | 0.56 | 0.99 | 0.30 | 0.60 | 0.36 | 0.33 | 0.07 | 1.02 |

Table 6-4. Calculation of number of samples required to obtain mean deposition values within 10% of the true mean.

| Date | Depth | DOC | Ca | Mg | Na | K | H | NH4 | NO3 | SO4 |
|---|---|---|---|---|---|---|---|---|---|---|
| *Chrysolepsis sempervirens* | | | | | | | | | | |
| 85/09/14 | 164 | 60 | 58 | 72 | 41 | 49 | 35 | 157 | 27 | 152 |
| 85/09/20 | 46 | 9 | 6 | 8 | 7 | 10 | 2 | 4 | 8 | 3 |
| 86/10/15 | 20 | 6 | 1 | 5 | 1 | 4 | 3 | 140 | 1 | 3 |
| 87/06/11 | 27 | 4 | 3 | 10 | 7 | 5 | 2 | 6 | 10 | 1 |
| 87/10/29 | 113 | 24 | 16 | 28 | 11 | 19 | 13 | 19 | 72 | 182 |
| *Pinus monticola* | | | | | | | | | | |
| 85/09/14 | 72 | 5 | 3 | 5 | 6 | 6 | 4 | 15 | 3 | 7 |
| 85/09/20 | 103 | 6 | 5 | 10 | 2 | 6 | 356 | 20 | 12 | 18 |
| 86/10/15 | 188 | 2 | 2 | 3 | 5 | 2 | 41 | 2 | 1 | 1 |
| 87/06/11 | 276 | 5 | 17 | 25 | 26 | 19 | 37 | 5 | 3 | 1 |
| 87/10/29 | 270 | 23 | 2 | 5 | 22 | 33 | 24 | 20 | 8 | 4 |
| *Salix orestera* | | | | | | | | | | |
| 85/09/14 | 293 | 39 | 56 | 72 | 78 | 54 | 254 | 520 | 317 | 19 |
| 85/09/20 | 38 | 25 | 10 | 10 | 10 | 10 | 27 | 51 | 109 | 3 |
| 86/10/15 | | | | | | | | | | |
| 87/06/11 | 18 | 14 | 2 | 5 | 1 | 8 | 30 | 212 | 38 | 1 |
| 87/10/29 | 22 | 34 | 11 | 10 | 7 | 10 | 15 | 9 | 17 | 19 |
| *Bulk Deposition* | | | | | | | | | | |
| 85/09/14 | 2 | 9 | 3 | 6 | 1 | 30 | 3 | 30 | 8 | 3 |
| 85/09/20 | 5 | 13 | 6 | 28 | 7 | 90 | 68 | 30 | 17 | 3 |
| 86/10/15 | 38 | 2 | 1 | 7 | 20 | 3 | 6 | 1 | 1 | 2 |
| 87/06/11 | 7 | 2 | 1 | 1 | 7 | 3 | 5 | 1 | 1 | 1 |
| 87/10/29 | 54 | 47 | 9 | 37 | 31 | 198 | 10 | 42 | 11 | 1 |

Table 6-5. Calculated net throughfall deposition at ELW by event
1985-1987.

| Date | Ca | Mg | Na | K | H | NH4 | Cl | NO3 | SO4 | HCO3 | DOC | Period | Depth |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | umol/m2 | | | | | mg/m2 | d | mm |
| *Chrysolepsis sempervirens* | | | | | | | | | | | | | |
| 07/23/85 | 723 | 47 | 385 | 804 | 335 | 127 | 394 | 244 | 108 | -2 | 806 | 20 | 6.3 |
| 07/27/85 | 136 | 59 | 238 | 292 | NA | 168 | -28 | 137 | -15 | -2 | 257 | 4 | 1.4 |
| 09/14/85 | 482 | 235 | 361 | 1142 | 132 | -253 | 78 | 330 | -131 | -1 | 505 | 49 | 35.8 |
| 09/20/85 | 189 | 76 | -152 | 205 | 214 | 3 | -3 | -41 | -22 | -6 | 267 | 6 | 10.2 |
| 07/24/86 | 245 | 151 | 72 | 842 | -589 | -480 | 239 | -358 | -583 | 108 | 423 | 12 | 13.6 |
| 08/21/86 | NA | NA | -118 | NA | -0 | -10 | NA | 223 | NA | 166 | 187 | 28 | 2.2 |
| 09/20/86 | 105 | 84 | 31 | 415 | 173 | 104 | 5536 | 226 | 54 | -12 | 252 | 30 | 5.1 |
| 10/15/86 | 668 | 184 | 76 | 855 | 1761 | -850 | 128 | 462 | 49 | -34 | 1001 | 25 | 53.6 |
| 06/11/87 | 184 | 101 | 318 | 426 | 547 | -1069 | 535 | -388 | -76 | -57 | 439 | 14 | 16.4 |
| 09/01/87 | NA | NA | NA | NA | 67 | NA | 417 | -200 | -62 | NA | NA | 7 | 0.9 |
| 09/03/87 | 262 | 255 | 458 | 1129 | 444 | -904 | 445 | -621 | -41 | 155 | 669 | 2 | 7.7 |
| 09/12/87 | 77 | 57 | 123 | 397 | 37 | -93 | 79 | -171 | 14 | NA | 233 | 9 | 3.2 |
| 10/22/87 | NA | NA | NA | NA | 6 | NA | 25 | -143 | -22 | NA | NA | 9 | 1.7 |
| 10/24/87 | 406 | NA | NA | NA | 81 | 112 | 60 | 59 | 4 | NA | 399 | 2 | 15.4 |
| 10/29/87 | 57 | 76 | 117 | 393 | -6 | -79 | 18 | -145 | -18 | 10 | 443 | 5 | 13.0 |
| *Pinus monticola* | | | | | | | | | | | | | |
| 07/23/85 | 1213 | 336 | 233 | 766 | 90 | 1302 | 176 | 472 | 330 | -2 | 807 | 20 | 2.7 |
| 07/27/85 | 12 | 9 | 63 | -47 | NA | -171 | 20 | -62 | -8 | -2 | 33 | 4 | 0.5 |
| 09/14/85 | 2733 | 960 | 785 | 2112 | 615 | 3459 | 52 | 7710 | 662 | -1 | 1390 | 49 | 36.7 |
| 09/20/85 | 174 | 75 | 332 | 229 | -21 | 68 | 95 | 141 | -13 | 0 | 154 | 6 | 7.5 |
| 07/24/86 | 581 | 171 | 46 | 413 | -609 | 1526 | 618 | 2321 | -455 | 1223 | 517 | 12 | 15.9 |
| 08/21/86 | NA | NA | 437 | NA | -9 | 1544 | NA | 181 | NA | 23 | 121 | 28 | 1.3 |
| 09/20/86 | 593 | 240 | 148 | 577 | 8 | 1509 | NA | 2083 | NA | 49 | 169 | 30 | 5.7 |
| 10/15/86 | 467 | 211 | 499 | 517 | 127 | 800 | 507 | 1119 | 209 | 140 | 210 | 25 | 40.7 |
| 06/11/87 | 278 | 84 | 178 | 192 | -197 | -74 | 356 | 610 | 155 | -44 | 195 | 14 | 10.2 |
| 09/03/87 | 1087 | 300 | 485 | 685 | 65 | 1772 | 505 | 2862 | 396 | NA | 327 | 2 | 4.5 |
| 09/12/87 | 234 | 68 | 114 | 325 | 24 | 276 | 124 | 796 | 76 | NA | 215 | 9 | 3.0 |
| 10/22/87 | NA | NA | NA | NA | -0 | NA | 145 | 1744 | 143 | NA | NA | 9 | 1.3 |
| 10/24/87 | 453 | 149 | NA | NA | 57 | 1124 | 374 | 1165 | 287 | 362 | 1073 | 2 | 11.4 |
| 10/29/87 | 292 | 105 | 84 | 236 | -4 | 263 | 192 | 434 | 88 | -12 | 703 | 5 | 9.2 |

Table 6-5. Continued.

| Date | Ca | Mg | Na | K | H | NH4 | Cl | NO3 | SO4 | HCO3 | DOC | Period | Depth |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | umol/m2 | | | | | mg/m2 | d | mm |
| | | | | | | *Salix orestera* | | | | | | | |
| 07/23/85 | 128 | 105 | 82 | 282 | NA | -184 | 172 | -155 | -28 | -2 | 72 | 20 | 2.0 |
| 07/27/85 | 14 | 40 | -46 | 41 | NA | -267 | -27 | -191 | -24 | -2 | 28 | 4 | 0.8 |
| 09/14/85 | 588 | 486 | 107 | 1398 | -231 | -382 | 183 | -697 | 38 | 806 | 483 | 49 | 43.5 |
| 09/20/85 | 188 | 128 | -100 | 444 | -62 | -150 | 99 | -213 | 17 | 1099 | 68 | 6 | 13.1 |
| 08/21/86 | NA | NA | -25 | -22 | -12 | -79 | NA | -221 | NA | 362 | 56 | 28 | 2.3 |
| 09/20/86 | 190 | 137 | 27 | 466 | -25 | -56 | -90 | -5 | 6 | 852 | 83 | 30 | 5.3 |
| 10/15/86 | 1153 | 581 | 707 | 1455 | -23 | -979 | 217 | -831 | 127 | 2527 | 488 | 25 | 50.3 |
| 09/01/87 | NA | NA | NA | NA | 1 | NA | 40 | 109 | 59 | NA | NA | 7 | 1.8 |
| 09/03/87 | 328 | 204 | 723 | 436 | 70 | -447 | 745 | -155 | -31 | -341 | 130 | 2 | 10.8 |
| 09/12/87 | 174 | 95 | NA | NA | -14 | -51 | 100 | 16 | 19 | NA | 220 | 9 | 4.4 |
| 10/22/87 | NA | NA | NA | NA | 2 | NA | 224 | -159 | 96 | NA | NA | 9 | 3.8 |
| 10/24/87 | 1656 | 894 | NA | NA | 243 | -54 | 498 | -67 | 198 | 92 | 1530 | 2 | 15.0 |
| 10/29/87 | 2081 | 1186 | 297 | 979 | 70 | -57 | 293 | -55 | 107 | 247 | 847 | 5 | 23.7 |

Negative values indicate flux into the foliage, positive values indicate foliar leaching and wash-off.

NA not sufficient sample.

period is the time elapsed since last rainfall event washed leaves.

Table 6-6. Regression of net throughfall deposition against antecedent period and depth of throughfall.

| Element | $b_1$ | SE | $b_2$ | SE | n | r |
|---|---|---|---|---|---|---|
| | --umol/$m^2$/da-- | | ---mmol/$m^3$--- | | | |
| *Chrysolepsis sempervirens* | | | | | | |
| Ca | 5.5 | 6.3 | 7.7 | 6.2 | 10 | 0.61 |
| Mg | 2.6 | 0.6 | 2.7 | 0.6 | 10 | 0.92 |
| K | 19.0 | 5.4 | 8.8 | 5.3 | 10 | 0.76 |
| NH4 | 3.8 | 9.6 | -21.7 | 10.2 | 11 | 0.43 |
| NO3 | -0.6 | 5.9 | 7.6 | 6.5 | 11 | 0.46 |
| SO4 | -2.2 | 3.1 | 1.0 | 3.2 | 10 | 0.00 |
| Org | 6.2 | 5.2 | 15.1 | 5.5 | 11 | 0.41 |
| *Pinus monticola* | | | | | | |
| Ca | 42.8 | 12.7 | -4.1 | 14.8 | 10 | 0.85 |
| Mg | 14.1 | 3.9 | 0.2 | 4.6 | 10 | 0.88 |
| K | 30.0 | 10.9 | 2.3 | 12.6 | 10 | 0.84 |
| NH4 | 50.7 | 22.0 | -0.5 | 27.6 | 11 | 0.73 |
| NO3 | 57.0 | 35.0 | 47.6 | 44.3 | 12 | 0.73 |
| SO4 | 13.5 | 14.5 | -8.8 | 15.4 | 10 | 0.34 |
| Org | 14.5 | 7.8 | 8.0 | 9.8 | 11 | 0.59 |
| *Salix orestera* | | | | | | |
| Ca | -16.4 | 14.4 | 38.2 | 13.3 | 8 | 0.69 |
| Mg | -5.4 | 8.4 | 19.6 | 7.8 | 8 | 0.61 |
| K | 0.0 | 4.6 | 31.7 | 4.6 | 8 | 0.95 |
| NH4 | -4.4 | 6.0 | -10.4 | 6.0 | 8 | 0.58 |
| NO3 | -10.0 | 5.6 | -7.7 | 5.7 | 11 | 0.54 |
| SO4 | -3.2 | 1.9 | 4.4 | 1.8 | 10 | 0.66 |
| Org | -2.0 | 4.6 | 14.5 | 4.6 | 9 | 0.70 |

$b_1$ dry deposition coefficient
$b_2$ foliar exchange coefficient
SE standard error
n number of samples
r corelation coefficient

Table 6-7. Estimates of ANC, $NO_3^-$, and $SO_4^{2-}$ flus from ELW subbasin C+D above pond (transect site 14, basin area = 44.8 ha).

| Date | Depth | ANC | $NO_2^-$ | $SO_4^{2-}$ |
|---|---|---|---|---|
| | mm/da | umol/$m^2$/da | | |
| 04/30/87 | 15 | 151 | 307 | 86 |
| 07/02/87 | 4 | 179 | 32 | 16 |
| 08/14-87 | 2 | 87 | 11 | 8 |
| 10/29/87 | 1 | 11 | 46 | 3 |
| Totals* | 0.82 | 19.86 | 13.83 | 4.15 |

* integration of 4/30-10/29 using trapezoidal approximation of flux.

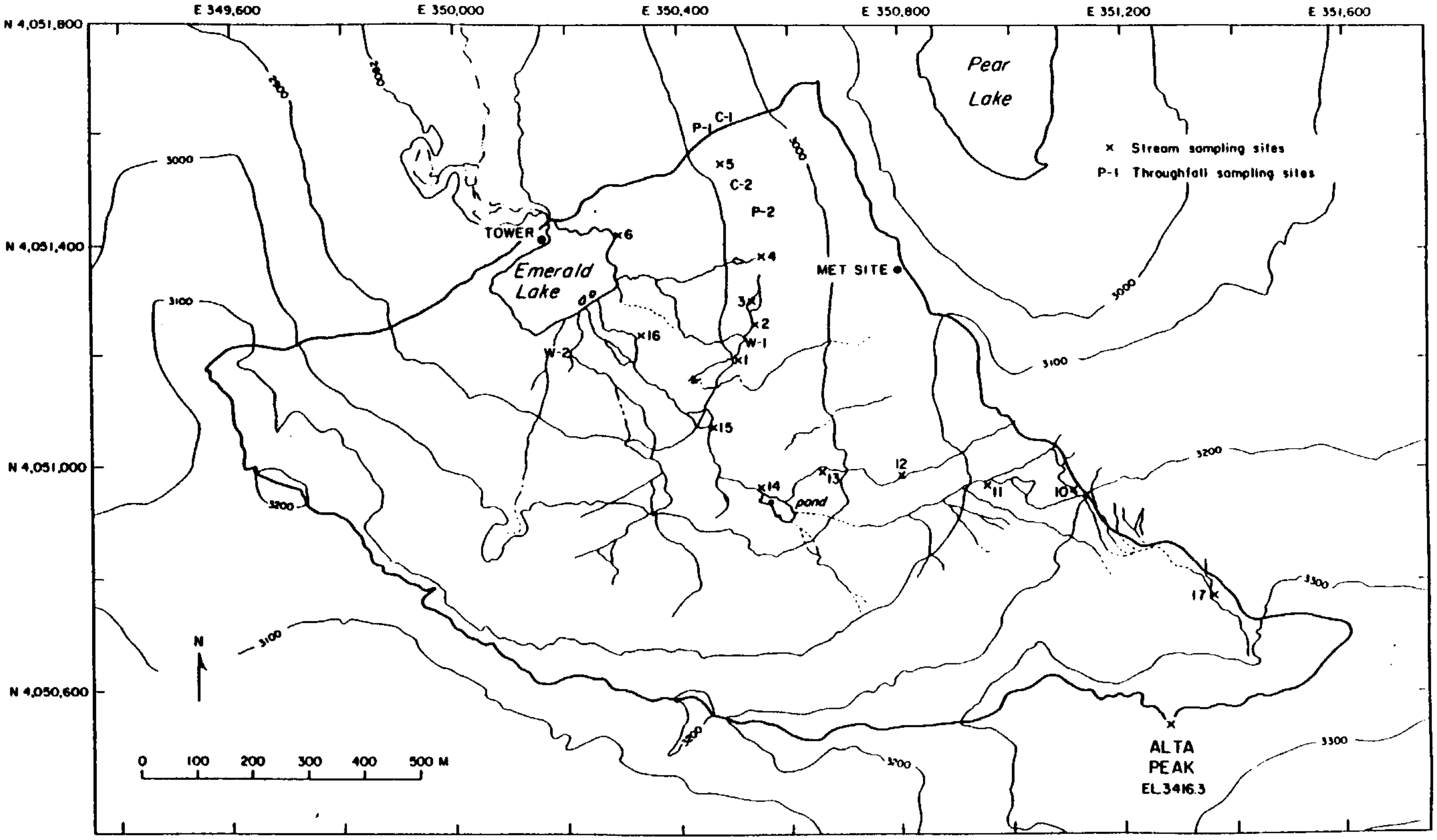


Figure 6-1. Location of stream sample and sample sites at ELW. P - *Pinus monticola*, C - *Chrysolepsis sempervirens*, S - *Salix orestera*.

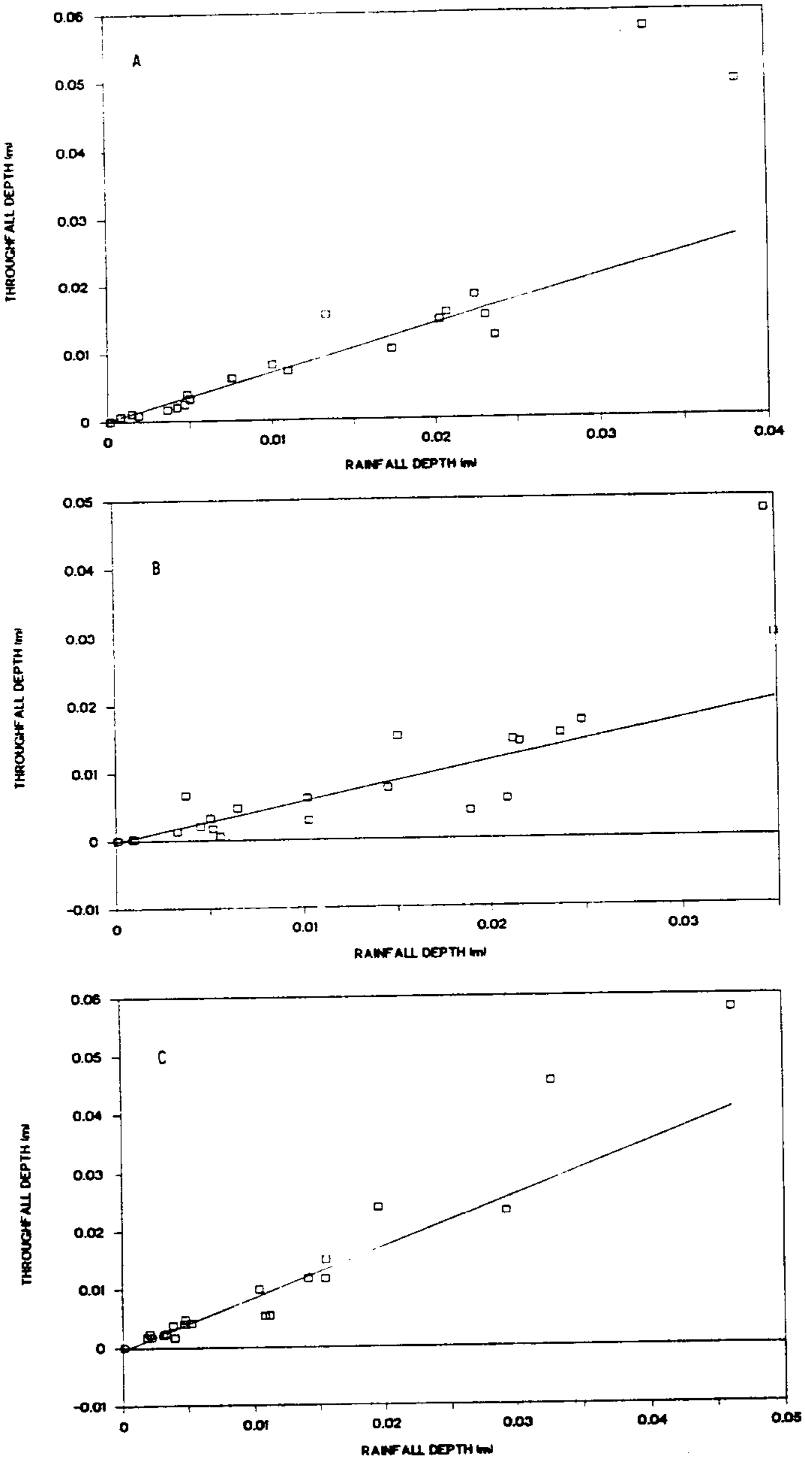


Figure 6-2. Interception of rainfall by a) *C. sempervirens*, b) *P. monticola*, c) *S. orestera*.

Figure 6-3a

Stream Acidification

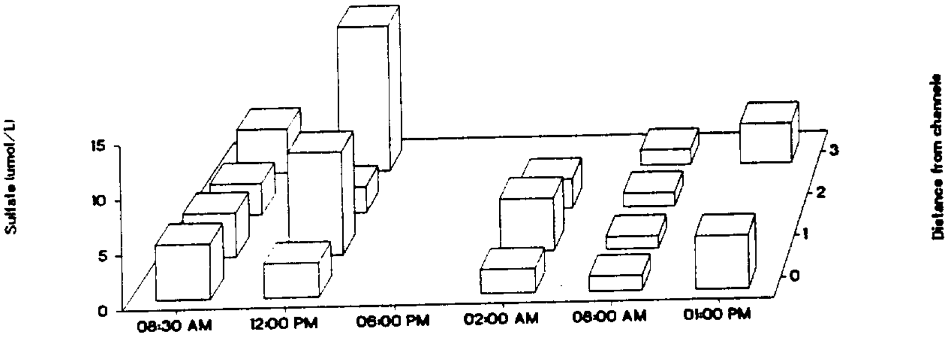


Figure 6-3b

Stream Acidification

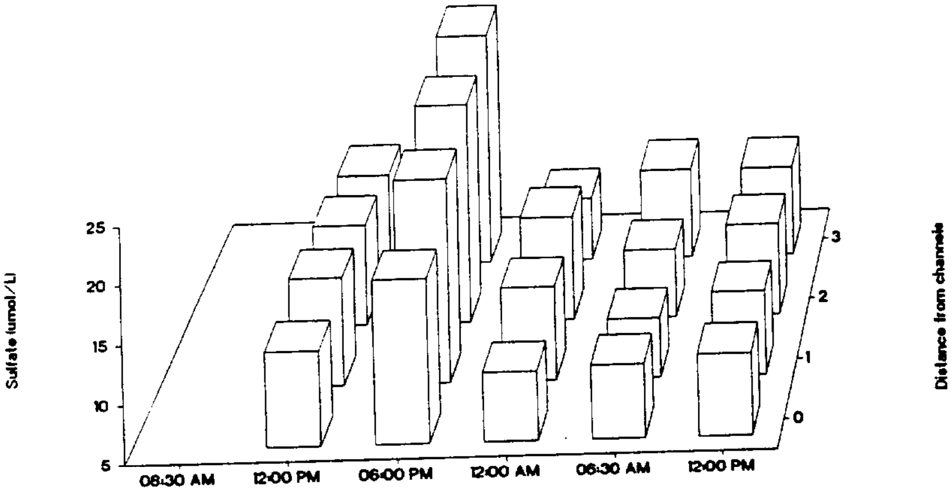


Figure 6-3. Spatial distribution of $SO_4^{2-}$ in stream water below the stream acidification channels on a) August 20-21, 1986 and b) September 4-5, 1986.

Figure 6-4a

Soil Response to Acidification

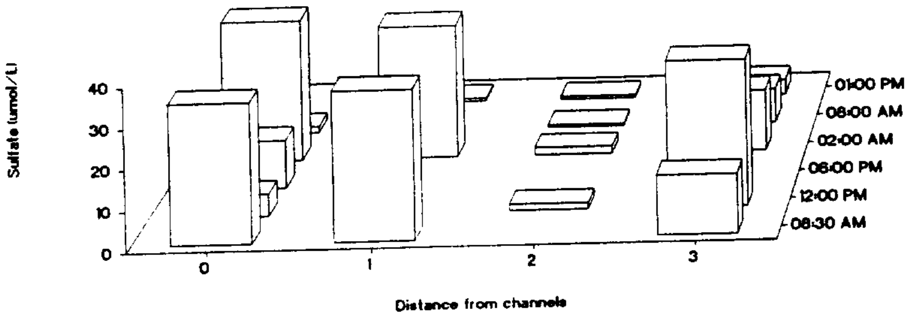


Figure 6-4b

Soil Response to Acidification

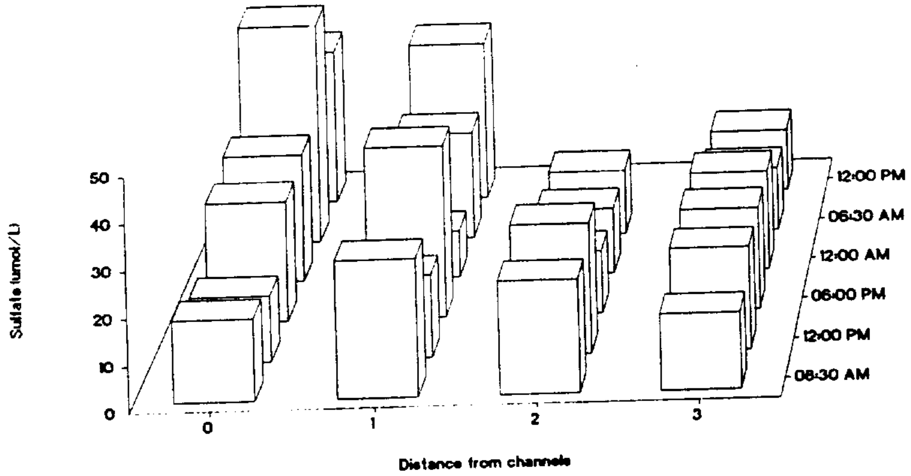


Figure 6-4. Spatial distribution of $SO_4^{2-}$ in piezometers below the stream acidification channels on a) August 20-21, 1986 and b) September 4-5, 1986.

Figure 6-5a

Stream Acidification

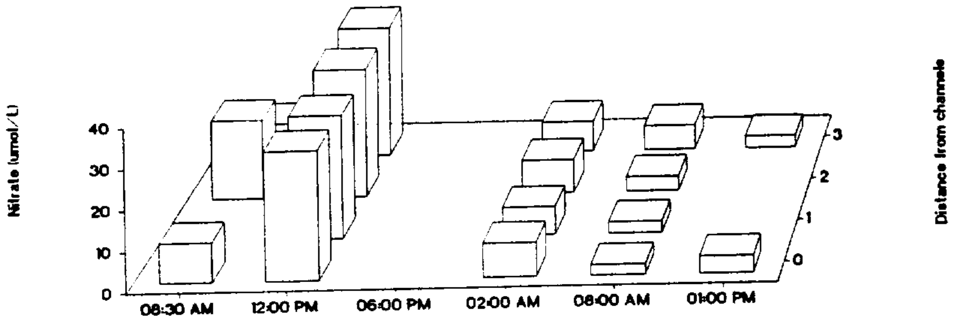


Figure 6-5b

Stream Acidification

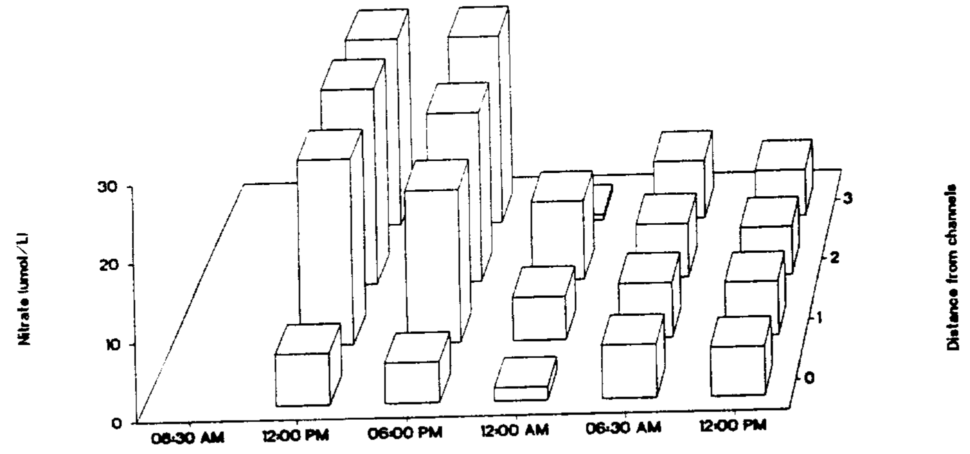


Figure 6-5. Spatial distribution of $NO_3^-$ in stream water below the stream acidification channels on a) August 20-21, 1986 and b) September 4-5, 1986.

Figure 6-6a

Soil Response to Acidification

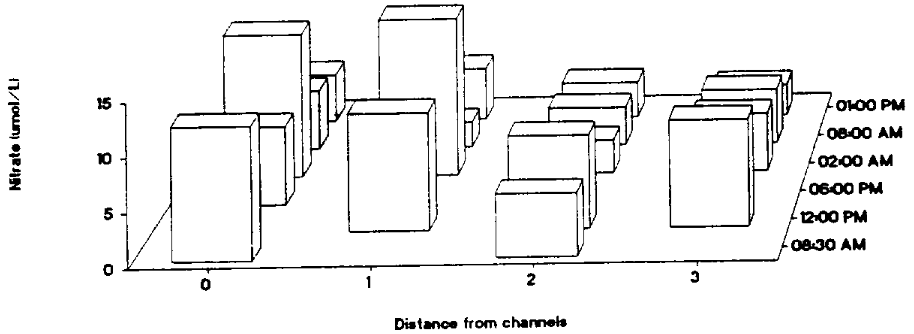


Figure 6-6b

Soil Response to Acidification

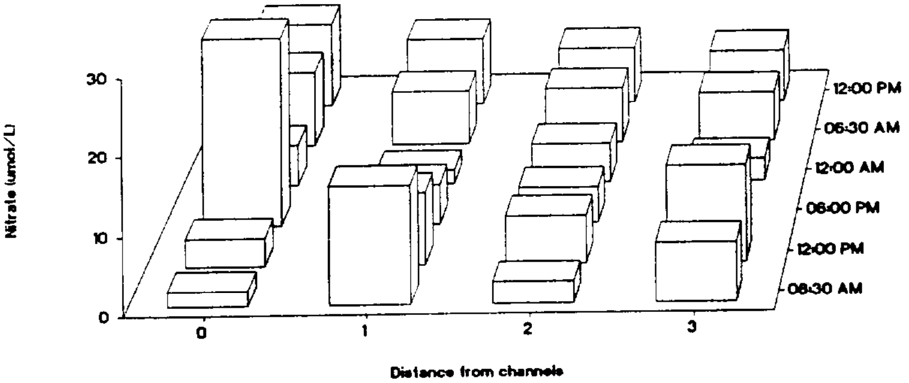


Figure 6-6. Spatial distribution of $NO_3^-$ in piezometers below the stream acidification channels on a) August 20-21, 1986 and b) September 4-5, 1986.

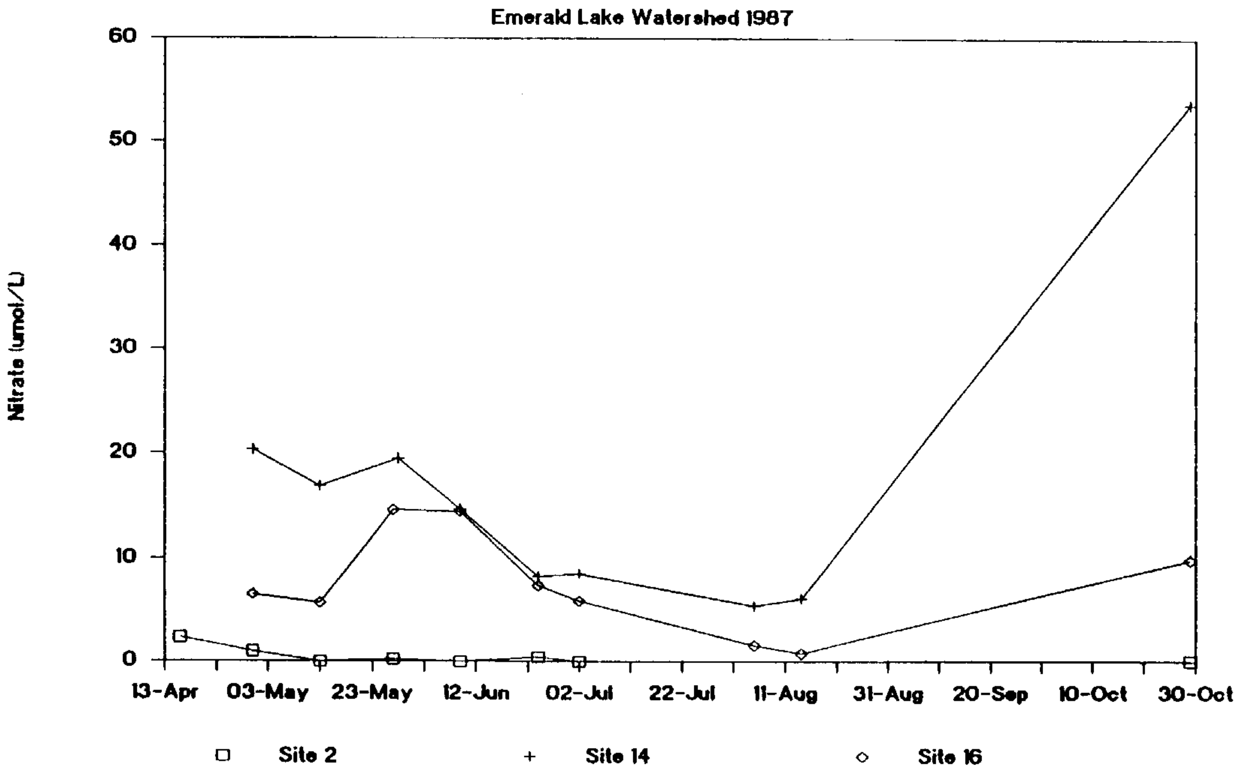


Figure 6-7. Temporal variation in $NO_3^-$ concentrations at three sites along ELW streams in 1987.

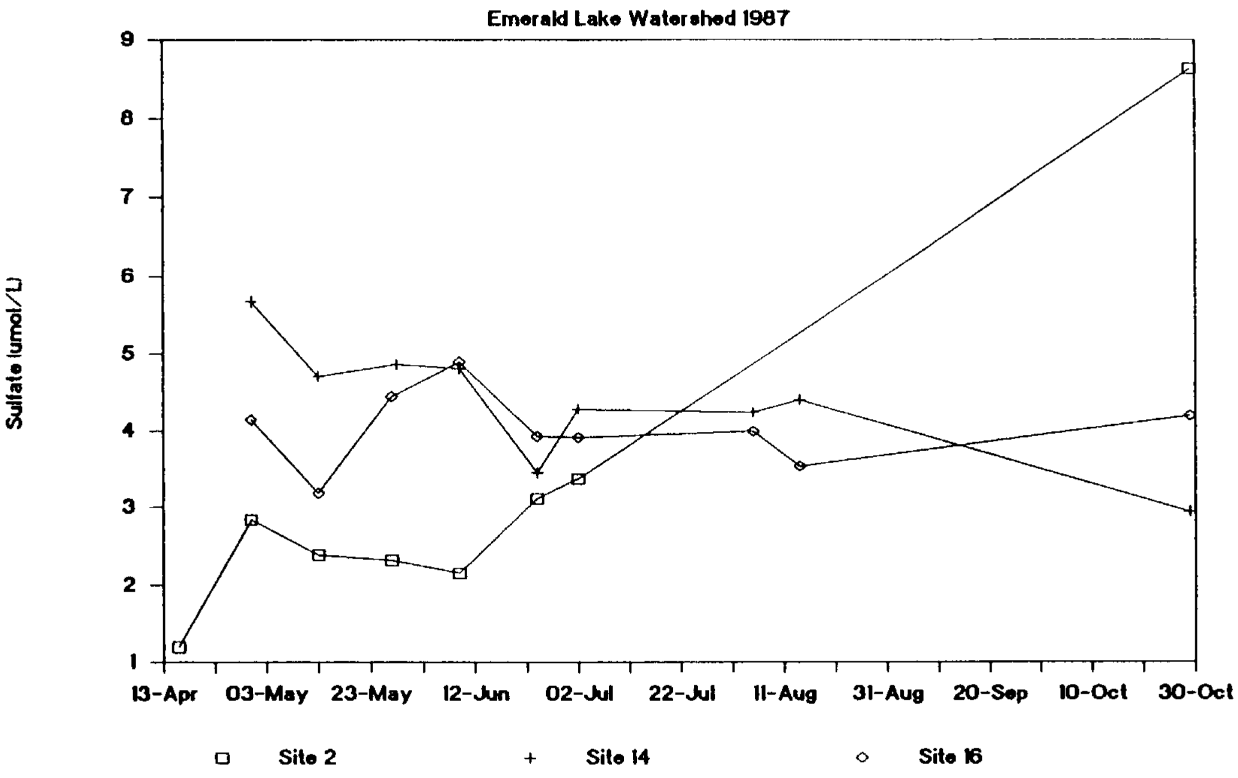


Figure 6-8. Temporal variation in $SO_4^{2-}$ concentrations at three sites along ELW streams in 1987.

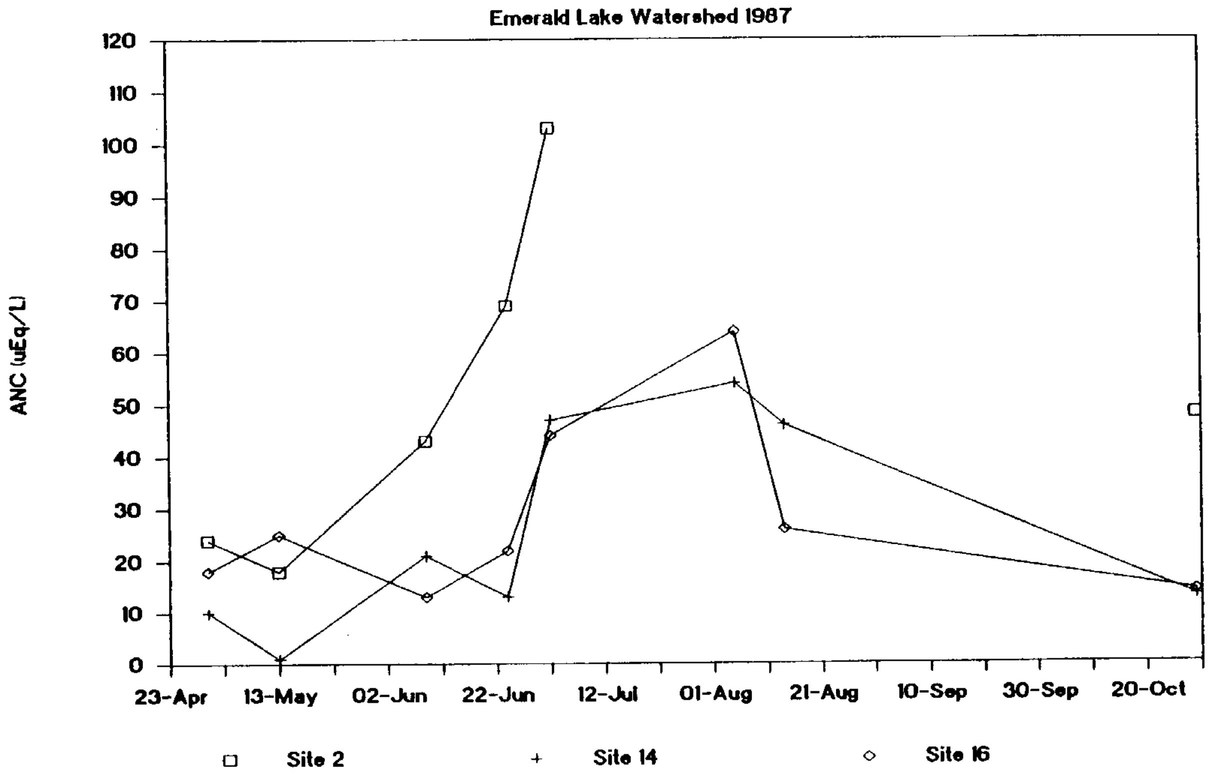


Figure 6-9. Temporal variation in ANC at three sites along ELW streams in 1987.

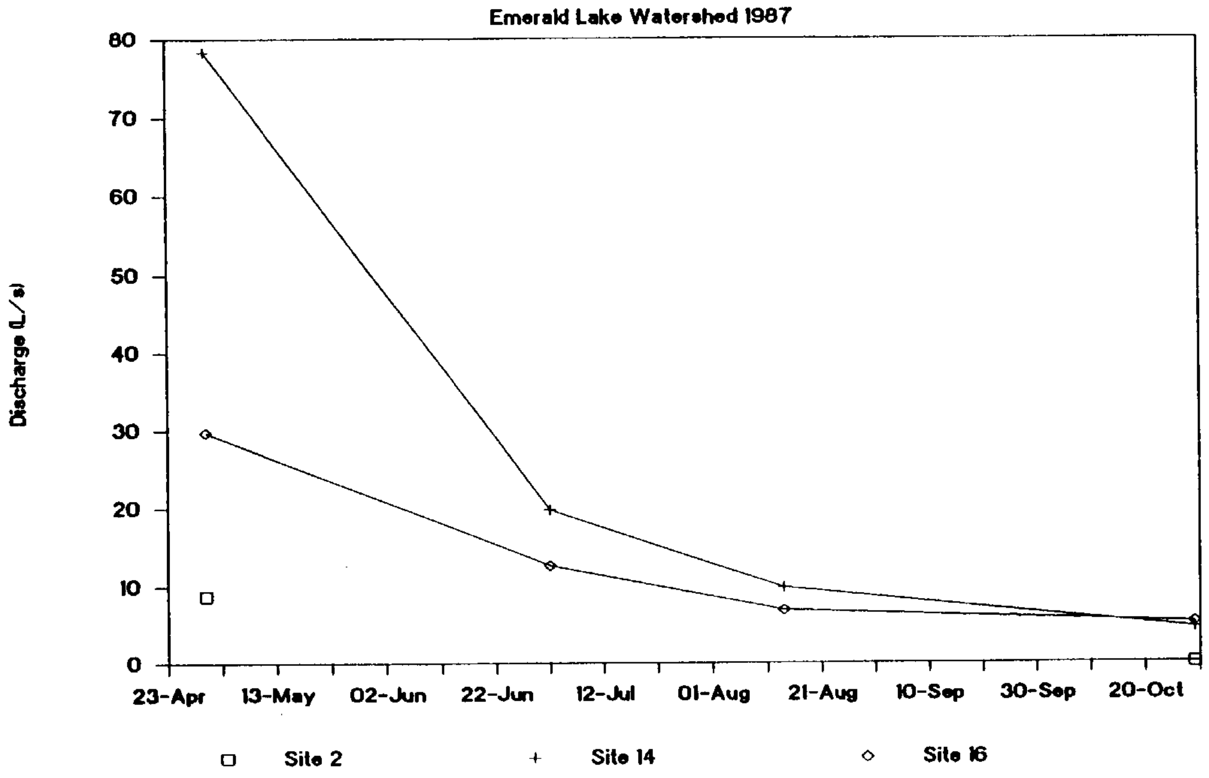


Figure 6-10. Discharge measurements for three sites along ELW streams in 1987 (Stephen Hamilton, UCSB, personal communication).

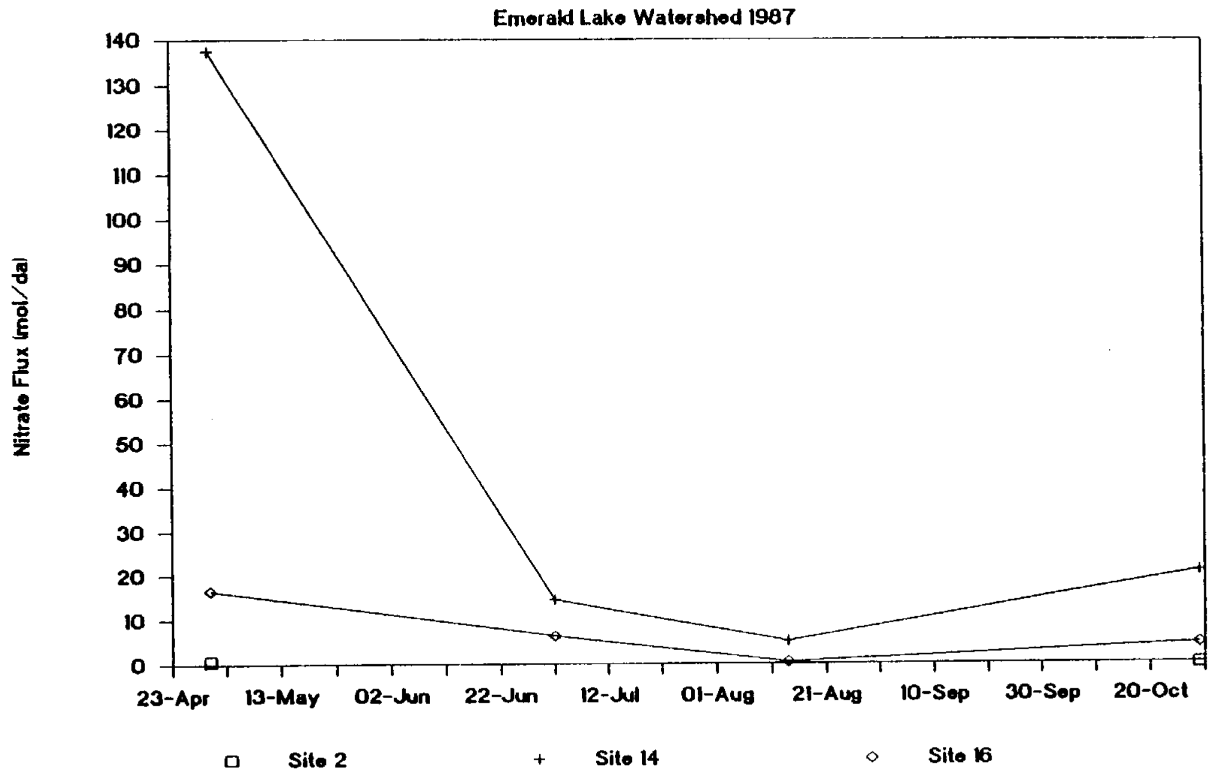


Figure 6-11. Temporal variation in $NO_3^-$ flux at three sites along ELW streams in 1987.

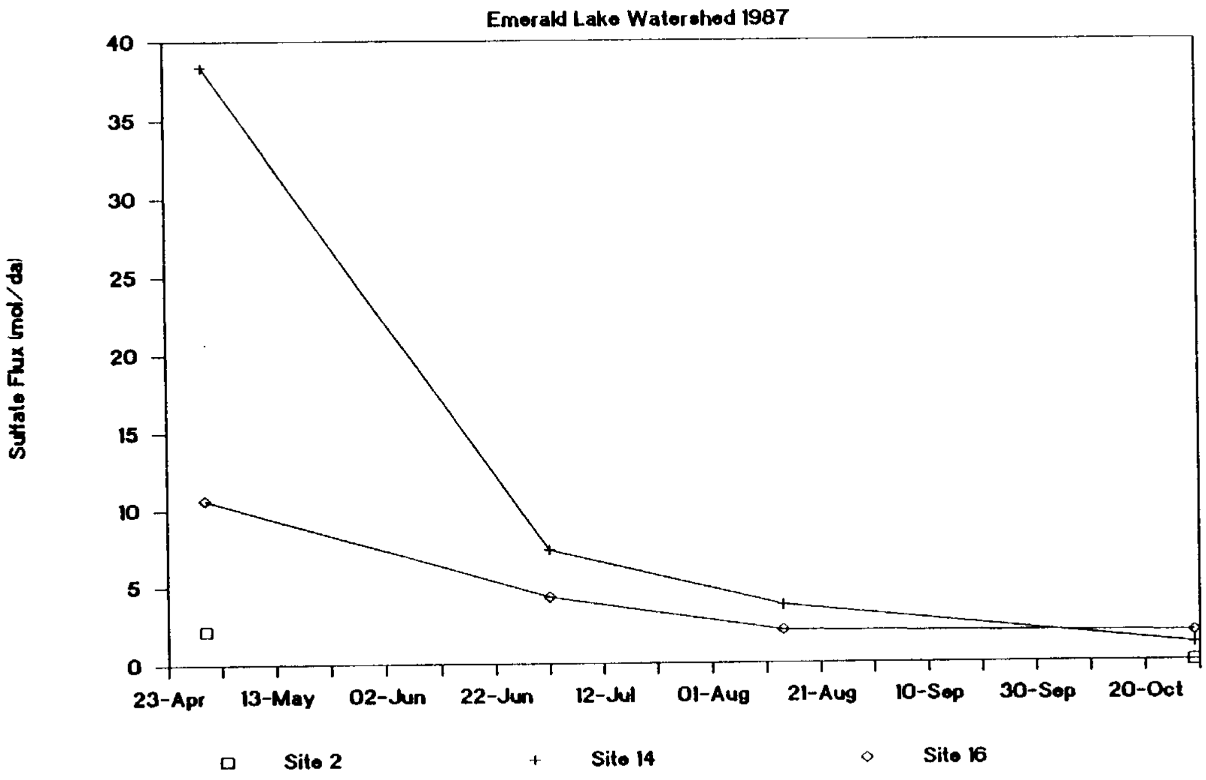


Figure 6-12. Temporal variation in $SO_4^{2-}$ flux at three sites along ELW streams in 1987.

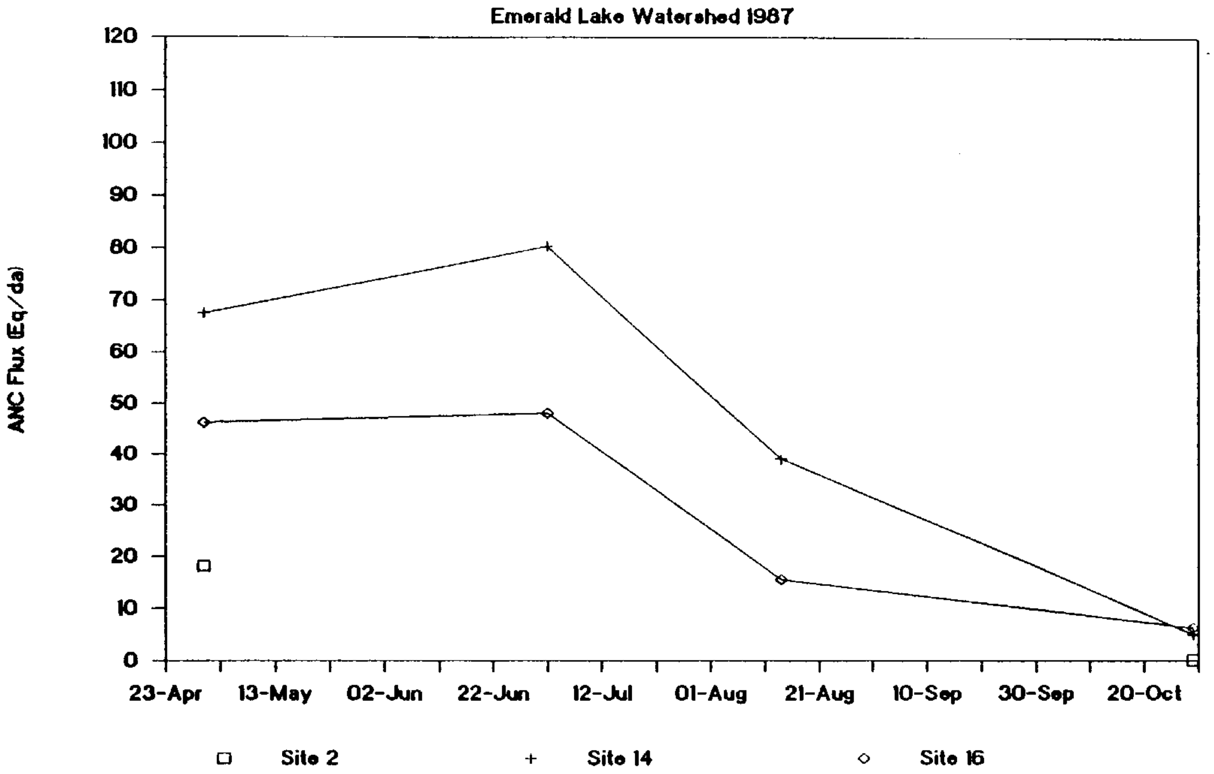


Figure 6-13. Temporal variation in ANC flux at three sites along ELW streams in 1987.

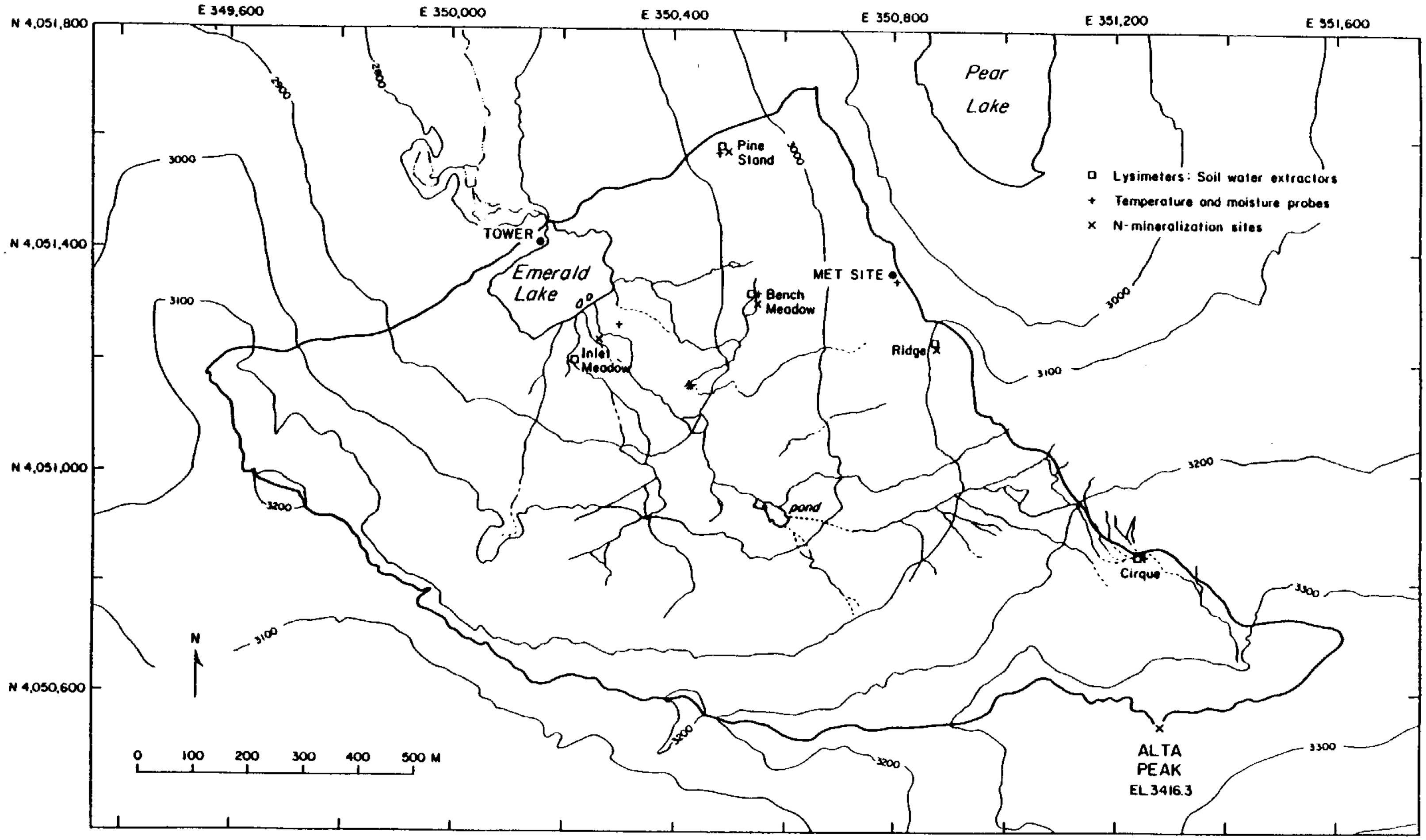


Figure 6-14. Map of soil lysimeters and soil $CO_2$ sample sites.

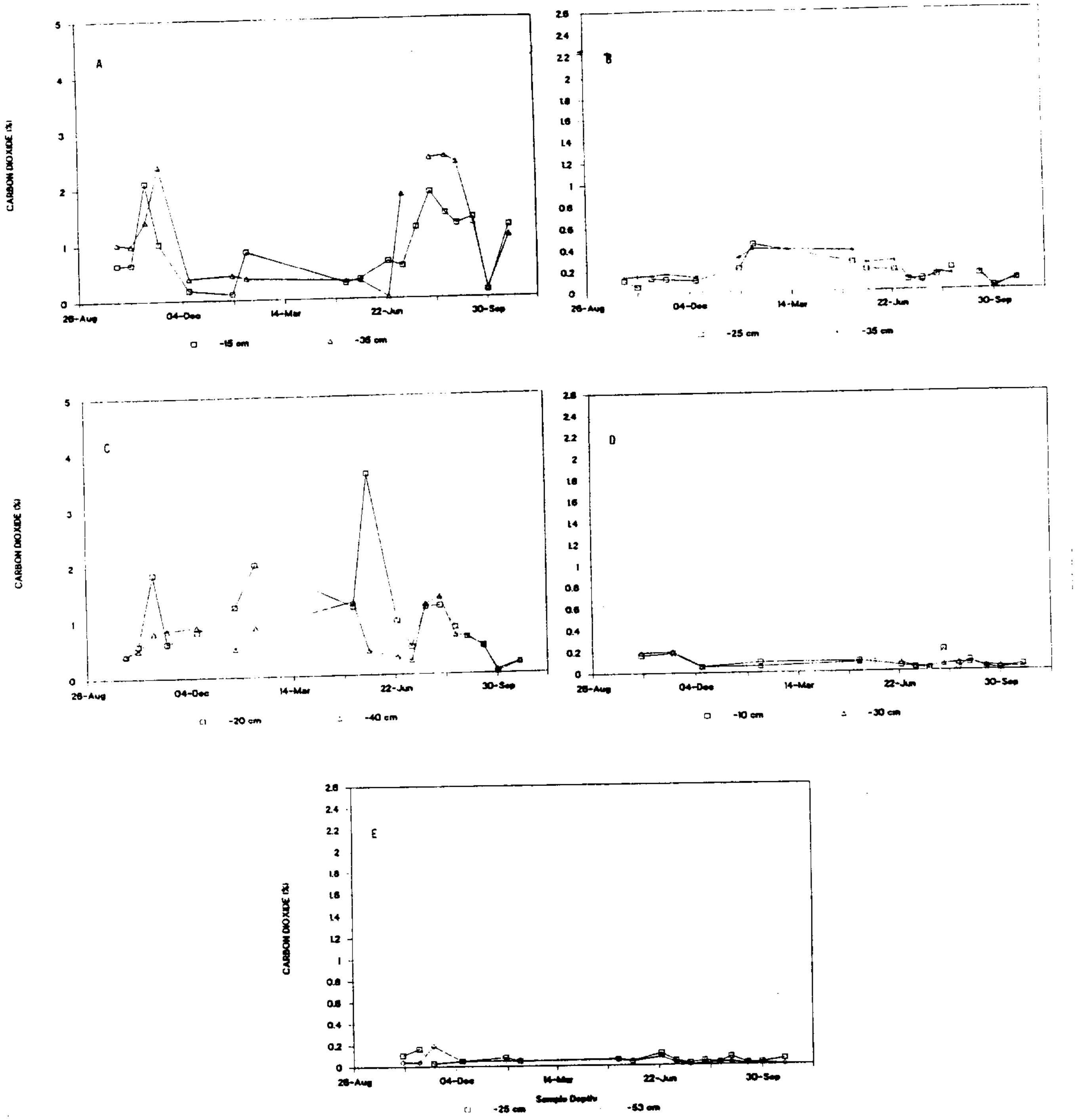


Figure 6-15. Temporal variation in $CO_2$ concentrations in ELW soil profiles a) bench meadow, b) pine stand, c) inlet meadow, d) ridge, e) cirque.

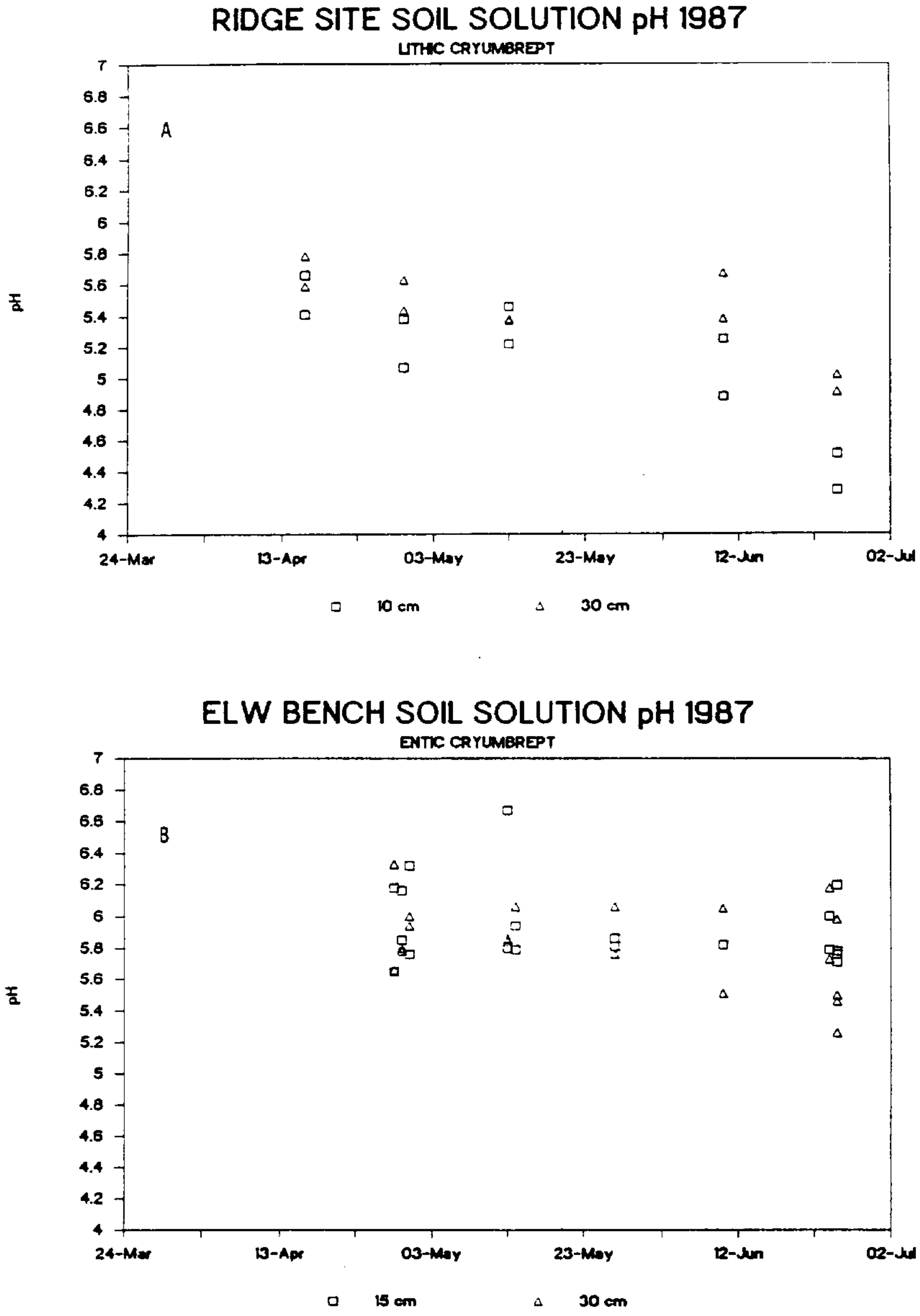


Figure 6-16. Temporal variation of pH of the soil solution at two depths, replicated sample collectors, during snowmelt 1987 at a) ridge site and b) bench site.

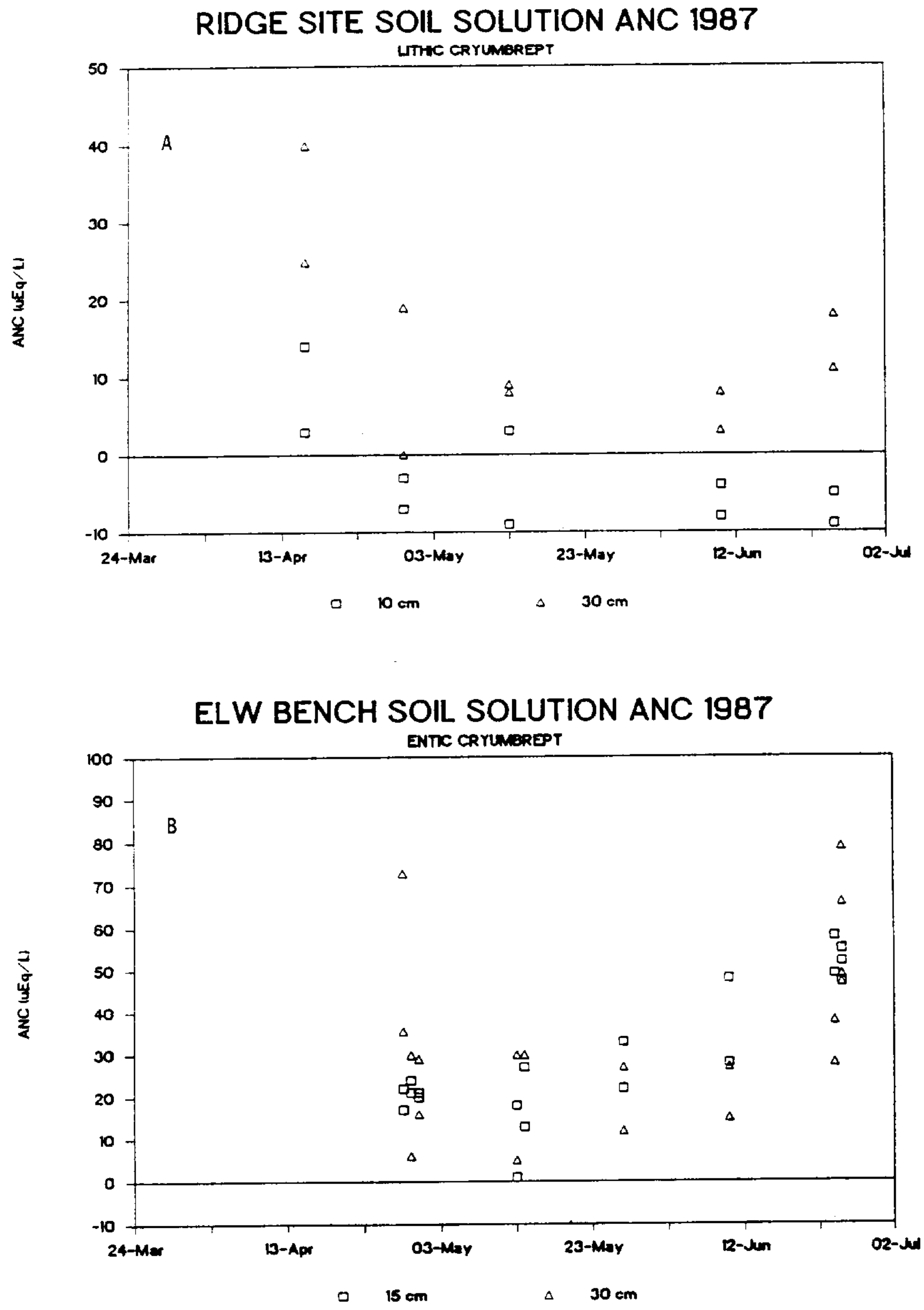
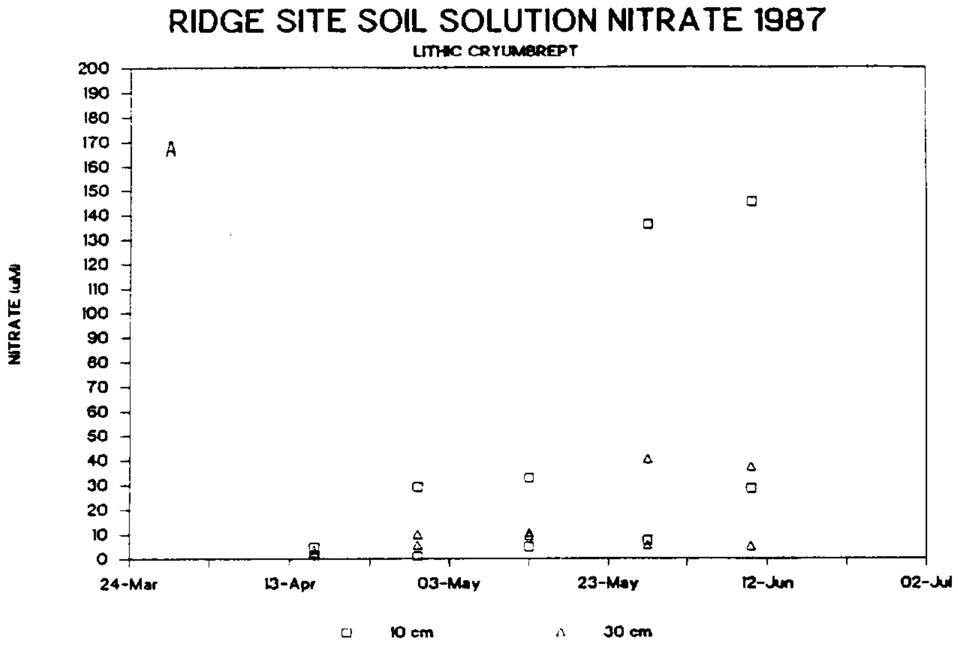


Figure 6-17. Temporal variation of soil solution ANC during snowmelt 1987 at a) ridge site and b) bench site.



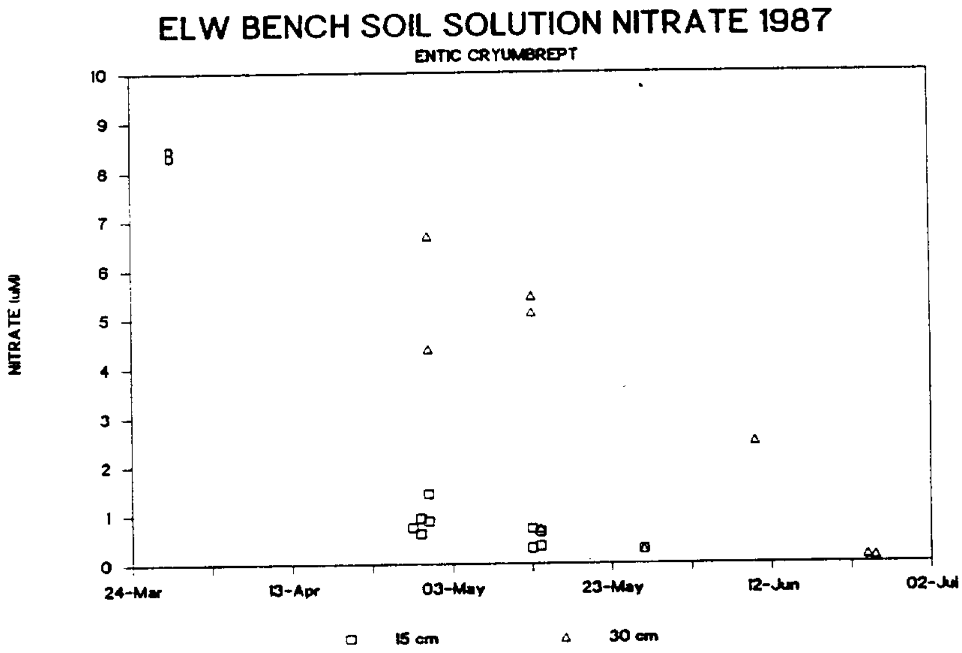


Figure 6-18. Temporal variation of soil solution $NO_3^-$ during snowmelt 1987 at a) ridge site and b) bench site.

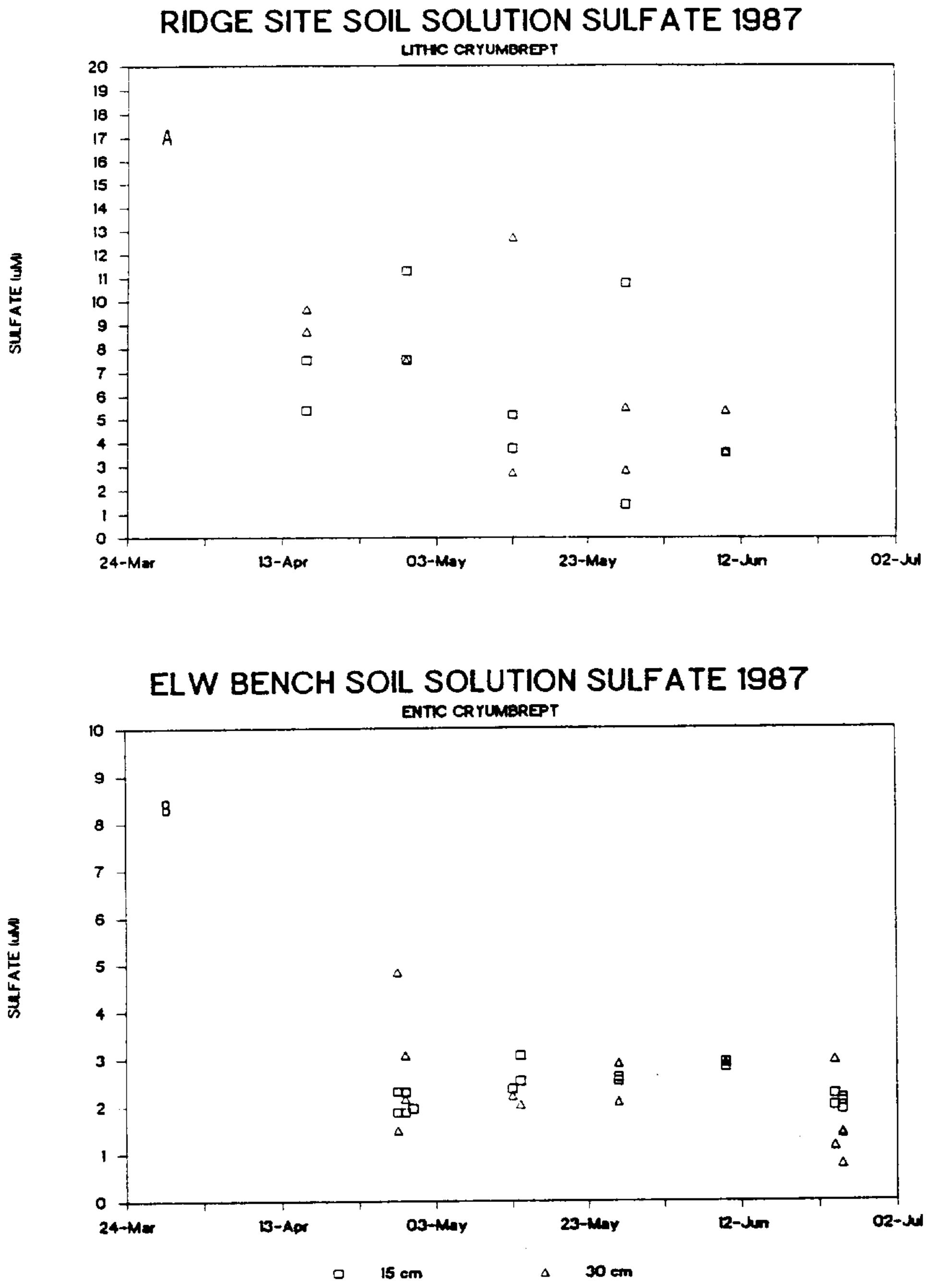


Figure 6-19. Temporal variation of soil solution $SO_4^{2-}$ during snowmelt 1987 at a) ridge site and b) bench site.

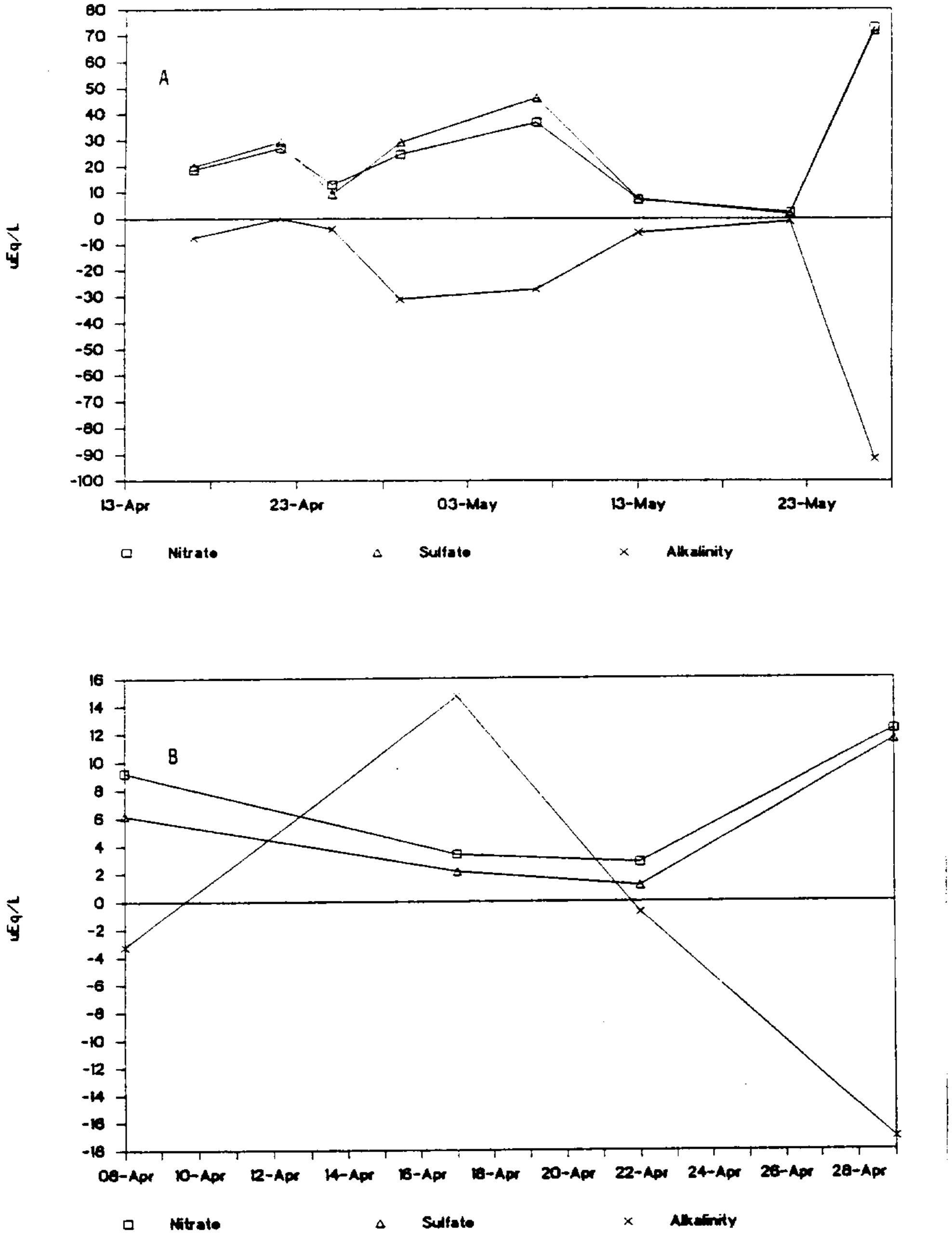


Figure 6-20. Temporal variation of snowmelt composition during April and May 1987 at a) cirque site and b) bench site (M. Williams, UCSB, personal communication).

# APPENDIX

# GLOSSARY

## Abbreviations

| | |
|---|---|
| Al | aluminum |
| ANC | acid neutralizing capacity |
| C | carbon |
| Ca | calcium |
| CEC | cation exchange capacity |
| $CO_2$ | carbon dioxide (gas) |
| DOC | dissolved organic carbon |
| EC | electrolytic conductivity |
| ELW | Emerald Lake Watershed, Sequoia National Park, CA |
| $H^+$ | hydrogen ion, proton |
| $HCO_3^-$ | bicarbonate |
| K | potassium |
| Mg | magnesium |
| N | nitrogen |
| Na | sodium |
| $NH_4^+$ | ammonium (solution cation) |
| $NO_3^-$ | nitrate (solution anion) |
| $N_2O$ | nitrous oxide |
| $O_2$ | oxygen (gas) |
| P | phosphorus |
| pH | -log (concentration of hydrogen ions) |
| $PO_4^{3-}$ | phosphate (solution anion) |
| S | sulfur |
| Si | silicon |
| $SO_4^{2-}$ | sulfate (solution ion) |

<u>Commonly Used Terms</u>

| | |
|---|---|
| acid | said of igneous rocks that contain more than 60 percent silica; e.g. granite, granodiorite. |
| adsorption | attraction of an ion to a charged surface of a soil mineral; adsorbed ions are no longer strictly in solution, but can easily return to solution by exchanging for an ion of similar charge. Often termed "sorption." |
| alluvium | general term for detrital deposits made in overbank flooding from stream channels. |
| Alta cirque | subbasin in ELW below Alta Peak. |
| aqueous | dissolved in water. |
| aquic soil moisture regime | - the whole soil is saturated and reducing conditions prevail for at least a few days when the soil temperature is above 5 C. |
| available water | water held in soil at potentials between -30kPa and -1500kPa. Water which is available for plant use. |
| base cation | solution cations $Ca^{2+}$, $Mg^{2+}$, $Na^+$, and $K^+$. |
| basic | said of igneous rocks having relatively low silica content - roughly 45 to 50 percent; e.g. gabbro, diorite. |
| bench meadow | area of the watershed southeast of Emerald Lake which is relatively level. |
| buffer | a component which provides resistance to change. |

| | |
|---|---|
| bulk density | the weight of soil per unit volume of soil. |
| *Chrysolepsis sempervirens* | a broad-leafed, evergreen shrub commonly called a chinquapin. |
| cambic horizon | a subsoil horizon of alteration by pedogenic processes rather than from significant accumulation by translocation within the soils. |
| cation exchange | solution cations such as $Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$, $Al^{3+}$, and $H^{+}$ are attracted to negatively charged soil clay mineral surfaced and organic matter soils; these exchangeable cations are not strictly in solution, but can easily be returned to solution by trading or exchanging for another cation. |
| colluvium | a general term applied to loose and incoherent deposits on land slopes brought there chiefly by gravity and often lubricated by moisture. In this report, pertains mainly to earthy material, not rock fragments alone (see talus). |
| complex | an association of more than one free ion and/or compounds in solution. |
| Cryaquept | a soil formed in a cold climate that is saturated with water much of the time. |
| cryic soil temperature | regime - mean annual soil temperatures range from $0^{\circ}$ to $8^{\circ}C$, and if well drained, have cool mean summer soil temperatures; if poorly drained, mean summer soil temperatures are cold. |
| Cryorthent | a soil formed in a cold climate with poorly developed horizonation. |

| | |
|---|---|
| Cryorthod | a weathered soil formed in a cold climate with well developed horizonation. This classification is tentative (Huntington and Akeson, 1987). |
| Cryumbrept | a soil formed in a cold climate with a thick, dark surface horizon but low nutrient content. |
| decomposition | the microbial breakdown of organic matter in the soil to simpler compounds. |
| denitrification | the biochemical reduction of $NO_3$ to gaseous forms which are unavailable to plants and may be lost to the atmosphere. |
| diffusion | movement of a chemical species as a response to a concentration gradient. |
| electrolytic conductivity | a measure of how easily a solution conducts electricity; this is directly related to the total salt concentration. |
| exchangeable base cation | base cations associated with soil clays and organic matter. |
| free ion | a dissociated ion either positively or negatively charged. |
| free water | water which is held at potentials between 0 and -30kPa. Water which drains quickly from soil by gravitational forces. |
| immobilization | the incorporation of inorganic substances ($NH_4^+$, $NO_3^-$, $SO_4^{2-}$, $PO_4^{3-}$, etc.) into microbial biomass and other organic compounds which are unavailable to plants. |

# GLOSSARY (continued)

| | |
|---|---|
| *in situ* | experiment in the field rather than in the laboratory; in place. |
| inlet meadow | area of the watershed near the lake inlet. |
| ionic strength | a measure of the total salt concentration of a solution; one-half the sum of the products of all solution ions and the square of their respective charges. |
| joint | a surface of fracture or parting in a rock without displacement. |
| kinetics | a description of how fast a chemical or biological process occurs. |
| leaching | the loss of constituents in soil solution by movement of water through the soil. |
| lithic contact | a boundary between soil and underlying continuous, hard rock. |
| litter | plant debris including leaves, stems, twigs, branched, etc. which have fallen to the ground. |
| mafic | said of an igneous rock composed chiefly of dark ferromagnesian minerals; e.g. gabbro, diorite. |
| mass transport | movement of a substance from one point to another without any chemical transformations. |
| mass water content | amount of water in soil measured as the mass of water per unit mass of soil. |

| | |
|---|---|
| matric potential | portion of water potential that can be attributed to the attraction of the soil or plant matrix for water. |
| mineral | a homogeneous solid, usually crystalline. |
| mineralization | the microbially mediated release of inorganic substances from organic matter (the reverse of immobilization). |
| miscellaneous area | a mapping unit for areas of land that have little or no natural soil; e.g. rock outcrop. |
| organic carbon | all carbon that is bound up in organic matter (excludes $CO_2$ and $HCO_3^-$). |
| pedon | the smallest practical volume that can be called "a soil", yet large enough to permit study of the nature of horizons present. Its vertical dimension is the depth of a complete profile; its area, roughly hexagonal in shape, ranges from 1 to 10 m2, depending on the variability and continuity of its horizons. |
| pH | a measure of the acidity of a solution in terms of free $H^+$. |
| _Pinus monticola_ | a needle-bearing evergreen tree; western white pine. |
| pimo stand | area of ELW approximately 300m NE of Emerald Lake which has a stand of _Pinus monticola_. |
| pore space | the volume of voids in soil occupied by air and water. |

| | |
|---|---|
| porosity | the volume of soil pores expressed as a percentage of soil volume. |
| reserve sulfur | organic S plus reduced inorganic S. |
| residuum | unconsolidated and partly weather mineral material accumulated by disintegration of consolidated rock in place. |
| respiration | the consumption of organic matter and oxygen releasing carbon dioxide, water and energy for biological activity |
| Ridge | area in ELW from 400m NE to 600m E of Emerald Lake at about 3100m elevation. |
| *Salix orestera* | a deciduous shrub; willow. |
| saturated hydraulic conductivity | - rate of water flow through a saturated soil column. |
| saturation percentage | - maximum amount of water a soil will hold. generally considered to be equal to the percent pore space when expressed on a volume basis. |
| similar soils | alike or much alike associated, but taxonomically distinct soils; can be expected to behave similarly, or there are no major differences in interpretation for various uses. |
| soil | bodies of unconsolidated mineral or organic matter on the surface of the earth, capable of serving as a medium for plant growth, whose unique properties are the product of processes controlled by factors of parent material, climate, organisms, and topography acting over time. |

# GLOSSARY (continued)

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| soil association | a soil map unit in which two or more defined soil taxonomic units occurring together in a characteristic pattern are combined because the purpose of the map makes separate mapping impractical. |
| soil complex | a soil map unit consisting of two or more dissimilar soils or miscellaneous areas which cannot be mapped separately at the scale used. The components are identified in the unit name. Lesser areas of other kinds of soil or miscellaneous areas may occur as inclusions. |
| soil depth classes | very shallow: <25 cm; shallow: 25 to 50 cm; moderately deep: 50 to 100 cm; deep: 100 to 150 cm; very deep: >150cm. soil map unit a cartographic representation of the perception of a phase of a soil taxonomic unit on the landscape. May represent one or more soil taxonomic units plus inclusions of other similar or dissimilar soils or miscellaneous areas. |
| soil phase | subdivision of a soil taxonomic unit on the basis of non-taxonomic criteria or properties that are important to the use or behavior of a soil. |
| soil solution | soil water plus all dissolved constituents. |
| substrate | food for microbial or plant growth. |
| throughfall | precipitation which reaches the soil surface by dripping off plant surfaces. |

total Kjeldahl nitrogen - organic N plus inorganic $NH_4^+$.

unsaturated hydraulic conductivity - rate of water flow through a non-saturated soil column.

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|---|---|
| volume water content | amount of water in soil measured as a volume of water per unit volume of soil. |
| weathering | the chemical (and physical) breakdown of minerals to form more stable minerals or soluble substances. |