

Reprinted from

JOURNAL OF HYDROLOGY

Journal of Hydrology 196 (1997) 251–270

Tracer-based studies of soil water movement in semi-arid forests of New Mexico

Brent D. Newman^{a,b,*}, Andrew R. Campbell^a, Bradford P. Wilcox^a

^a*Environmental Science Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

^b*Earth and Environmental Science Department, New Mexico Institute of Mining and Technology, Socorro,
NM 87801, USA*

Received 22 July 1996; accepted 13 September 1996



ELSEVIER

A large, stylized handwritten signature in black ink, located in the bottom right corner of the page. The signature appears to be 'C. D. Newman'.

Editors

R. Krzysztofowicz, Charlottesville, VA, USA
G. Teutsch, Tübingen, Germany
G. Vachaud, Grenoble, France
P. van Cappellen, Atlanta, GA, USA

Associate Editors

A. Bardossy, Stuttgart, Germany
J.A. Barker, London, UK
A. Becker, Berlin, Germany
R. Berndtsson, Lund, Sweden
G. Blösch, Vienna, Austria
B. Bobee, Quebec, Que., Canada
I.R. Calder, Ewelme, UK
R.T. Clarke, Porto Alegre, Brazil
M. Franchini, Bologna, Italy
M. French, Louisville, KY, USA
E.O. Frind, Waterloo, Ont., Canada
J.H.C. Gash, Wallingford, UK
K.P. Georgakakos, San Diego, CA, USA
J.J. Gómez-Hernández, Valencia, Spain
S. Guo, Wuhan, People's Republic of China
Tissa H. Illangasekare, Boulder, CO, USA
V. Kaleris, Patras, Greece
W.E. Kelly, Washington, DC, USA
W.F. Krajewski, Iowa City, IA, USA
L.S. Kuchment, Moscow, Russia
R. Liedl, Tübingen, Germany

D.R. Maidment, Austin, TX, USA
J.J. McDonnell, Syracuse, NY, USA
A.I. McKerchar, Christchurch, New Zealand
A. Mermoud, Lausanne, Switzerland
U. Moiseello, Pavia, Italy
E.M. Murphy, Richland, WA, USA
H.P. Nachtnebel, Vienna, Austria
C. Neal, Wallingford, UK
A.J. Peck, Subiaco, W.A., Australia
H.N. Phien, Bangkok, Thailand
H. Savenije, Delft, Netherlands
G.A. Schultz, Bochum, Germany
H.M. Seip, Oslo, Norway
W.J. Shuttleworth, Tucson, AZ, USA
M. Sivapalan, Nedlands, W.A., Australia
M. Sophocleous, Lawrence, KS, USA
C.I. Steefel, Tampa, FL, USA
D. Stephenson, Johannesburg, South Africa
Y. Tagutschi, Tsukuba, Japan
J.H. Tellam, Birmingham, UK
A. van der Beken, Brussels, Belgium

Scope of the journal

The *Journal of Hydrology* publishes original research papers and comprehensive reviews in all the subfields of the hydrological sciences. These comprise, but are not limited to the physical, chemical, biogeochemical, stochastic and systems aspects of surface and groundwater hydrology, hydrometeorology and hydrogeology. Relevant topics in related disciplines such as climatology, water resource systems, hydraulics, agrohydrology, geomorphology, soil science, instrumentation and remote sensing, civil and environmental engineering are also included. Papers have empirical, theoretical and applied orientations.

Publication information

Journal of Hydrology (ISSN 0022-1694). For 1997 volumes 187–199 are scheduled for publication. Subscription prices are available upon request from the publishers. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL (Surface Air Lifted) mail is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan*, Malaysia, Mexico, New Zealand, Pakistan, China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within 6 months of our publication (mailing) date.

For orders, claims, product enquiries (no manuscript enquiries) please contact the Customer Support Department at the Regional Sales Office nearest to you: **New York**, Elsevier Science, P.O. Box 945, New York, NY 10159-0945, USA. Tel: (+1) 212-633-3730, [Toll Free number for North American customers: 1-888-4ES-INFO (437-4636)], Fax: (+1) 212-633-3680, E-mail: usinfo-f@elsevier.com – **Amsterdam**, Elsevier Science, P.O. Box 211, 1000 AE Amsterdam, The Netherlands. Tel: (+31) 20-485-3757, Fax: (+31) 20-485-3432, E-mail: nlinfo-f@elsevier.nl – **Tokyo**, Elsevier Science, 9-15, Higashi-Azabu, Minato-ku, Tokyo 106, Japan. Tel: (+81) 3-5561-5033, Fax: (+81) 3-5561-5047, E-mail: kyf04035@niftyserve.or.jp – **Singapore**, Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192. Tel: (+65) 434-3727, Fax: (+65) 337-2230, E-mail: asiainfo@elsevier.com.sg

Advertising Information

Advertising orders and enquiries may be sent to: **International**: Elsevier Science, Advertising Department, The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK; Tel: (0) 1865 843565; Fax: (0) 1865 843952. **USA and Canada**: Weston Media Associates, Dan Lipner, P.O. Box 1110, Greens Farms, CT 06436-1110, USA; Tel: (203) 261 2500; Fax: (203) 261 0101. **Japan**: Elsevier Science Japan, Advertising Department, 1-9-15 Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan; Tel: (3) 5561 5033; Fax: (3) 5561 5047.

Copyright © 1997 Elsevier Science B.V. All rights reserved.

0022-1694/97/\$17.00

This journal and the individual contributions contained in it are protected by the copyright of Elsevier Science B.V., and the following terms and conditions apply to their use:

Photocopying

Single photocopies of single articles may be made for personal use as allowed by national copyright laws. Permission of the publisher and payment of a fee is required for all other photocopying, including multiple or systematic copying, copying for advertising or promotional purposes, resale, and all forms of document delivery. Special rates are available for educational institutions that wish to make photocopies for non-profit educational classroom use.

In the USA, users may clear permissions and make payment through the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, USA. In the UK, users may clear permissions and make payment through the Copyright Licensing Agency Rapid Clearance Service (CLARCS), 90 Tottenham Court Road, London W1P 0LP, UK. In other countries where a local copyright clearance centre exists, please contact it for information on required permissions and payments.

Derivative Works

Subscribers may reproduce tables of contents or prepare lists of articles including abstracts for internal circulation within their institutions. Permission of the publisher is required for resale or distribution outside the institution.

Permission of the publisher is required for all other derivative works, including compilations and translations.

Electronic Storage

Permission of the publisher is required to store electronically any material contained in this journal, including any article or part of an article. Contact the publisher at the address indicated.

Except as outlined above, no part of this publication may be reproduced, stored in a retrieval system or transmitted in any form or by any means, electronic, mechanical, photocopying, recording or otherwise, without prior written permission of the publisher.

Disclaimers

No responsibility is assumed by the publisher for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions or ideas contained in the material herein.

Although all advertising material is expected to conform to ethical (medical) standards, inclusion in this publication does not constitute a guarantee or endorsement of the quality or value of such product or of the claims made of it by its manufacturer.

Ⓢ The paper used in this publication meets the requirements of ANSI/NISO Z39.48-1992 (Permanence of Paper).

Printed in The Netherlands

Tracer-based studies of soil water movement in semi-arid forests of New Mexico

Brent D. Newman^{a,b,*}, Andrew R. Campbell^a, Bradford P. Wilcox^a

^a*Environmental Science Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

^b*Earth and Environmental Science Department, New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA*

Received 22 July 1996; accepted 13 September 1996

Abstract

The related issues of water movement and contaminant transport in arid and semi-arid environments have generated considerable interest and concern in the last few decades. Essential to understanding these issues is knowledge of how water moves through the soils that form the uppermost part of the vadose zone. The use of tracers, both natural and artificially introduced, is proving to be an effective method for gaining such knowledge in dry regions, where investigation by other means is difficult. In this study, natural stable-isotope and chloride tracers were used to investigate water movement in the soils of a piñon–juniper woodland and of a ponderosa pine forest on the Pajarito Plateau in northern New Mexico. The objectives were to (1) estimate and compare near-surface flux rates and evaluate the importance of evaporation in the two communities, and (2) determine to what extent differences in flux rates and evaporation are due to differences in plant cover and/or soil hydraulic properties. The results of this study will aid in evaluating the potential for contaminant mobility in semi-arid systems such as the Pajarito Plateau and, in addition, will increase understanding of nutrient distributions and plant water use in semi-arid environments. The stable-isotope data indicate a similarity between the piñon–juniper and ponderosa communities with respect to evaporation: in both, it is restricted mainly to the upper 10 cm of soil. Chloride profiles from the two communities, on the other hand, show a distinct difference with respect to downward fluxes: in the ponderosa pine forest, these fluxes ($\approx 0.02 \text{ cm year}^{-1}$) are an order of magnitude lower than those in the piñon–juniper woodland ($\approx 0.2 \text{ cm year}^{-1}$), even though total precipitation is about 4 cm year^{-1} higher in the ponderosa pine forest. This difference, however, appears to be related not to plant cover, but to differences in soil hydraulic properties. The soils of the ponderosa pine forest contain clay-rich B horizons that appear to restrict downward movement of water through the soil matrix, whereas the soils of the piñon–juniper community have B horizons much lower in clay content. The effect of differing soil properties on water movement suggests that contaminant

* Corresponding author.

distributions will vary across the Pajarito Plateau. The data on soil water ages support this hypothesis: they indicate that water (and, thus, contaminants) moves through the soil matrix in less than a decade in some areas, whereas in other areas, water takes hundreds of years to pass through the entire soil profile. © 1997 Elsevier Science B.V.

1. Introduction

Understanding the hydrology of the vadose zone is becoming increasingly important, especially in dry regions of the western United States, as growing cities and communities struggle with problems of environmental contamination, waste storage, and dwindling water supplies (Reith, 1992; Phillips, 1994). However, the generally low moisture content of the soils in these areas has made hydrologic studies somewhat difficult; physically based approaches, such as Darcy's Law and water-balance determinations, give rise to unacceptably large uncertainties (Scanlon, 1991; Phillips, 1994; Allison et al., 1994). To circumvent this difficulty, tracer techniques (using, for example, natural stable isotopes (δD and $\delta^{18}O$) and chloride) have been developed that permit quantitative estimates of soil water movement in dry regions (Phillips, 1994; Allison et al., 1994).

The use of stable isotopes involves measuring the δD and $\delta^{18}O$ of soil water with depth. The isotopic composition of soil water is affected by evaporation, which preferentially moves light isotopes into the vapor phase, leaving the remaining liquid enriched in heavy isotopes. The depth at which δD and $\delta^{18}O$ reach their maximum (heaviest) values coincides with the depth of an evaporation front (Barnes and Allison, 1983; Allison et al., 1983). In other words, the stable-isotope profile can be used to determine the depth of an evaporation front in the soil, which is particularly useful for comparing the effects of evaporation at different sites. In addition, the isotopic composition of the soil water can provide important clues as to the major source of that water (e.g. snowmelt vs summer rain).

The use of chloride tracers (commonly known as the chloride mass balance method) involves measuring chloride concentrations in soil water with depth. These concentrations serve as indicators of downward flux and soil water age (Allison et al., 1983; Stone, 1984). Stated simply, the amount of chloride accumulation in the soil is inversely proportional to the downward flux: high chloride concentrations, which represent many years of meteoric chloride accumulation coupled with evapotranspirative removal of water, indicate a low downward soil water flux; relatively low chloride concentrations indicate a high downward flux, that is, water is able to move through the soil fast enough that evapotranspiration effects are minimized.

In this study, stable-isotope and chloride tracers were used to estimate and compare near-surface water fluxes at three sites in northern New Mexico. Two of these are located within a piñon–juniper (*Pinus edulis* and *Juniperus monosperma*) community and the third within a ponderosa pine (*Pinus ponderosa*) community. The two plant communities are found adjacent to one another throughout the southwestern United States and are important both environmentally and economically; however, no previous studies have

attempted to estimate and compare near-surface water fluxes in these regions. Such information is valuable in two major ways: as input for hydrologic and risk models, it helps us assess the potential for human and ecological exposure to contamination; and it helps us better understand plant water use and nutrient distributions in semi-arid soils.

The study is specifically focused on the hydrology of the soil zone. Multiple cores were taken at each site as a basis for examining the horizontal spatial variability of the flux rates. The main objectives were to (1) estimate and compare flux rates and evaluate the importance of evaporation in the piñon–juniper and ponderosa pine communities, and (2) determine the extent to which flux rates and evaporation are influenced by plant cover and/or by soil hydraulic properties.

2. Description of the study area

The study area is located on the Pajarito Plateau in north central New Mexico, which is characterized by a semi-arid, temperate mountain climate (Fig. 1). Average annual precipitation varies from less than 360 mm year⁻¹, at lower elevations near the Rio Grande, to over 500 mm year⁻¹ near the Jemez mountains. The plateau comprises four major vegetation zones (Fig. 2), which are also governed largely by elevation: juniper grassland

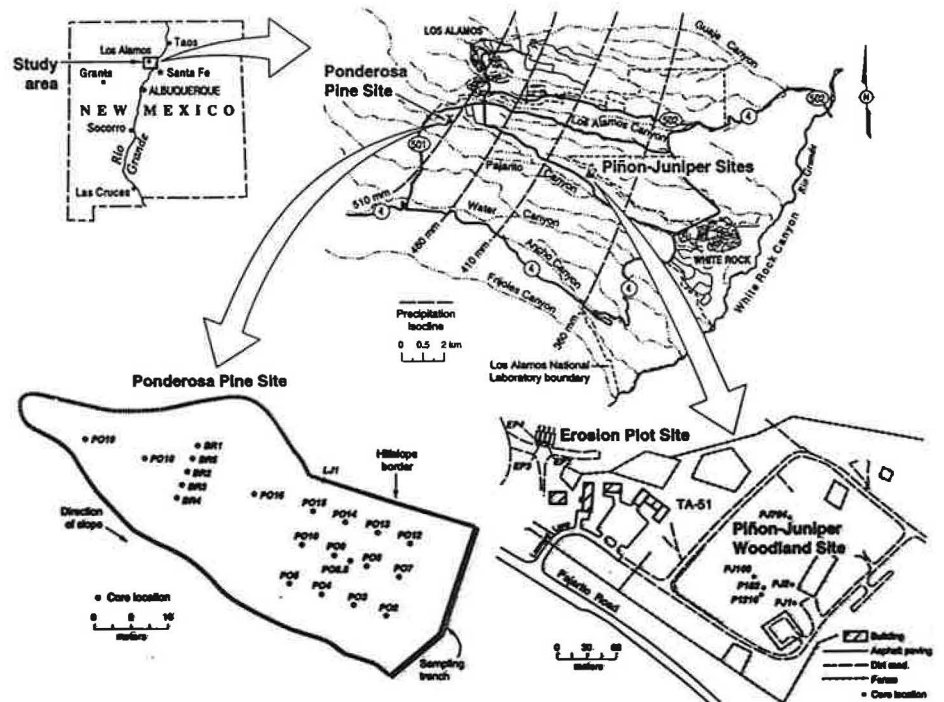


Fig. 1. Location map of the ponderosa pine, piñon–juniper woodland, and erosion plot sites, showing core sampling locations and annual precipitation isoclines (the latter from Bowen, 1990).

(1600–1900 m), piñon–juniper woodland (1900–2100 m), ponderosa pine forest (2100–2300 m), and mixed conifer forest (2300–2900 m) (Allen, 1989). Topographic effects create some variations within these zones, producing the ‘fingering’ appearance in the figure. For example, plants typical of higher elevations also grow in cooler and more moist environments at lower elevations, such as along canyon walls and bottoms. The greater part of the Los Alamos National Laboratory is within the piñon–juniper and the ponderosa pine zones.

The study site within the ponderosa pine zone is an 870-m² hillslope (elevation 2315 m) where investigations of runoff processes are currently under way (Wilcox et al., 1996; Fig. 1). The soil stratigraphy of the site, described by D.W. Davenport (unpublished data, 1994), is illustrated in Fig. 3. The thicknesses and depths of the horizons vary across the hillslope, but the variations in the overall stratigraphy are relatively minor. A dense, clay Bt horizon is present throughout the site.

The two study sites in the piñon–juniper zone (elevation 2140 m) are (1) a relatively

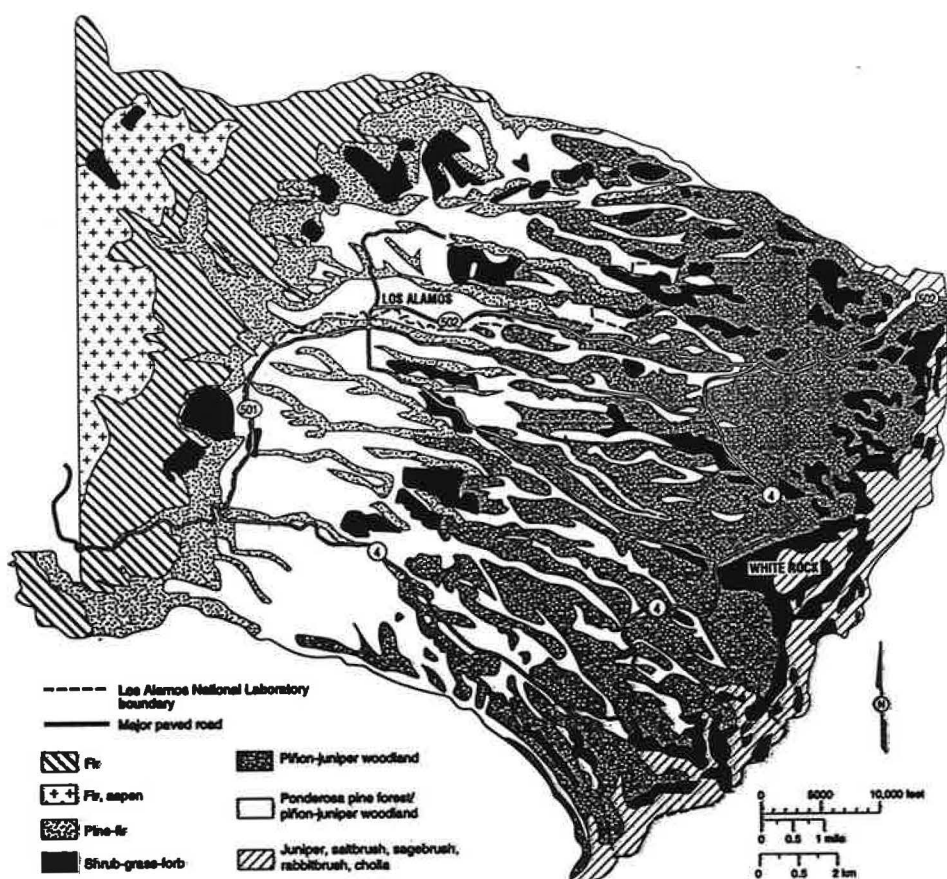


Fig. 2. Major vegetation types on the Pajarito Plateau (from Los Alamos Environmental Research Park, 1976).

undisturbed woodland measuring approximately 16 000 m² and (2) a treeless area (hereafter called the erosion plot site) comprising four small (3.04 × 10.64-m) plots (Wilcox, 1994). All vegetation, cryptogamic crust, litter, and rock cover were removed from Erosion Plots 1 and 4 in 1987 (Wilcox, 1994); currently, these plots have a sparse grass and forb cover. Erosion Plots 2 and 3 have an undisturbed grass cover. The piñon–juniper woodland site and the erosion plot site are approximately 180 m apart.

Cores taken from the two piñon–juniper sites and the ponderosa pine site show the soils in the piñon–juniper zone to be much more variable than those in the ponderosa pine zone (Fig. 3). Soil stratigraphy in the piñon–juniper zone varies greatly over horizontal scales of only a few meters, and this variability can take the form of differences in type and number

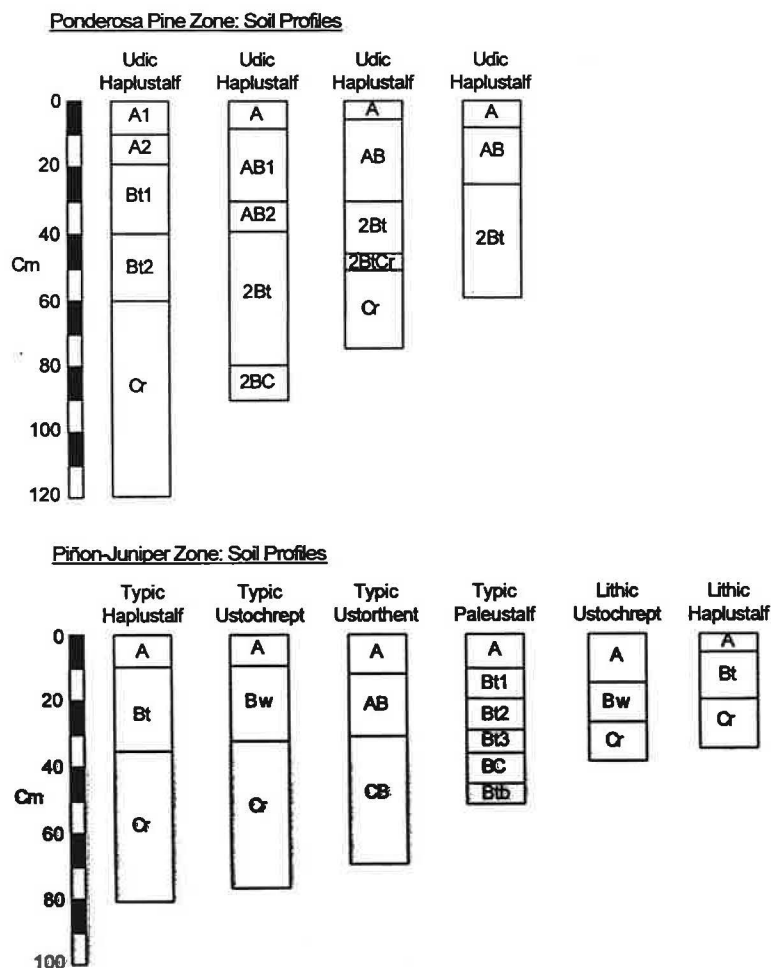


Fig. 3. Examples of soil profiles for the ponderosa pine and piñon–juniper zones (D.W. Davenport, unpublished data, 1994; Davenport et al., 1996).

of soil horizons or of differences in soil texture within the same horizon (Davenport et al., 1996). The Bt horizon usually has a clay loam texture (which indicates a lesser degree of development than the Bt horizon in the ponderosa pine zone) or is absent entirely.

3. Methods and materials

3.1. Core collection

Details of the core sampling and analyses performed are summarized in Table 1. All cores

Table 1
Core sampling and analysis information

Core	Date sampled	Isotope analysis	Chloride analysis	Depth (cm)
<i>Ponderosa pine site</i>				
LJ	1993	Yes	Yes	255
BR1	1994	No	Yes	110
BR2	1994	No	Yes	90
BR3	1994	No	Yes	85
BR4	1994	No	Yes	110
BR5	1995	No	Yes	110
PO2	1994	No	Yes	123
PO3	1994	No	Yes	110
PO4	1994	No	Yes	130
PO5	1994	No	Yes	130
PO7	1994	No	Yes	70
PO8	1994	No	Yes	90
PO8.5	1995	No	Yes	80
PO9	1994	No	Yes	90
PO10	1994	No	Yes	100
PO12	1994	No	Yes	60
PO13	1994	No	Yes	130
PO14	1994	No	Yes	100
PO15	1994	No	Yes	100
PO16	1994	No	Yes	90
PO18	1994	No	Yes	125
PO19	1994	No	Yes	110
<i>Piñon-juniper woodland site</i>				
PJ1	1993	Yes	Yes	130
PJ2	1995	No	Yes	100
PJ160	1995	No	Yes	30
PJ182	1995	No	Yes	60
PJ704	1995	No	Yes	110
PJ1216	1995	No	Yes	70
<i>Erosion plot site</i>				
EP2	1993	No	Yes	140
EP3	1993	No	Yes	130
EP4	1993	Yes	Yes	130

were collected during the summer months (June–August) and included the entire soil profile and a portion of the underlying tuff. The locations from which cores were taken at the three sites are shown in Fig. 1. At the ponderosa pine site, 22 cores were taken: one in 1993, 19 in 1994, and two in 1995. At the piñon–juniper woodland site, six cores were taken: one in 1993 and five in 1995. At the erosion plot site, three cores were taken, all in 1993.

For the 1993 sampling, cores were collected by means of a truck-mounted drill rig. Immediately upon removal from the core barrel, each core was cut into 10-cm sections; each section was stored in a clean, glass mason jar with a vacuum-grease-sealed lid. Both stable-isotope and chloride profiles were obtained for all of the cores except cores EP2 and EP3, from the erosion plot site, for which only chloride profiles were obtained.

For the 1994 and 1995 sampling, cores were collected by hand auger, and each 10-cm section was stored in a zip-lock bag. All of these cores were analyzed for chloride only. (Throughout the core sampling process, personnel wore latex gloves to avoid contaminating samples by skin contact.)

3.2. Stable isotopes

The stable-isotope analyses were carried out at the New Mexico Tech Stable Isotope Laboratory. Soil water was extracted by high-temperature vacuum distillation, following Shurbaji et al. (1995), and $\delta^{18}\text{O}$ and δD measurements were made on a Finnegan-Mat, Delta-E stable-isotope-ratio mass spectrometer using OZ-Tech gas standards. The hydrogen and oxygen isotopes are reported in delta (δ) notation as per mil (‰) differences relative to the V-SMOW international standard:

$$\delta\text{D or } \delta^{18}\text{O} = \left[\frac{R_{\text{sample}} - R_{\text{SMOW}}}{R_{\text{SMOW}}} \right] \times 1000 \quad (1)$$

where R is the D/H or $^{18}\text{O}/^{16}\text{O}$ ratio. The value of $\delta^{18}\text{O}$ was determined from extractions made using the carbon dioxide equilibration technique of Socki et al. (1992). For the δD analyses, hydrogen was extracted using the zinc method of Kendall and Coplen (1985), and the analyses were corrected by means of a linear equation ($\delta\text{D}_{\text{actual}} = 1.06 \delta\text{D}_{\text{measured}} + 10.01$, R^2 of 0.99) based on regression analysis of V-SMOW (Vienna-Standard Mean Ocean Water) and GISP (Greenland Ice and Snow Precipitation) standards. The analytical precision for the $\delta^{18}\text{O}$ and δD analyses by mass spectroscopy was better than $\pm 0.2\text{‰}$ and $\pm 6\text{‰}$, respectively. A few of the distillates from the piñon–juniper woodland site gave much poorer δD precisions (up to $\pm 11\text{‰}$); these distillates, from samples from the top 20-cm, organic-rich A and AB horizons, contained an organic-looking material that evidently caused a variable fractionation during zinc extraction.

3.3. Chloride

Chloride concentrations in soil water were determined by leaching splits from the 10-cm core sections. After the samples had been air-dried for 48 h, 100 g of the soil was mixed with 100 ml of deionized water. The mixture was allowed to equilibrate for 48 h, during which it was periodically stirred. After equilibration, the leachate was centrifuged

and filtered through disposable, 0.2- μm Gelman ion-chromatography filters. Samples of the leachate were analyzed by ion chromatography, following Newman (1996). Analytical precision was $\pm 2\%$ or better, and accuracy was $\pm 10\%$ or better. Moisture content was determined gravimetrically or by neutron probe. The chloride concentrations found in the leachate were then used to calculate the original concentrations in the soil water (the bulk density values used for these calculations had been measured previously; see Stephens, 1993).

As stated earlier, the chloride mass balance method permits the estimation of both downward moisture flux (residual flux) and soil water age. According to Phillips (1994), the residual flux, if determined from samples taken below the root zone, is synonymous with recharge. In the case of the Los Alamos soil profiles, all are in the root zone; therefore, following the usage of Phillips, the term 'residual flux' will be used rather than 'recharge'.

Residual fluxes through the soils were calculated using the cumulative chloride–cumulative water method of Stone (1984). This method is based on the following assumptions: flow occurs largely as downward piston flow; dispersive mixing of water and chloride is small; atmospheric chloride deposition has been relatively constant and is the sole source of chloride to the system; and chloride uptake by plants is negligible. In the case of the ponderosa pine site, the first of these assumptions is violated, because lateral flow also occurs. However, a chloride mass balance calculation for the site (Newman, 1996) showed that maximum annual chloride removal by lateral flow is only about 0.2% of the chloride inventory, and therefore probably has only a small effect.

Cumulative chloride–cumulative water plots are used to identify changes in flux with depth in the soil profile. Linear segments on the plots (segments that appear as approximately straight lines) indicate zones of constant flux. The fluxes for these segments were estimated by

$$R = (Cl_p \times P) / Cl_{sw} \quad (2)$$

where R is the residual flux (m year^{-1}); Cl_p is the modern chloride content of precipitation (g m^{-3}); P is the modern average annual precipitation (m year^{-1}); and Cl_{sw} is the average chloride content of the samples represented by the segment (g m^{-3}). Chloride ages at the endpoints of line segments were estimated using the relationship

$$A = Cl_{swi} / (Cl_p \times P) \quad (3)$$

where A is the chloride age in years, and Cl_{swi} is the cumulative chloride content (g m^{-2}) in the unsaturated zone at that point.

For both calculations, the values used for P were 0.51 m year^{-1} for the ponderosa pine zone (Bowen, 1990) and 0.47 m year^{-1} for the piñon–juniper zone (J.W. Nyhan, unpublished data, 1995). For Cl_p , a value of 0.29 g m^{-3} was used for all sites; the ponderosa pine and piñon–juniper sites are close enough (6.6 km) that no significant differences in chloride input are expected. The 0.29 g m^{-3} average was measured at Sante Fe, New Mexico, by Anderholm (1994). This value appears to be reasonable for the Los Alamos area, judging from chloride concentrations in precipitation obtained by Adams et al. (1995). Moreover, values used in other studies in southern New Mexico and west Texas, given in Shurbaji and Campbell (1997), are consistent with the 0.29 g m^{-3} concentration.

4. Results

4.1. Stable-isotope profiles

Vertical $\delta^{18}\text{O}$ and δD profiles for the ponderosa pine site, the piñon–juniper woodland site, and the erosion plot site are shown in Fig. 4. The profiles for all three sites show the same general features, namely, a maximum isotopic value in the first 10 cm and, below the maximum, a slight bulge extending to light values. Unfortunately, the scale of sampling was not fine enough for the exact depth of the isotope maximum to be identified—and, thereby, for evaporative flux to be estimated.

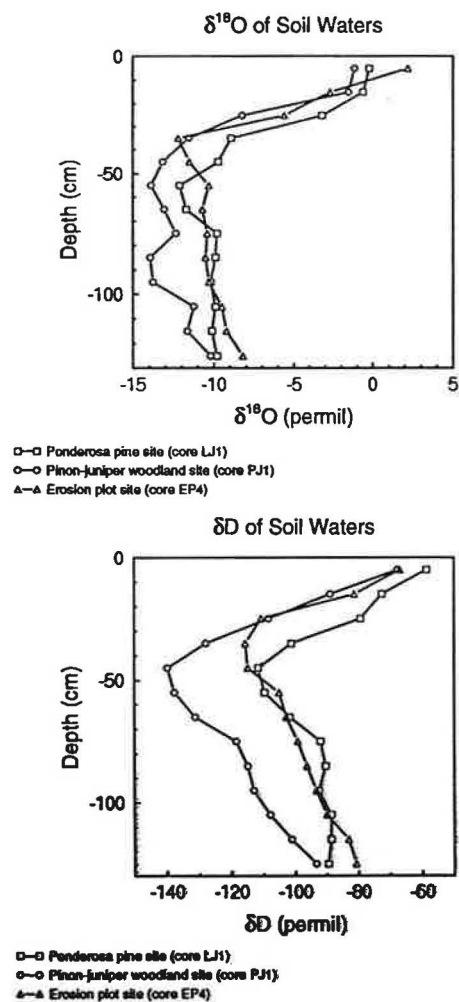


Fig. 4. Vertical $\delta^{18}\text{O}$ and δD profiles for cores from the ponderosa pine, piñon–juniper, and erosion plot sites.

4.2. Chloride profiles

For the ponderosa pine zone, chloride profiles show that chloride concentrations increase nonlinearly with depth to at least 100 cm and that the larger increases generally coincide with the Bt and deeper soil horizons (Fig. 5). The examples selected for this figure represent the range of concentrations in the profiles. Concentrations in the soils above the Bt horizon are consistently below 200 mg l⁻¹, while those in the Bt horizon can exceed 500 mg l⁻¹. Concentrations below the Bt horizon vary, but typically are the highest of all, exceeding 1000 mg l⁻¹ in some cores.

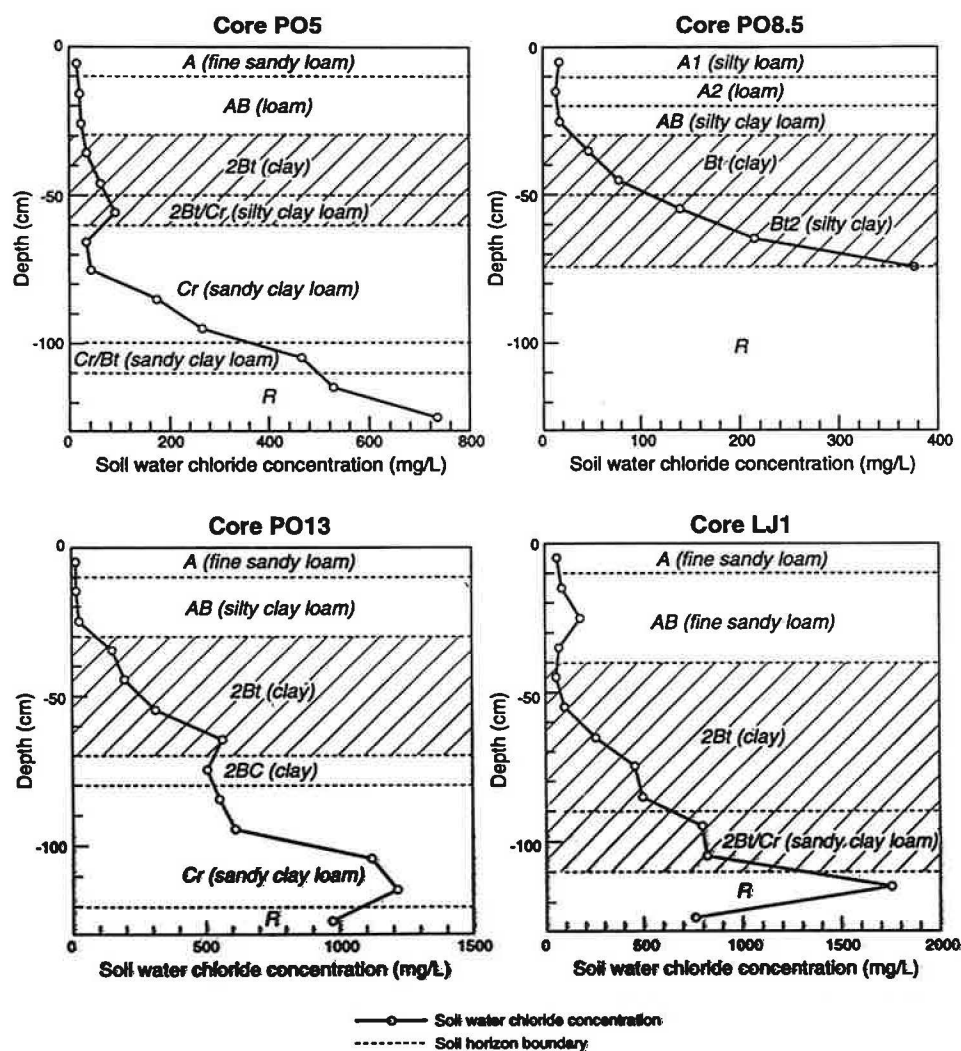


Fig. 5. Ponderosa pine site: examples of vertical chloride profiles.

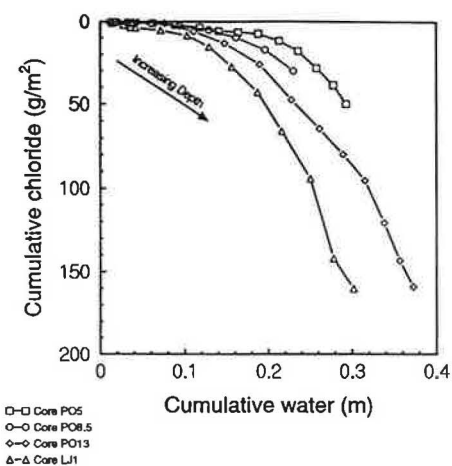


Fig. 6. Ponderosa pine site: examples of cumulative chloride–cumulative water plots.

Table 2

Ponderosa pine zone: residual flux estimates and soil water ages

Core	Date collected	Depth interval (cm)	Residual flux (cm year ⁻¹)	Age at bottom of depth interval (years)	Depth interval (cm)	Residual flux (cm year ⁻¹)	Age at bottom of depth interval (years)
LJ	1993	0–40	0.15	27	85–255	0.01	2147
BR1	1994	0–40	0.9	9	40–110	0.03	796
BR2	1994	0–30	0.9	11	50–90	0.04	329
BR3	1994	0–30	1.4	8	30–85	0.06	247
BR4	1994	0–30	1.4	11	30–110	0.05	518
BR5	1995	0–40	0.7	8	40–110	0.03	807
PO2	1994	0–40	0.7	16	75–123	0.02	550
PO3	1994	0–47	0.6	21	47–110	0.03	596
PO4	1994	0–50	0.5	29	60–130	0.04	491
PO5	1994	0–40	0.7	14	80–130	0.05	334
PO7	1994	0–30	0.6	13	30–70	0.1	116
PO8	1994	0–50	0.8	19	50–90	0.03	458
PO8.5	1995	0–30	0.9	6	50–80	0.06	204
PO9	1994	0–30	0.7	9	30–90	0.08	237
PO10	1994	0–40	0.8	10	70–100	0.03	390
PO12	1994	0–30	1.5	6	30–60	0.2	68
PO13	1994	0–30	1.1	7	30–130	0.02	1076
PO14	1994	0–30	0.7	7	60–100	0.02	910
PO15	1994	0–40	0.3	19	70–100	0.02	635
PO16	1994	0–40	0.4	15	40–90	0.02	541
PO18	1994	0–50	0.5	20	100–125	0.01	961
PO19	1994	0–30	1.6	4	60–110	0.04	586

Examples of cumulative chloride–cumulative water plots for the ponderosa pine zone are shown in Fig. 6. Most of these plots show two approximately linear segments. According to Stone (1984), such segments indicate relatively constant rates of precipitation, chloride input, and/or flux. The upper linear segments correspond to the sandy loam (A and AB) horizons, and the lower linear segments correspond to the Bt, weathered tuff (CR), and tuff (R) horizons. The upper segments have shallow slopes, indicating larger residual fluxes, whereas the lower segments have steeper slopes, indicating smaller fluxes. The residual fluxes and soil water ages for the ponderosa pine cores are given in Table 2;

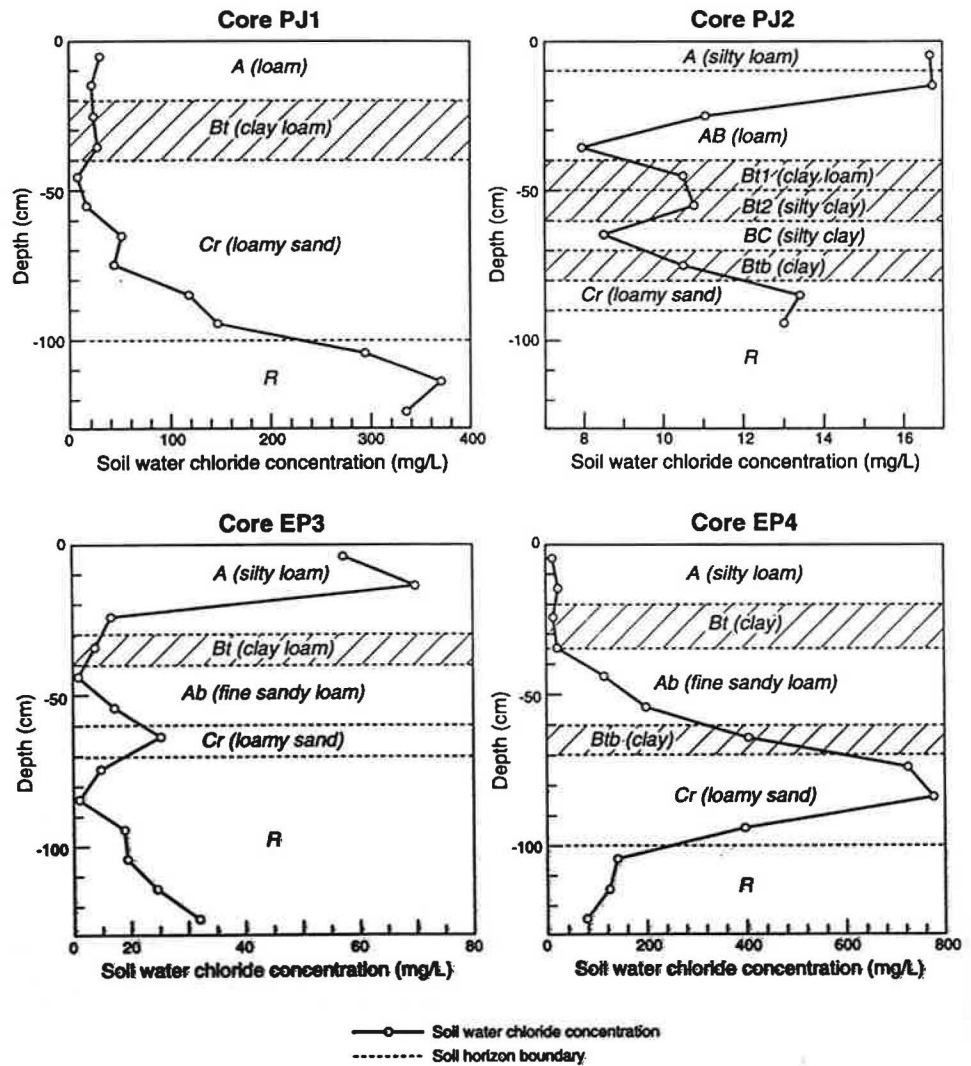


Fig. 7. Piñon–juniper woodland and erosion plot sites: examples of vertical chloride profiles.

these typically show a decrease of about one order of magnitude between the sandy loam horizons and the deeper clay and tuff horizons.

For the piñon–juniper zone, chloride profiles and cumulative water–cumulative chloride plots show a great deal of variability. The examples shown in Figs 7 and 8 were selected to illustrate the range of this variability. Except for cores EP2 (not shown in the figures) and EP4, chloride concentrations are lower than those in the ponderosa pine zone. The residual fluxes and soil water ages for the piñon–juniper cores are given in Table 3. Like the stratigraphic and chloride profiles (Figs 3, and 7), the fluxes are highly variable; in the Bt and deeper horizons, they are substantially larger than those of the ponderosa pine zone (with the exception of cores EP2 and EP4).

5. Discussion

5.1. Stable-isotope data: ponderosa pine and piñon–juniper zones

The main determinants of the isotopic composition of soil waters are (1) the isotopic composition of the precipitation entering the soil, (2) the amount of evaporation, and (3) the extent of mixing of soil waters having different isotopic compositions. Root uptake is a nonfractionating process and thus does not affect the isotopic composition of the soil water (Dawson and Ehleringer, 1991); this is important, because transpiration effects can be disregarded when using isotope data to assess the role of evaporation.

A potentially complicating factor is that the isotopic composition of precipitation varies with elevation: it becomes lighter as elevation increases. At the Los Alamos study sites, however, this difference appears to be insignificant. Isotope analyses of precipitation for locations near the piñon–juniper and ponderosa pine sites (Adams et al., 1995) show an elevation effect that is very small—comparable in magnitude to the analytical errors. In other words, this effect is small enough that a direct comparison of the isotope results for the ponderosa pine and piñon–juniper zones is valid.

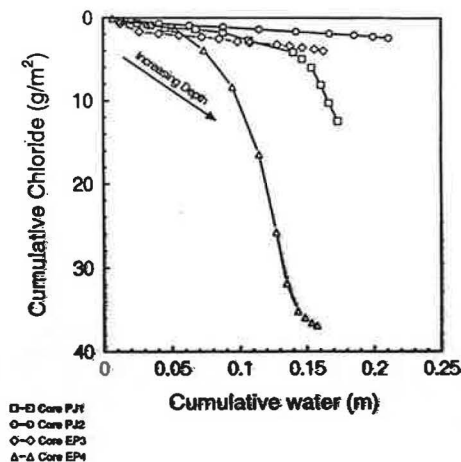


Fig. 8. Piñon–juniper woodland and erosion plot sites: examples of cumulative chloride–cumulative water plots.

Table 3
Piñon–juniper zone: residual flux estimates and soil water ages

Core	Date sampled	Depth interval (cm)	Residual flux (cm year ⁻¹)	Age at bottom of depth interval (years)	Depth interval (cm)	Residual flux (cm year ⁻¹)	Age at bottom of depth interval (years)	Depth interval (cm)	Residual flux (cm year ⁻¹)	Age at bottom of depth interval (years)
<i>Piñon–juniper woodland site</i>										
PJ1	1993	0–60	0.6	13	60–90	0.2	37	100–130	0.05	92
PJ2	1995	0–100	1.1	12						
PJ160	1995	0–30	0.65	5.8						
PJ182	1995	0–30	0.18	2.1	30–60	0.8	18			
PJ704	1995	0–20	0.08	1.7	20–80	0.68	32	80–110	0.11	49
PJ1216	1995	0–40	0.15	36	40–70	0.34	44			
<i>Erosion plot site</i>										
EP2	1993	0–40	0.4	17	40–140	0.02	318			
EP3	1993	0–20	0.2	12	20–130	0.7	30			
EP4	1993	0–40	0.5	10	40–100	0.03	258	100–130	0.1	271

It was initially hypothesized that because plant cover influences the amount of solar radiation reaching the soil surface (Breshears et al., 1997), the different vegetation at the three sites, by controlling the amount of evaporation, would produce different isotope profiles. However, this does not appear to be the case; vertical $\delta^{18}\text{O}$ and δD profiles for the cores from the ponderosa pine site, the piñon–juniper woodland site, and the erosion plot site (shown in Fig. 4) all display similar trends, having isotope maximums in the top 10 cm of the soil profile. Throughout the plateau, Class A pan evaporation is much higher than annual precipitation (Bowen, 1990), which suggests that evaporative demand may be so large that it masks any plant cover effects.

The less-than-10-cm depth of maximum isotopic enrichment indicates a shallow evaporative front. This is interesting, because the time of the year when the cores were taken, at the end of the early summer (when temperatures are high and relative humidity and precipitation rates are low), is the time when the evaporation front should be at its maximum depth. Once the mid-to-late summer monsoon season begins, the evaporation front should not move deeper into the profile.

According to the observations of Liu et al. (1995), infiltration of isotopically light precipitation during wet and cool periods produces a minimum bulge in the isotope profile, while evaporation during the drier, hotter periods produces a maximum bulge (see idealized curves in Fig. 9). The Los Alamos profiles, then, would be expected to show maximum bulges—but they do not. Instead, they show a persistent minimum bulge. Perhaps in the Los Alamos area, because the climate is relatively cool and wet for 9–10 months of the year, the evaporation front never moves deeply enough into the soil to convert the minimum bulge to a maximum bulge.

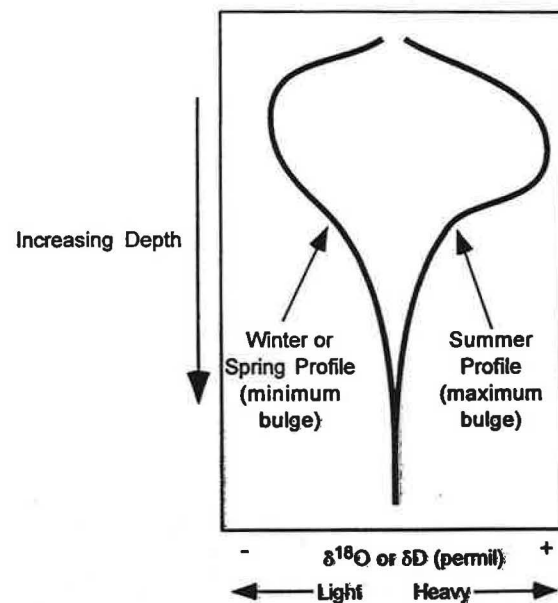


Fig. 9. Idealized stable-isotope profiles showing the seasonal change from minimum- to maximum-bulge profiles (as observed by Liu et al., 1995).

One way of determining the average initial isotopic composition of infiltrating water and the importance of evaporation is to calculate an evaporation trend line for the data and plot this line against the meteoric water line on a $\delta^{18}\text{O}$ – δD diagram. The evaporation trend line is obtained by calculating a linear regression of the soil water isotopic compositions. The point of intersection between the local meteoric water line and the evaporation trend line represents the average isotopic composition of infiltrating water.

The evaporation trend lines for the soil waters at the three sites are shown in Fig. 10 (the trend lines are based on data from the upper 40–50 cm only, which reflect isotopic compositions above the minimum bulges; these data yield better-constrained evaporation

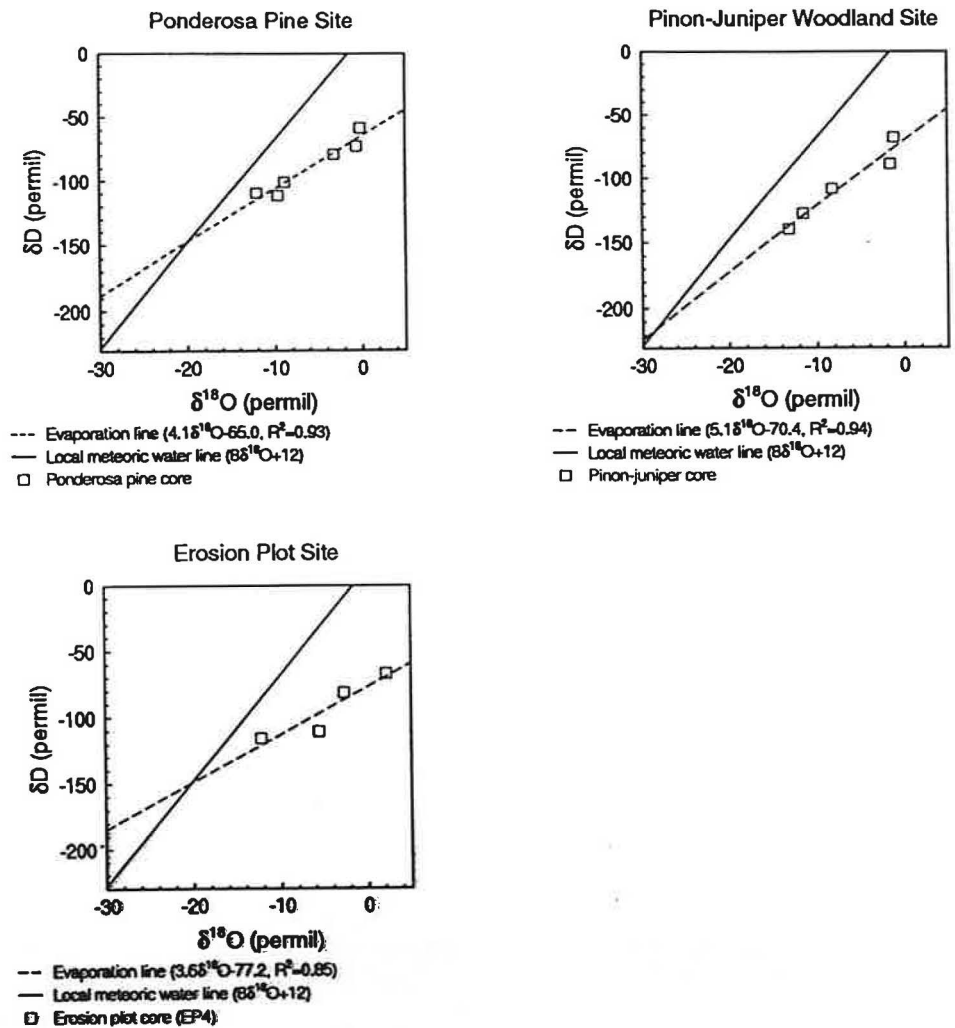


Fig. 10. $\delta^{18}\text{O}$ – δD plots of the soil water distillates in relation to the Los Alamos local meteoric water line of Vuataz and Goff (1986).

trend lines than does the entire data set). The evaporation trend lines for all three sites have shallow slopes (3.6 for the erosion plot site, 4.1 for the ponderosa pine site, and 5.1 for the piñon–juniper woodland site), indicating evaporation through a dry soil layer (Barnes and Allison, 1983, 1988). In addition, the average isotopic compositions of infiltrating water are light ($< -21\text{‰}$ $\delta^{18}\text{O}$ and $< -150\text{‰}$ δD) in all three cases. Light values are consistent with a snowmelt- and spring-rain-dominated system, but these values appear to be too light. The intersection values should be at least as heavy as infiltrating precipitation, but all three are lighter than the lightest precipitation values reported in Adams et al. (1995) and Newman (1996); this result strongly suggests that there is a systematic error in either the distillation or the analysis process. That the error is an analytical one is unlikely, because such errors should be random, and the δD data were corrected for hydrogen fractionation during the zinc reaction. Therefore, it is probable that the light bias resulted from some flaw in the soil water distillation process.

Other researchers have observed a systematic light-bias error with the use of vacuum extraction. Walker et al. (1994) found that for dry clay soils, high-temperature vacuum distillation can produce a fractionation in which the distillate can be too light by over 19‰ in δD and over 1‰ in $\delta^{18}\text{O}$. They suggest incomplete extraction as the cause. Araguás-Araguás et al. (1995) also found a light bias in distillates of clay soils, but attributed the problem to isotopically light water that was weakly bound to the clay and was extracted during distillation. In their study, high-temperature vacuum distillation of samples from a clay soil column resulted in values that were 10‰ too light in δD and 0.5‰ too light in $\delta^{18}\text{O}$ compared with mobile soil water eluted from the column. These two studies provide good evidence that the vacuum distillation process can produce values that are erroneously light; the bias becomes apparent through comparison of the values with those of precipitation. At the same time, even if the Los Alamos δD and $\delta^{18}\text{O}$ values had been 20‰ and 1‰ heavier, respectively, they would still indicate a light water input, consistent with a snowmelt- and spring-rain-dominated system.

5.2. Chloride data: ponderosa pine site

There is good agreement between residual fluxes calculated for similar depth intervals of the various cores taken at the ponderosa pine site (Table 2), indicating that downward fluxes are relatively homogeneous across the site. In addition, changes in the values of the flux estimates with depth are consistent with differences in the soil textural properties and hydraulic conductivities of the various horizons: the flux values are typically higher in the upper sandy loam horizons than in the clay Bt horizon (Table 2), and the same is true of the saturated hydraulic conductivity values (which range from $7.5 \times 10^{-5} \text{ cm s}^{-1}$ to $5.7 \times 10^{-7} \text{ cm s}^{-1}$ in the sandy loam versus $2.5 \times 10^{-8} \text{ cm s}^{-1}$ in the Bt horizon; Stephens, 1993). These findings suggest that the Bt horizon has a substantial inhibitory effect on downward water movement at the ponderosa pine site.

5.3. Chloride data: piñon–juniper woodland and erosion plot sites

The chloride profiles for the undisturbed piñon–juniper woodland and erosion plot sites show a great deal of variability (Fig. 7), which is consistent with the high

degree of spatial variability in soil textural properties and stratigraphy described by Davenport et al. (1996). Most of the residual flux estimates for the piñon–juniper zone (Table 3) are an order of magnitude larger, and less uniform, than those for the ponderosa pine zone (Table 2). These findings are consistent with those of other studies in the piñon–juniper zone on the plateau. D.D. Breshears (unpublished results, 1995), using neutron-probe data, has estimated near-surface flux rates similar to those reported here along a transect through the piñon–juniper woodland. The absence, or weaker development, of the Bt horizon in the piñon–juniper zone is probably the reason for the larger fluxes.

When the fluxes calculated for the piñon–juniper woodland site are compared with those for the treeless erosion plot site, no consistent differences are found that can be attributed to the differences in plant cover. Cores EP2 and EP4 from the erosion plot site did yield small deep-flux estimates for the piñon–juniper zone, but this does not seem to be a function of surface cover. Rather, it appears to be a function of the degree of development of the Bt horizon; these cores have the most well-developed Bt horizons of any in the piñon–juniper zone. Thus, the low flux estimates for these cores are probably attributable to soil textural properties. Core EP3, taken from the area between EP2 and EP4 (Fig. 1), has a weakly developed Bt horizon (low clay content) and a large flux estimate, consistent with the relationship between soil properties and flux estimates for the majority of the piñon–juniper cores.

6. Summary and conclusions

Comparison of the stable-isotope results for the ponderosa and piñon–juniper zones shows that the effect of evaporation on the soil waters is similar in the two zones, occurring mainly in the shallowest (upper 10 cm) soil horizon. In addition, the estimated average isotopic compositions of precipitation contributing to infiltration are quite light in both zones, suggesting that the major sources of infiltrating water are cool-weather snowmelt and spring rains.

The chloride results show that deep fluxes are typically more uniform in the ponderosa pine zone than in the piñon–juniper zone, and are about an order of magnitude lower. These differences are probably due to the more homogeneous soils and the more well-developed Bt horizons in the ponderosa pine zone. The piñon–juniper zone has spatially heterogeneous soils that typically lack well-developed Bt horizons. Because such differences affect the vertical movement of water through the soil matrix, contaminants may move much more slowly through the soils in the ponderosa zone, with their well-developed Bt horizons, than through those areas of the piñon–juniper zone where Bt horizons are poorly developed or absent. No plant cover effects were discerned, either in the flux estimates or in the stable isotope profiles, but this does preclude the existence of minor plant-cover effects.

Acknowledgements

Bridget Bergquist, James Corboy, David Davenport, Greg Hill, Vivi Hriscu, Andi Kron,

and Donna Sharp are all thanked for their contributions to this work. Funding was provided by the Los Alamos National Laboratory Environmental Restoration Program, and the program's support is very much appreciated. Fred Phillips and the *Journal of Hydrology* reviewers are also thanked for their comments on the manuscript.

References

- Adams, A.I., Goff, F. and Counce, D., 1995. Chemical and isotopic variations of precipitation in the Los Alamos region, New Mexico. Los Alamos National Laboratory Report LA-12985-MS, Los Alamos, NM, 35 pp.
- Allen, C.D., 1989. Changes in the landscape of the Jemez Mountains, New Mexico. Ph.D. Dissertation, University of California, Berkeley, 346 pp.
- Allison, G.B., Barnes, C.J. and Hughes, M.W., 1983. The distribution of deuterium and ^{18}O in dry soils 2: experimental. *J. Hydrol.*, 64: 377–397.
- Allison, G.B., Gee, G.W. and Tyler, S.W., 1994. Vadose-zone techniques for estimating groundwater recharge in arid and semiarid regions. *Soil Sci. Soc. Am. J.*, 58: 6–14.
- Anderholm, S.K., 1994. Ground-water recharge near Sante Fe, north-central New Mexico. USGS Water-Res. Invest. Rep. 94-4078, 68 pp.
- Araguás-Araguás, L., Rozanski, K., Gonfiantini, R. and Louvat, D., 1995. Isotope effects accompanying vacuum extraction of soil water for stable isotope analyses. *J. Hydrol.*, 168: 159–171.
- Barnes, C.J. and Allison, G.B., 1983. The distribution of deuterium and ^{18}O in dry soils. 1. Theory. *J. Hydrol.*, 60: 141–156.
- Barnes, C.J. and Allison, G.B., 1988. Tracing of water movement in the unsaturated zone using stable isotopes of hydrogen and oxygen. *J. Hydrol.*, 100: 143–176.
- Bowen, B.M., 1990. Los Alamos Climatology. Los Alamos National Laboratory Report LA-11735-MS, 254 pp.
- Breshears, D.D., Rich, P.M. and Barnes, F.J., 1997. Overstory-imposed heterogeneity in solar radiation and soil moisture in a semiarid woodland. *Ecolog. Appl.*, 7(4): in press.
- Davenport, D.W., Wilcox, B.P. and Breshears, D.D., 1996. Soil morphology of canopy and intercanopy sites in a piñon–juniper woodland. *Soil Sci. Soc. Am. J.*, 60: 1881–1887.
- Dawson, T.E. and Ehleringer, J.R., 1991. Streamside trees that do not use stream water. *Nature*, 350: 335–337.
- Kendall, C. and Coplen, T.B., 1985. Multisample conversion of water to hydrogen by zinc for stable isotope determination. *Anal. Chem.*, 57: 1437–1446.
- Liu, B., Phillips, F., Hoines, S., Campbell, A.R. and Sharma, P., 1995. Water movement in desert soil traced by hydrogen and oxygen isotopes, chloride, and chlorine-36, southern Arizona. *J. Hydrol.*, 168: 91–110.
- Los Alamos Environmental Research Park, 1976. The Los Alamos National Environmental Research Park. Los Alamos National Laboratory Report, Los Alamos, NM, 37 pp.
- Newman, B.D., 1996. Geochemical investigations of calcite fracture fills and mesa-top water dynamics on the Pajarito Plateau, New Mexico. Ph.D. Dissertation, New Mexico Institute of Mining and Technology, Socorro, NM, 255 pp.
- Phillips, F.M., 1994. Environmental tracers for water movement in desert soils of the American southwest. *Soil Sci. Soc. Am. J.*, 58: 15–24.
- Reith, C.C., 1992. Waste management and the arid-land disposal concept. In: C.C. Reith and B.M. Thomson (Editors), *Deserts as Dumps? The Disposal of Hazardous Material in Arid Ecosystems*. University of New Mexico Press, Albuquerque, pp. 3–19.
- Scanlon, B.R., 1991. Evaluation of moisture flux from chloride data in desert soils. *J. Hydrol.*, 128: 137–156.
- Shurbaji, A.-R.M. and Campbell, A.R., 1997. A study of evaporation and recharge in desert soils using environmental tracers, New Mexico, USA. *Environ. Geol.*, 29: 147–151.
- Shurbaji, A.-R.M., Phillips, F.M., Campbell, A.R. and Knowlton, R.G., 1995. Application of a numerical model for simulating water flow, isotope transport, and heat transfer in the unsaturated zone. *J. Hydrol.*, 171: 143–163.
- Socki, R.A., Karlsson, H.R. and Gibson, E.K., 1992. Extraction technique for the determination of oxygen-18 in water using preevacuated glass vials. *Anal. Chem.*, 64: 829–831.

- Stephens, D.B., 1993. Laboratory analysis of hydraulic properties of soil samples. Report No. 2-LN3-6860J-1, Daniel B. Stephens and Assoc. Inc., Albuquerque, NM.
- Stone, W.J., 1984. Recharge in the Salt Lake Coal Field based on chloride in the unsaturated zone. New Mexico Bureau of Mines and Mineral Resources, Open-File Report 214, 64 pp.
- Vuataz, F.-D. and Goff, F., 1986. Isotope geochemistry of thermal and nonthermal waters in the Valles Caldera, Jemez Mountains, Northern New Mexico. *J. Geophys. Res.*, 91(B2): 1835–1853.
- Walker, G.R., Woods, P.H. and Allison, G.B., 1994. Interlaboratory comparison of methods to determine the stable isotope composition of soil water. *Chem. Geol.*, 111: 297–306.
- Wilcox, B.P., 1994. Runoff and erosion in intercanopy zones of piñon–juniper woodlands. *J. Range. Manage.*, 47: 285–295.
- Wilcox, B.P., Newman, B.D., Allen, C.D., Reid, K.D., Brandes, D., Pitlick, J. and Davenport, D.W., 1996. Runoff and erosion on the Pajarito Plateau: observations from the field. In: F. Goff, B. Kues, M.A. Rogers, L.D. McFadden and J.N. Gardner (Editors), *The Jemez Mountains Region: New Mexico Geological Society Forty-Seventh Annual Field Conference Guidebook*. New Mexico Geol. Soc., Socorro, NM, USA, pp. 433–439.

A detailed *Guide for Authors* is available upon request from the Publisher, Elsevier Editorial Services, Mayfield House, 256 Banbury Road, Oxford OX2 7DH, UK, and will also be printed each year (for 1997: Vol. 87, Nos. 1-2). Please pay attention to the following notes:

Language

The official language of the journal is English.

Preparation of the text

- The manuscript should preferably be prepared on a word processor and printed with double spacing and wide margins and include an abstract of not more than 500 words.
- The title page should include the name(s) of the author(s), their affiliations, fax and e-mail numbers. In case of more than one author, please indicate to whom the correspondence should be addressed.

References

- References in the text consist of the surname of the author(s), followed by the year of publication in parentheses. All references cited in the text should be given in the reference list and vice versa.
- The reference list should be in alphabetical order and on sheets separate from the text.

Tables

Tables should be compiled on separate sheets and should be numbered according to their sequence in the text.

Illustrations

- All illustrations should be numbered consecutively and referred to in the text.
- Drawings should be lettered throughout, the size of the lettering being appropriate to that of the drawings, but taking into account the possible need for reduction in size. The page format of the journal should be considered in designing the drawings.
- Photographs must be of good quality, printed on glossy paper.
- Figure captions should be supplied on a separate sheet.
- If contributors wish to have their original figures returned this should be requested at proof stage at the latest.
- Colour figures can be accepted providing the reproduction costs are met by the author. Please consult the publisher for further information.

Proofs

One set of proofs will be sent to the corresponding author, to be checked for typesetting/editing. The author is not expected to make changes or corrections that constitute departures from the article in its accepted form.

Page charges and reprints

There will be *no page charge*. Each author receives with his galley proofs a reprint order form which must be completed and returned to the Publisher with the proofs, Elsevier Editorial Services, Mayfield House, 256 Banbury Road, Oxford OX2 7DH, UK, tel. (1865) 314900; telefax (1865) 314990. Additional reprints (minimum 100) can be ordered at quoted prices. *Fifty reprints* of each article are supplied *free of charge*.

Submission of manuscripts

One original and two copies should be submitted to: Editorial Office, Journal of Hydrology, P.O. Box 1930, 1000 BX Amsterdam, The Netherlands. The indication of a fax and e-mail number on submission of the manuscript could assist in speeding communications. Illustrations: Please note that on submission of a manuscript **three sets** of all photographic material printed **sharply on glossy paper** or as **high-definition laser prints** must be provided to enable meaningful review. Photocopies and other low-quality prints will not be accepted for a review. Submission of an article is understood to imply that the article is original and unpublished and is not being considered for publication elsewhere. Upon acceptance of an article by the journal, the author(s) will be asked to transfer the copyright of the article to the publisher. This transfer will ensure the widest possible dissemination of information.

Authors in Japan please note: Upon request, Elsevier Science Japan will provide authors with a list of people who can check and improve the English of their paper (*before* submission). Please contact our Tokyo office: Elsevier Science Japan, 9-15 Higashi-Azabu, Minato-ku, Tokyo 106. Tel: (03)-5561-5033, Fax (03)-5561-5047.

Submission of electronic text

In order to publish the paper as quickly as possible after acceptance, authors are encouraged to submit the final text also on a 3.5" or 5.25" diskette. Both double density (DD) and high density (HD) diskettes are acceptable. Make sure, however, that the diskettes are formatted according to their capacity (HD or DD) before copying the files onto them. Similar to the requirements for manuscript submission, main text, list of references, tables and figure legends should be stored in separate text files with clearly identifiable file names. The format of these files depends on the word processor used. Texts made with DisplayWrite, MultiMate, Microsoft Word, Samna Word, Sprint, Volkswriter, Wang PC, WordMARC, WordPerfect, Wordstar, or supplied in DCA/RFT, or DEC/DX format can be readily processed. In all other cases the preferred format is DOS text or ASCII. It is essential that the name and version of the wordprocessing program, type of computer on which the text was prepared, and format of the text files are clearly indicated. Authors are requested to ensure that the contents of the diskette correspond exactly to the contents of the hard copy manuscript. Discrepancies can lead to proofs of the wrong version being made. The word processed text should be in single column format. Keep the layout of the text as simple as possible; in particular, do not use the word processor's options to justify or to hyphenate the words. If available, electronic files of the figures should be included on a separate floppy disk.

US mailing notice - *Journal of Hydrology* (ISSN 0022 1694) is published monthly by Elsevier Science B.V., (Molenwerf 1, Postbus 211, 1000 AE Amsterdam). Annual subscription price in the USA US\$3475.00 (valid in North, Central and South America), including air speed delivery. Application to mail at second class postage rate is paid at Jamaica, NY 11431.

USA POSTMASTERS: Send address changes to *Journal of Hydrology* Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003. **AIRFREIGHT AND MAILING** in the USA by Publications Expediting, Inc., 200 Meacham Avenue, Elmont, NY 11003.