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Study of evaporation and recharge in desert soil using environmental tracers, New Mexico, USA

A. R. Shurbaji · A. R. Campbell

Abstract The purpose of this study is to investigate the rates and mechanisms of recharge and evaporation in soils of a desert environment using two environmental tracers (chloride and oxygen-18). The profiles of chloride concentration and oxygen-18 enrichment in soil-water, together with the depth distribution of water content in soil, reveal information about long-term recharge and instantaneous evaporation processes without needing to know the physical properties of the soil. Three holes were hand-dugured, in different desert settings in southeastern New Mexico. The chloride concentration profiles were used, with the chloride mass balance method, to estimate long-term recharge rates in these three holes as 0.5, 0.8, and 2.4 mm yr⁻¹. Analysis using a bimodal flow and transport model shows that possibly 85% of the recharge occurs via movement of water through preferred pathways in the root zone. Preferential flow was evident in all three sampling sites. Clay layers have a noticeable effect on the development of water content distribution and thus on oxygen-18 enrichment and chloride concentration profiles. The spatial variation in clay layering partly explains the variation in recharge rate estimates.

Key words Recharge · Evaporation · Oxygen-18 · Chloride · Environmental tracers

Introduction

Recent research involving deuterium (²H) and oxygen-18 (¹⁸O) enrichment in soil-water has used the isotope depth profiles in soil-water to study evaporation from arid-zone

soils (e.g., Barnes and Allison 1983, 1988; Shurbaji and Phillips 1995; Shurbaji and others 1995). Chloride, Cl⁻, also an environmental tracer, has proved useful for evaluating long-term drainage of water in arid zones (Allison and Hughes 1978; Sharma and Hughes 1985; Scanlon 1991). Drainage water below the root zone eventually constitutes recharge to groundwater aquifers. Reliable estimates of recharge are important for the hydrologic characterization and the performance assessment of arid sites considered for nuclear waste storage. In addition, wise management of groundwater aquifers in arid zones relies on recharge, as a component of the water budget. Considering a long-term downward movement of chloride in soil and average atmospheric input of chloride with precipitation, the chloride mass balance equation is given by:

$$RC = PCT_0 \quad (1)$$

where *R* is the average recharge rate (millimeters per year), *C* is the average chloride concentration of soil-water draining below the root zone (milligrams per liter), *P* is the average precipitation rate (mm/yr), and *C*₀ is the average chloride concentration (mg/l) in rainwater. In investigating evaporation using ¹⁸O, the focus was on second-stage evaporation, in which case the soil surface would be dry. Under this condition, the depth of the evaporation front is useful in determining the instantaneous evaporation rate from drying soils. ¹⁸O enrichment is caused by evaporation, and the depth of the evaporation front corresponds to the peak in the ¹⁸O profile (Barnes and Allison 1983). Assuming that relative humidity is changing linearly from 1.0 at the evaporation front to the prevailing value at the soil surface, Fick's Law of diffusion can be utilized to calculate the instantaneous evaporation rate according to:

$$E = \frac{D_v^*}{\rho} \frac{\partial \rho_v}{\partial z} \quad (2)$$

where *E* is the upward volumetric vapor flux (centimeters per second), *D*_v^{*} is the effective diffusion coefficient of water vapor in soil (centimeters squared per second), *ρ* is the liquid water density (grams per cubic centimeter), *ρ*_v is the water vapor density (g cm⁻³) which depends on temperature, ∂/∂z is the gradient operator for one-dimensional flow in the *z* direction, and *z* is the depth below the surface and is positive downward. For second-stage

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A. R. M. Shurbaji (✉)
Hydrologic Science, Vellmeyer Hall, University of California,
Davis, CA 95616-8628, USA

A. R. Campbell
Department of Earth and Environmental Sciences, New Mexico
Tech., Socorro, NM 87801, USA

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evaporation, evaporation rates are usually low and are limited by the availability of water in the soil and the characteristic relations of the soil such as the retention relation and the unsaturated hydraulic conductivity.

Materials and methods

Study area

The study area (32.5°N and 104.5°E) is in southeastern New Mexico near Carlsbad. From precipitation records, at the nearby Carlsbad airport over the years 1970 to 1987, the average annual precipitation was determined as 380 mm. The average chloride input for this area was not available, but it was estimated as 0.32 mg l⁻¹ based on interpolation with the surrounding areas. Precipitation chloride input for Las Cruces, New Mexico (32.5°N and 105.0°E) is 0.35 mg l⁻¹, that for Socorro, New Mexico (34.0°N and 106.8°E) is 0.38 mg l⁻¹ (Phillips and others 1988), and that at Hueco Bolson, Texas (31.0°N and 105.0°E) is 0.29 mg l⁻¹ (Scanlon 1991). Vegetation in this area consists mostly of mesquite (*Prosopis velutina* and *Prosopis glandulosa*) with roots extending down to depths between 1 and 2 m.

The atmospheric relative humidity and temperature data utilized were from a field study in Socorro (34.0°N and 106.8°E). During the summer, relative humidity ranges between 10% during the day and 90% during the night with an average value of 50%. The air temperature at the soil surface ranges between 10 °C and 42 °C with an average of 26 °C (Shurbaji and others 1995).

Sampling and analysis

Locations of the three augured holes were selected in different geomorphic settings of the study area: a sinkhole, a site with deep unconsolidated sediments, and a trough between sand dunes. These holes will be referred to as holes 1, 2, and 3, respectively. Figure 1 shows the sampling locations. Sampling was done over two years, and no rainfall data were available.

The soil profile consists predominantly of pure medium sand with, in some holes, one or more clay layers. Soil samples were taken at 0.05-m depth intervals and sealed promptly in air-tight jars. Water from the soil was extracted by vacuum distillation following the procedure described by Shurbaji and others (1995). Water content was determined from weight loss of soil during distillation. The ¹⁸O composition of soil-water was measured using the CO₂-H₂O equilibration method following the procedure outlined by Roether (1970) and Socki and others (1992) modified for small (0.5 ml) water samples. Isotopic measurements were performed on a Finnegan-MAT Delta E mass spectrometer using O₂-tech gas standards. The dry soil remaining after moisture extraction was sent to the New Mexico Waste Management Education and Research Consortium Soil Testing laboratory at New Mexico State University for chloride analysis. The analysis started by mixing the dry soil with deionized water at

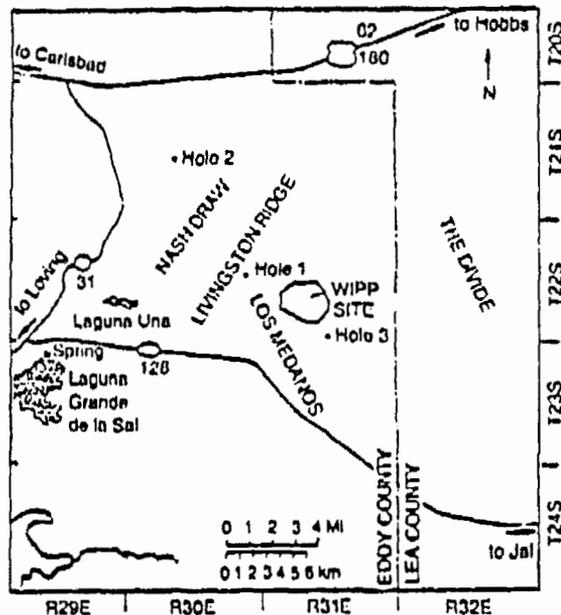


Fig. 1
Sampling locations

a 1:5 ratio. The mixture was shaken for 30 min and then gravity filtered, and the extract was analyzed for chloride concentration. The chloride concentration was determined colorimetrically using mercuric thiocyanate and ferric nitrate solution (O'Brien 1962). The concentration of chloride is reported as the concentration in the soil-water solution.

Results and discussion

Chloride concentration and ¹⁸O enrichment of soil-water and the corresponding volumetric water content of the soil as functions of depth for the three holes are presented in Figs. 2-4, respectively. A continuous solid line was used in the chloride concentration profile to represent a 3-point moving average that should minimize the measurement error and show a clear trend in the concentrations. The following is a discussion of the profiles from each hole in relation to water movement processes (recharge and evaporation).

Hole 1 (Fig. 2)

Personal observations indicated that large rainfall events leave standing water at this sink hole site. At 0.35 m depth, a thin clay layer is present, which explains the rise in water content at this depth. Because of its retention characteristics, the clay layer partially delays the loss of water from soil to the atmosphere through evaporation. The water content throughout the soil profile is as high

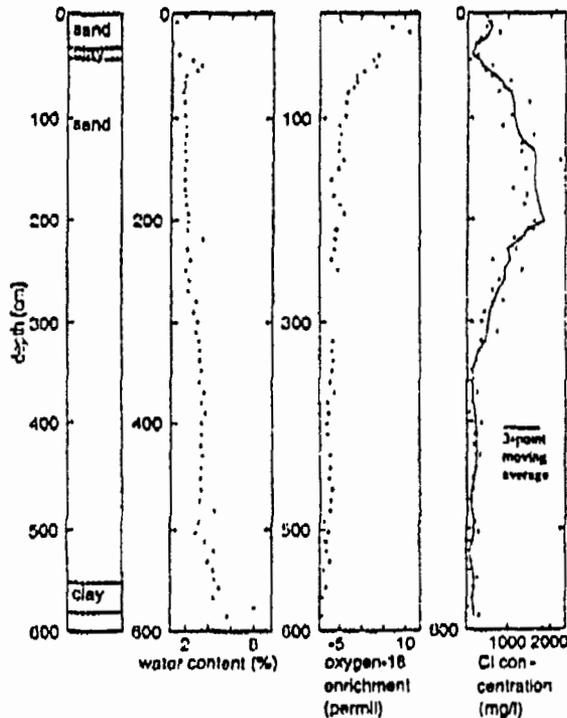


Fig. 2
Depth distributions of water content, oxygen-18 enrichment, and chloride concentration in hole 1

as 3%. Higher water content in this soil profile below a 5.0-m depth may be attributed to the presence of another clay layer between depths 5.5 and 5.8 m. Clay has a lower hydraulic conductivity than sand, and this significantly delays downward drainage of water and results in more water being available in the soil profile above the clay layer.

The chloride concentration distribution shows some variability, but a bimodal distribution can be identified. Concentrations as high as 1836 mg l^{-1} were observed above 2.0 m depth, which corresponds to the bottom of the root zone, while below this depth the concentrations were lower than 250 mg l^{-1} . The gradual increase in chloride concentration with depth in the root zone is expected and can be explained as follows: when water containing chloride percolates into a soil subject to water loss by transpiration, it is expected that (at steady state and under conditions of piston flow) chloride concentrations in soil-water will increase monotonically through the root zone (Gardner 1967). The observed increase in chloride concentration can be explained mathematically using Eq. 1, in which the product RC is constant. C will increase with depth when infiltration rate R decreases with depth as a result of root extraction of soil-water. The chloride peak then corresponds to the maximum depth of extraction of water by roots.

The chloride profile also revealed evidence for preferential flow. For piston flow, which is assumed in Eq. 1, the chloride concentration should be uniform with depth beneath the bottom of the root zone. Because the chloride concentration below the root zone is lower than the maximum concentration at the bottom of the root zone, the chloride profile observed here suggests that long-term water infiltration at this location cannot be explained by piston flow through the root zone. The most likely explanation is that infrequent heavy rainfall events percolate through the root zone via preferred pathways to the bottom of the root zone without effectively leaching the soil profile. It is possible that the root channels form part of these fast water-percolating pathways.

At depths between 3.5 and 4.5 m, the profile has an almost uniform water content ($\approx 3\%$), implying gravity drainage and also a uniform chloride concentration ($C = 240.0 \text{ mg l}^{-1}$). This condition suggests that quasi-steady-state piston flow can be justifiably assumed and that a drainage rate can be calculated using the chloride mass balance equation (Eq. 1). The drainage rate was estimated as 0.50 mm yr^{-1} using $C = 240.0 \text{ mg l}^{-1}$, $P = 380 \text{ mm yr}^{-1}$, and $C_p = 0.32 \text{ mg l}^{-1}$. This value of drainage rate has two components in the root zone, water flux through the soil matrix (R_m), and water flux through preferred pathways (R_p). Following Sharma and Hughes (1985) in their bimodal flow model, conservation of mass of water and chloride in this flow system can be represented, respectively, by the two equations

$$R = R_p + R_m \quad (3)$$

$$RC = R_m C_m + R_p C_p \quad (4)$$

Assuming that the preferred water has a chloride content similar to precipitation ($C_p = 0.32 \text{ mg l}^{-1}$) and using the concentration at the bottom of the root zone for C_m (1836 mg l^{-1}), R (0.5 mm yr^{-1}), and C (240 mg l^{-1}), the value of R_p calculated to be 0.43 mm yr^{-1} constituting 86% of the drainage rate below the root zone. The peak of oxygen-18 enrichment (which identifies the evaporation front) corresponds to a depth of 0.27 m. Using this depth and the prevailing temperature and relative humidity conditions at the soil surface, evaporation rates ranged between 0.004 and 0.037 mm d^{-1} , and an average value of 0.020 mm d^{-1} can be calculated from Eq. 2.

Hole 2 (Fig. 3)

Previous well logs at this site showed unconsolidated sands to be about 20 m thick, providing the deepest unconsolidated sediments in the sampling study area. However, for the purpose of this study, this hole was augured to 4.5 m depth.

The water content in the soil profile was relatively high and a local rise in the water content at the same depth as in hole 1 (0.35 m) is due to a clay layer. The rise in volumetric water content at this clay layer to 11% fingerprints a preceding rainfall event (with isotopically light water) that did not penetrate deep in the soil. Sufficient time elapsed (at least ten days) before sampling, so that no lo-

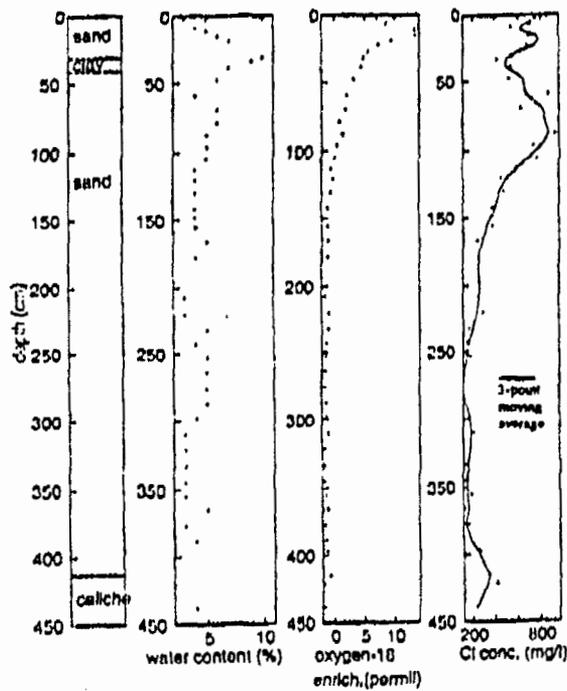


Fig. 3
Depth distributions of water content, oxygen-18 enrichment, and chloride concentration in hole 2

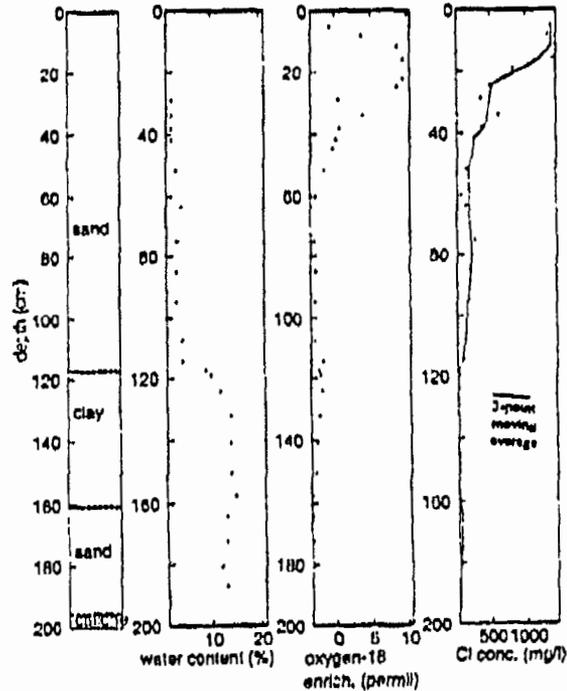


Fig. 4
Depth distributions of water content, oxygen-18 enrichment, and chloride concentration

cal ^{18}O minimum was identified. Below this depth, the soil profile was still draining. Local rises in the water content distribution are attributed to thin clay layers embedded in the soil profile. A caliche layer is present at depth 4.12 m, which has a similar hydraulic effect as the clay layer at the bottom of hole 1, delaying the drainage of water.

At depths between 3.0 and 3.5 m, the profile has almost uniform water content ($\approx 2\%$), implying gravity drainage, and also uniform chloride concentration ($C \approx 150 \text{ mg l}^{-1}$). Using this value for chloride concentration, the drainage rate at depth 3.5 m is estimated to be 0.81 mm yr^{-1} . A bimodal distribution is identified for chloride concentration, which is further evidence that preferential flow is an important mechanism for downward water movement through the root zone.

The depth of the evaporation front (as indicated from the peak in the ^{18}O profile) is 20 cm, which gives an average evaporation rate of 0.027 mm d^{-1} .

Hole 3 (Fig. 4)

The location of this hole, in a trough between dunes, has a potential for topography-induced infiltration. During auguring, a clay layer was encountered between depths 1.17 and 1.55 m. At 1.99 m, a caliche layer was encountered. The presence of the clay layer explains the higher water content in these depths than the overlying sand.

Having a low hydraulic conductivity, the bottom caliche layer delays the downward water movement, causing a further rise in the water content.

The shape of the ^{18}O peak is broad, unlike the sharp peaks in holes 1 and 2. Similar broad deuterium peaks were measured by Allison and others (1983). Shurbaji and Phillips (1995) produced a broad deuterium peak by considering a zone of combined vapor and liquid fluxes surrounding the evaporation front in their numerical model. The evaporation front is at 20 cm depth, giving an average evaporation rate of 0.027 mm d^{-1} .

During auguring, no roots were encountered below 0.60 m, which explains why the chloride peak is closer to the surface than for holes 1 and 2. A bimodal distribution is identified for chloride concentration in this site, thus showing that preferential flow is an important mechanism for downward water movement through the root zone in deserts.

Based on average chloride concentration between depths 1.20 and 2.00 m, $C \approx 50 \text{ mg l}^{-1}$, the downward drainage rate is estimated to be 2.4 mm yr^{-1} , which is higher than values determined for the other two settings. This relatively high value is attributed to less vegetation at this site, to the absence of a surficial clay layer (which would retain rainwater and expose it to more evaporation), and to topography-induced infiltration during heavy rainfall events.

Conclusions

Environmental tracers such as chloride and oxygen-18 in soil water reveal valuable information about recharge and evaporation in arid environments. Oxygen-18 profiles give insight into the evaporation process in the topsoil and provide a basis for evaporation estimates in soils undergoing second-stage evaporation. On the other hand, chloride profiles reveal information about mechanisms of water drainage in the unsaturated zone and provide a basis for estimating recharge rates.

The chloride mass balance method was used to estimate the local recharge rate at three different settings in south-eastern New Mexico. The bimodal distribution of chloride concentration in all sampling sites provided evidence for preferential flow through the root zone. Analysis using a bimodal flow and chloride transport model for one site showed that preferential flow represents 85% of the long-term recharge rate. The spatial variability in chloride concentrations below the root zone (or recharge rates) can be attributed partly to the variation in the distribution of clay layers embedded within the sands. In soils undergoing evaporation, layers with higher clay content will contain more water and thus will take a longer time to be enriched with ^{18}O isotopes. Layering and preferential flow should be accounted for when modeling the development of chloride and oxygen-18 profiles in soils. Future research must pay attention to these factors for better understanding of water movement in the unsaturated zone.

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