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WATER BUDGETS IN XERIC SOIL MOISTURE REGIMES IN CALIFORNIA'S CENTRAL VALLEY: CAN DEEP LEACHING OCCUR UNDER TODAY'S CLIMATE?

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Introduction

Studies of soil development on alluvial landforms in California's Central Valley have largely focused on the evolution of soil properties as a function of landscape age (e.g., Busacca *et al.,* 1989). However, palynological evidence suggests that the climate in the Sacramento area 100,000 years ago was cooler than it is now (Ritter and Hatoff, 1977). Vegetation life zones were probably lowered about 600 to 750 m, so that the Valley may have been occupied by conifers.

It is tempting to speculate that this cooler climate may have been more effective for soil weathering than the present-day climate. Thus, some of the apparently time-dependent variation in soil properties may in fact be relicts of effectively wetter climates. This climate-dependent soil genesis model has been applied widely to soils in arid regions (e.g., McFadden, 1988).

More recent field work in the southwestern Sacramento Valley (Munk, 1993) showed that Palexeralfs on geomorphic surfaces with estimated ages of 200,000 to 400,000 years before present (YBP) were wetted to the base of the solum (2 to 3 m deep), even though the previous six years had less-than-average precipitation, suggesting that deep leaching is occurring and that some soil properties observed are the result of weathering under climates similar to today's.

We ask the basic questions: 1) Can soil properties, such as thick Bt horizons and abrupt textural changes in Palexeralfs on Pleistocene-age landscapes, be accounted for by leaching and weathering under current climatic conditions? and 2) how do predicted leaching depths based on daily data compare with those based on long-term precipitation averages? We tried to answer these questions by developing a water budget model based on daily weather data to estimate depth of leaching, and by testing the model with field measurements of soil water conditions (Thomas, 1996).

Materials and Methods

There were three steps to this project. The first consisted of establishing field sites to obtain real world data on soil moisture changes in response to precipitation. The next involved developing a computer model to predict leaching depths for soils based on known profile characteristics, and checking the model's predictions against field observations. Finally, we compared model predictions of leaching depth based on one year's daily precipitation data

(1994-95) with depth predictions based on long-term precipitation averages.

Field sites

We selected three sites representing a sequence of soils formed on alluvial deposits in the Dunnigan Hills, approximately 50 km NW of Davis: a Haplic Palexeralf, a Typic Palexeralf, and a Typic Xerofluvent (Table 1). Soils, stratigraphy, and geomorphology of this area were described previously by Munk (1993). At each of the three locations we installed three neutron access tubes, a piezometer, and a precipitation gauge.

Table 1. Age and landform of three study sites.

Soils	**Surface Age (YBP)**	**Landform**
Fine-loamy, mixed, active, thermic Haplic Palexeralf	>192,000 < 400,000	Anticline cap
Clayey-skeletal, mixed, superactive, thermic Typic Palexeralf	>17,200 <55,000-75,000	Alluvial terrace
Loamy-skeletal, mixed, superactive, thermic Typic Xerofluvent	< 2,000	Alluvial terrace

We used a constant-head permeameter (Amoozegar, 1989) to measure the saturated hydraulic conductivity at three or four depths (to 1.5 m) in each soil.

Field measurements were made from August 1994 through August 1995. Soil water content was monitored frequently by neutron probe (NP) following rains to determine how quickly water was redistributed in the soils and to determine the depth of leaching. Calibration curves for each NP depth increment were developed by correlating NP count with the soil mass water content.

We obtained soil samples periodically throughout the rainy season by auger within 5 m of the permanent sites and at the same time measured NP counts. Gravimetric soil water content measurements and particle size analyses were performed on these soil samples according to the methods described in the Soil Survey Laboratory Methods Manual (Soil Survey Laboratory Staff, 1996).

Computer model

We developed an Excel-based soil water budget compartment model based on daily evapotranspiration (ET) and precipitation data, soil saturated hydraulic conductivity (Ksat), estimated available soil water holding capacity (AWC), and saturated water-holding capacity (SWC).

Compartment model assumptions and operation

1. AWC is solely a function of texture;
2. AWC of a given horizon is completely filled before water moves to the next horizon;
3. Water movement is adjusted daily and is limited by Ksat of the underlying horizon;
4. Surface horizons are assigned a higher proportion of daily ET loss than subsurface horizons;

5. Since all sites had slopes of less than 5%, and at least 80% vegetation cover by January 1, 1995, the model assumed 100% rainfall infiltration, minus ET, providing that the surface horizon was not saturated;
6. No lateral flow or preferential flow in large pores, but run-off is allowed if the surface soil is saturated;
7. A bottom horizon, underlying the deepest horizon described by Munk (1993), was created to serve as a sink for all water permeating past the bottom of the profile;
8. Water content at the beginning of the season was based on measurements made in early November 1994.

The structure of the model is illustrated in Figure 1.

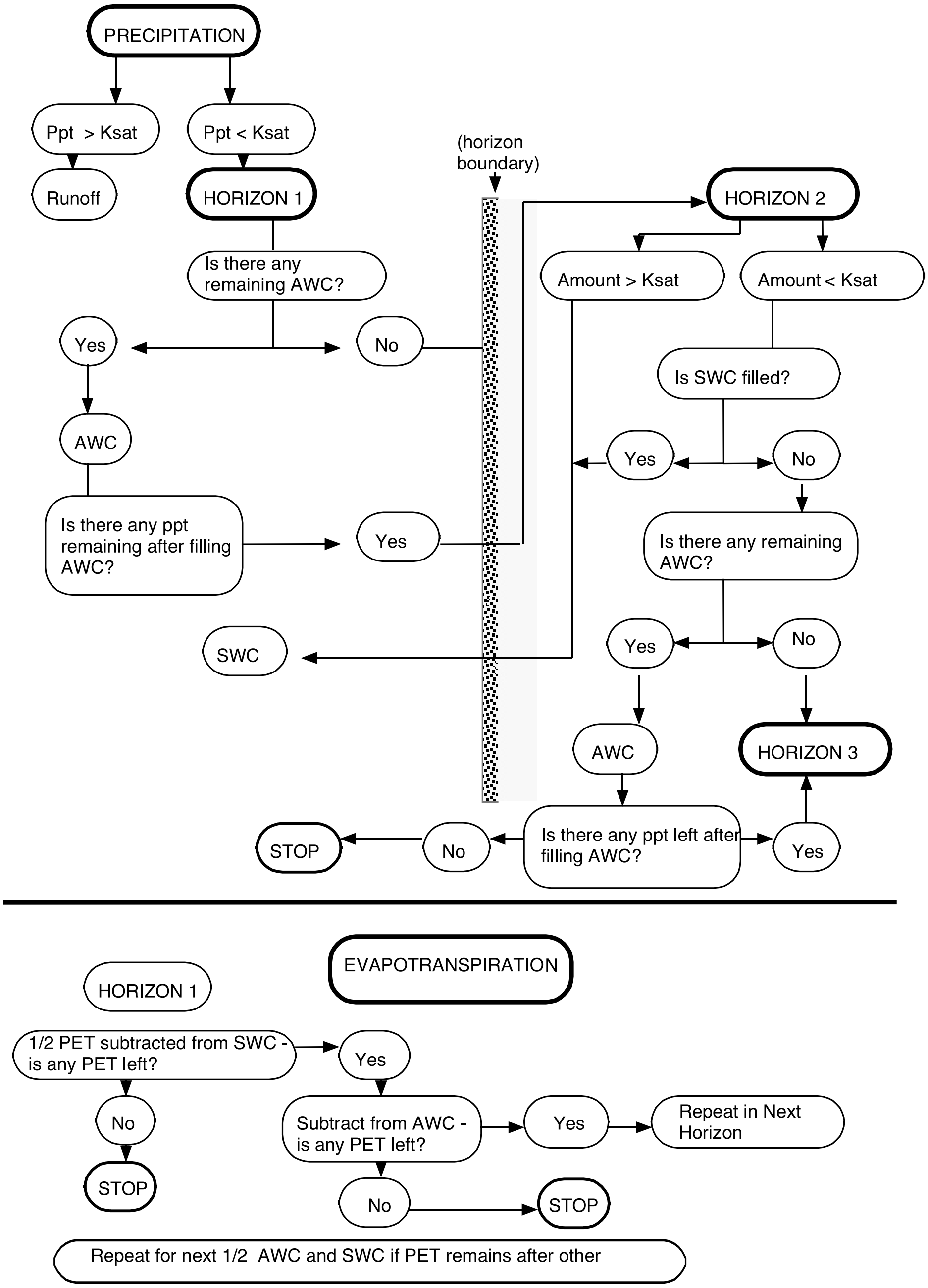

Figure 1. Flow of water in computer model

The basic flow of the model is as follows: The final balances for AWC and SWC for each day are the starting balances for the next day. Precipitation enters the surface horizon, to the extent allowed by the Ksat for that horizon. Precipitation exceeding the Ksat (which is calculated in cm/day) of the surface horizon is lost to runoff. The precipitation that infiltrates begins to fill the horizon's AWC. If the first horizon's AWC is exceeded, water begins to fill the AWC of the horizon below (once again limited by Ksat), and so on through all the horizons. For example, if the Ksat of the second horizon prevents infiltration of some amount of water from the first horizon, that water begins to fill the first horizon's SWC.

In this model, water is removed by ET and percolation only (no lateral subsurface flow), on a horizon-by-horizon basis in two passes, with water more easily removed from upper horizons than deeper ones. The second pass occurs in upper horizons before the first pass has been made in some lower horizons, in a rough approximation of how water is first extracted by roots.

This was accomplished by weighting ET extractions from the lower horizons, so that more ET was required to remove a given amount of water. This rationale for extraction of ET was based on an average rooting depth of annual herbs and grasses of 50 cm (Jackson et al., 1988), as these are the dominant vegetation at all three sites. Results of this daily precipitation model were then compared to results based on long-term average climate data (Arkley, 1963).

Data sources

AWC. Available water-holding capacity (AWC), that water held between 33 kPa and 1,500 kPa tension, was calculated for each horizon by converting our measured textures to AWC using USDA Berkeley Soil Conservation Service data tables, henceforth referred to as Berkeley SCS AWC (Soil Survey Staff, 1968) (Table 2).

The fine-earth textures (<2-mm) on which our estimates of the Dunnigan Hill soils' AWC were based were averages of the particle size analysis done in our lab, adjusted for gravel contents estimated by Munk (1993). We used Munk's gravel contents to adjust the AWC for coarse fragments, because Munk's coarse fragment estimates were based on nearby backhoe pit pedon samples and probably more accurately reflect soil coarse fragment content than our auger samples.

Table 2. Textures and AWC values for three Dunnigan Hills soils.

Horizons	**Texture**	**Depth (cm)**	**Horizon thickness (cm)**	**Horizon AWC (cm)**	**Cumulative AWC (cm)**
Ap2	gscl	5-20	15	2.06	2.80
Bt1	gscl	20-46	26	3.30	6.10
Bt2	gscl	46-64	18	2.39	8.48
Btq1	vgscl	64-100	36	3.38	11.86
Btq2	vgscl	100-150	50	5.16	17.02
BCt	vgscl	150-230	80	6.10	23.11
C	xgcos	230-305	75	4.72	27.84
Typic Palexeralf					
Ap	sl	0-20	20	1.88	1.88
AB	fsl	20-40	20	2.31	4.19
Bt1	gcl	40-60	20	2.59	6.78
Bt2	gscl	60-91	31	3.68	10.46
Bt3	vgscl	91-135	44	4.27	14.73
Bt4	vgsl	135-180	45	4.63	19.36
Bt5	vgscl	180-224	44	4.04	23.40
2C	fsl	224-254	30	3.81	27.21
Typic Xerofluvent					
A	vgsl	0-21	21	1.50	1.50
C1	sl	21-36	15	1.78	3.28
C2	vgsl	36-57	21	0.69	3.96
C3	vgsl	57-109	52	1.09	5.05
C4	xgsl	109-160	51	1.42	6.48
C5	xgsl	160-230	70	2.51	8.99

* All AWCs adjusted for gravel content

Soil textures. Particle size analysis (PSA) was performed in the lab on samples from augered neutron probe access tube holes (Table 2).

Evapotranspiration. Daily evapotranspiration estimates for the Zamora weather station were downloaded from the California Irrigation Management Information System (CIMIS) database. The Zamora CIMIS station lies between 4 to 16 km from the Dunnigan Hills study sites.

Precipitation. Input was based on twice-weekly rain gauge measurements at each site.

Saturated water-holding capacity. SWC was calculated based on soil bulk density measurements by Munk (1993) (see discussion of AWC above). To determine SWC, we estimated the fraction of voids (available pore space) in each horizon based on Munk's fine earth fraction bulk density and on a solid bulk density value of 2.65 g/cm^3 according to: fraction of voids per cm depth†=†1†-†(ρ_b /2.65). The result was then adjusted to Munk's percent coarse fragment content, and this value was multiplied by the thickness of the horizon in centimeters to provide SWC for the horizon.

Saturated hydraulic conductivity. Two sources were used to obtain Ksat estimates: on-site field measurements with a constant-head permeameter [Amoozemeter] (Amoozegar, 1989), and the Yolo County Soil Survey soil permeability estimates (Andrews, 1972). The soil survey Ksat estimates were almost uniformly at least one order of magnitude higher than our field measurements, and sometimes nearly three orders of magnitude higher.

The discrepancy between our measured Ksats and the soil survey numbers may be the result of over-estimation of Ksats on the basis of soil properties in the soil survey, rather than on in-situ measurements. Additionally, our field Ksat measurements may be low due to the inherent difficulty of conducting Ksat measurements in auger holes without compacting the soil.

Comparison between field measurements and computer predictions

Two methods were used to compare the field data with computer model results:

(1) NP counts were converted to % AWC filled (%NP-AWC), and then plotted against model predictions. To accomplish this, the NP counts were first converted to mass water contents using the regression equations obtained from the NP calibration curves, then converted to volumetric water contents using Munk's (1993) bulk density data. These volumetric water contents were then translated to %AWC filled using Berkeley SCS-AWC for horizons of similar texture and thickness (Soil Survey Staff, 1968); and

(2) We plotted NP counts directly against model predictions of % AWC filled. Natural Resources Conservation Service (NRCS) research on mass water content at 100% AWC (33 kPa tension) for various soil textures enabled us to establish mass water contents for each of our soil horizons (Brasher et al., 1993). The resulting 100% AWC was used in an NP calibration equation for each soil horizon to obtain a corresponding NP count. On graphs comparing NP count with model-predicted % AWC filled, the 100% AWC line was set equal to the calculated NP count. The NP count matching 100% AWC for the 30-cm horizon of this Palexeralf was calculated as 12745. Maximum possible AWC was 100%, while NP count could continue to rise as water continued to fill remaining soil pore capacity.

Comparison of 1994-95 leaching depths with long-term averages

To compare predicted depth of leaching using daily precipitation data versus monthly long-term averages, we took advantage of 119 years of climate data recorded at the Davis 2†WSW Experimental Farm and published by the NOAA for the years 1872-1992 (119 water years). These data, in addition to those gathered from our fieldwork and from CIMIS, enabled us to run the computer model for each of the following sets of data:

- We used a long-term average of precipitation and evapotranspiration for each month during the wet season. Annual precipitation in Davis averaged 43.3 cm for the 119-year period. The maximum precipitation was 95.0 cm in 1889-90; the minimum was 13.0 cm in 1876-77. Evapotranspiration estimates were based on long-term lysimeter-based estimations of ET data for Davis from Snyder and Pruitt (1994).
- Also based on the long-term Davis data, we calculated leaching depth for the wet season for each of the 119 years.

- One year, 1984-85, had CIMIS-recorded total precipitation and ET similar to the 119-year average, although the seasonal distributions of precipitation were not identical for the two data sets. This enabled a comparison of the effects of using daily data versus long-term averages for the same annual precipitation.
- Using daily data for the 1994-95 year, with precipitation measured in the field, and leaching depth corroborated by NP data.
- Used monthly totals for the 1994-95 year to contrast with the results for a daily basis for the same year.
- To get a sense of the impact of a significantly wetter climate, used precipitation values that were double the 119 average.

Results and Discussion

Field study

The precipitation measured at the three field sites during 1994-95 ranged from 64 cm to 85 cm (Table 3). The 119-year average for this vicinity was 40 cm per year.

Table 3. Precipitation/evapotranspiration balance for three sites in 1994-95.

Site	Ppt (cm)	Ppt-ET* (cm)
Typic Xerofluvent	79.9	57.9
Typic Palexeralf	63.8	42.4
Haplic Palexeralf	84.6	62.8

NP readings and piezometer data confirmed that all three soils were wetted to a depth of 2†meters for some period during the 1994-95 season.

NP measurements of the three soils taken over the course of the season showed that water content changes were related to textural characteristics. For example, the Xerofluvent, with gravelly coarse textures, showed a rapid increase in NP counts in lower horizons in response to a heavy rainfall event, while the Palexeralfs showed a delay in NP count increase below the abrupt textural change. Also, water levels in a creek located 15 m from the Xerofluvent may have controlled water content in the lower horizons, as shown by consistently high NP counts and piezometer levels when the creek was flowing.

Computer model results

The soil water content curves predicted by the model generally reflected trends measured in the field by NP and piezometer. However, the model-predicted % AWC often differed greatly from that estimated using the NP count (%NP-AWC). Given the spatial variability frequently found in soils formed from alluvium, we speculate that these discrepancies are the result of errors in our estimates of coarse fragment content and bulk density in the NP access holes.

When NP counts were compared directly with model %AWC, without attempting to convert NP to %AWC, the soil moisture trends matched the predicted trends well for the

Haplic Palexeralf (Figure 2) and for the Typic Palexeralf (Figure 3). For the Xerofluvent (Figure 4), the model was premature by as much as two months in predicting rises in soil water content.

The most likely cause was underestimated AWCs for the Xerofluvent. Model sensitivity analysis showed that AWC estimates used in the model may have underestimated actual AWCs by up to 25% for some horizons. However, increasing AWC by more than 25% would have prevented the model from predicting the 2-meter wetting depth observed in the field. Sensitivity analyses also showed that the choice of estimated AWC had a much greater impact on predicted leaching depth than did estimated Ksat.

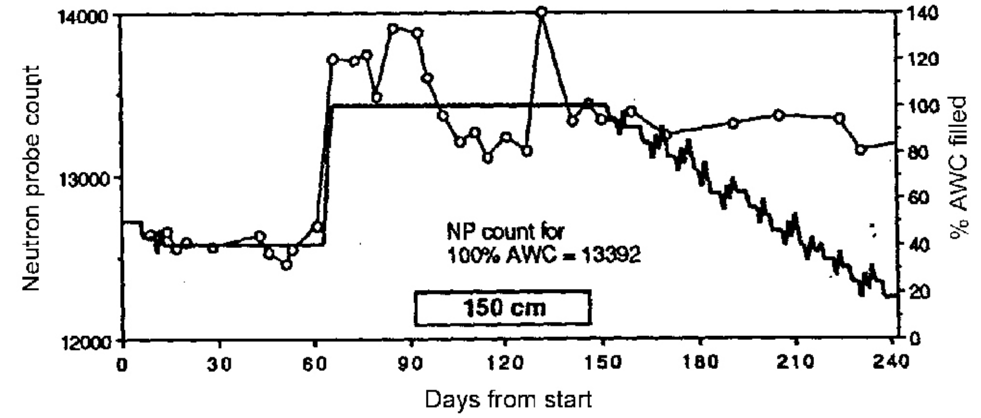

Figure 2. Field NP counts versus model-predicted %AWC for one horizon of the Haplic Palexeralf study site.

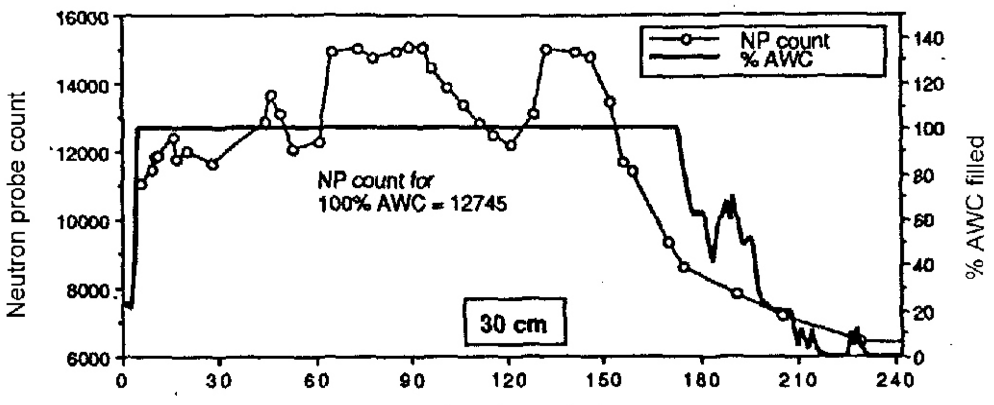

Figure 3. Example of NP count compared with model-predicted % AWC filled on the Typic Palexeralf study site.

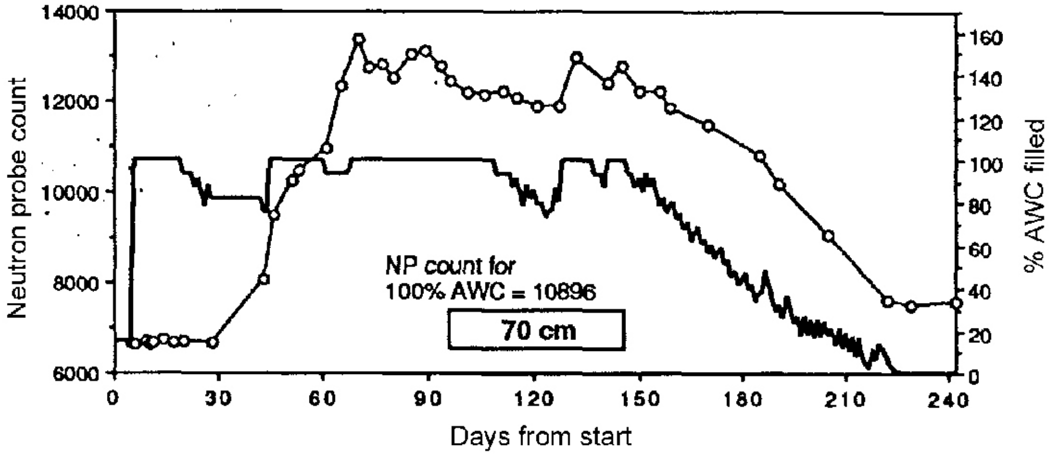

Figure 4. Field NP counts versus model-predicted %AWC for one horizon of the Typic Xerofluvent study site.

The model underpredicted depth of leaching when we used field-measured Ksat values. Measured Ksat values ranged from about 0.1 cm/day in the Bt horizons (very gravelly sandy clay loam) of the Xeralfs to about 400 cm/day in the C layers (extremely gravelly sandy loam) of the Xerofluvent. The best fit of the model to the field observations was obtained when we used Ksat values higher than those we measured, but lower than those estimated from the soil survey Ksat tables based on soil texture.

The ponding at the 2-m depth measured by piezometer at both Xeralf sites showed us that the initial model assumption of the absence of a water-movement-limiting bottom layer was not accurate for these soils. Clearly, a deep layer with very slow permeability was limiting vertical water movement in the Xeralfs.

Our model would probably have been improved had we been able to obtain better estimates of bulk density and coarse fragment content in the immediate vicinity of the NP access tubes. The gravelly textures limited our ability to retrieve suitable samples for lab characterisation during access tube installation. We were also unable to obtain relatively undisturbed soil clods or cores that would have allowed us to actually measure 33 kPa and 1500 kPa water contents, rather than to estimate AWC from soil texture data.

Despite the uncertainties in Ksat and AWC, the model reasonably predicted the timing and depth of wetting in two Palexeralfs over the course of the wet season.

Comparison with predictions based on historical averages

Finally, computer depth-of-leaching predictions were run for the three Dunnigan Hills soils based on precipitation data for 1994-95, 1984-85, and the 119-year long-term record (Tables 4 and 5).

Table 4. Annual precipitation and ET values used for computer model leaching predictions.

Annual values	**Period and location of precipitation measurement**					
	119-yr Davis average	**2 X 119-yr Davis average**	**1984-85 Davis**	**1994-95 Haplic Palexeralf**	**1994-95 Typic Palexeralf**	**1994-95 Typic Xero-fluvent**
Precipitation (cm)	43.3 (Range 13-95)	86.6	39.4	84.6	63.8	79.9
ET (cm)	132.6	132.6	146.5	122.2	122.2	122.2

Table 5. Soil leaching depths predicted by computer model for long-term average versus annual precipitation records.

Site	**Leaching depth based on data set for years shown**						
	119-yr avg monthly	**119-yr avg monthly**	**2 x 119-yr avg monthly ppt**	**1984-85 monthly**	**1984-85 daily**	**1994-95 monthly**	**1994-95 daily**
		Number of years wet to depth shown					
Haplic Palexeralf	1.07 m	2 m: 26 yrs 3 m: 17 yrs	>3.1 m: more than 89 yrs	0.53 m		> 3.1 m	> 3.1 m
Typic Palexeralf	1.42 m	2 m: 34 yrs 2.5 m: 24 yrs	>2.5 m: more than 89 yrs	0.86 m	1.35-1.8 m	> 2.5 m	> 2.5 m
Xerofluvent	> 2.30 m	2 m: 82 yrs	>2.3 m: more than 89 yrs	> 2.3 m		> 2.3 m	> 2.3 m

Using 119-yr average rainfall on a monthly basis, the model predicted that the Haplic Palexeralf would be leached to 107 cm and the Typic Palexeralf to 142 cm. The Xerofluvent, with its coarse textures, is the only soil that is predicted to be leached throughout its thickness by average long-term precipitation.

Thus, the use of long-term average data predicts leaching depths that are much less than the depths of the base of the B horizons in the Palexeralfs (230 cm for the Haplic Palexeralf and 224 cm for the Typic Palexeralf, see Table 2). These predictions might lead to the conclusion that the climate must have been significantly wetter in the past to account for the significantly deeper weathering. However, when monthly leaching was calculated for each of the 119 years, all of the soils were predicted to have been wet to the bottom of the solum a significant number of times.

If the 119-year monthly precipitation amounts were doubled, and if ET remained unchanged, each soil would be leached to the bottom of the profile more than 75% of the years of the 119-yr record. Munk (1993) estimated that very late Pleistocene precipitation averaged approximately 25 cm per year more than present (about 50% more than the 119-yr average). Our model suggests that these soils would have been leached to depths well below the present-day solum under such climatic conditions, and would likely show evidence of weathering (thicker solum) if this was the case.

Use of the 1984-85 monthly totals, which were roughly similar to the 119-yr monthly averages, resulted in predicted leaching to only 53 cm in the Haplic Palexeralf, and to 86 cm in the Typic Palexeralf, although water was again predicted to reach the bottom of the Xerofluvent. However, use of *daily* 1984-85 data for the Typic Palexeralf site predicted wetting 0.5 m to 1 m deeper than was predicted by the monthly data, although leaching still fell short of the full 2.54 m profile depth.

The 1994-95 precipitation approached the 119-year maximum, and led to computer predictions that both daily and monthly rainfall amounts would leach the entire profile at all sites. These predictions were corroborated by field observations that the soils were wet to depths significantly below the depth of the solum.

Conclusions

Our results show that significant deep leaching can occur under current climatic conditions and that long-term average climate data significantly underpredict the depth of leaching. Daily precipitation and ET measurements produced a much more reliable prediction of depth of wetting. Obviously daily climate data are not available in all locations, nor are they available for pedologically significant time periods.

Nonetheless our results clearly show that estimates of the depth of wetting based on long-term average data are very conservative and probably lead to inaccurate conclusions about environmental conditions under which many soils on old central California landscapes formed. We speculate that many of the properties of Xeralfs on Pleistocene-age landscapes in California's Central Valley are the result of weathering under conditions very similar to current conditions. These weathering processes may have been enhanced if cooler and wetter conditions prevailed during the Pleistocene.

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References

Amoozegar, A. 1989. A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone: comparison of the Glover solution with the simultaneous-equations approach for measuring hydraulic conductivity. Soil Science Society of America Journal 53:1356-1367.

Andrews, W.F. 1972. Soil survey of Yolo County, California. USDA-NRCS, U.S. Gov. Print. Office, Washington, DC.

Arkley, R.J. 1963. Calculations of carbonate and water movement in soil from climatic data. Soil Science 96:239-248.

Brasher, B.R., J. Favre, R.B. Grossman, and D.S. Harms. 1993. Evaluation of a model for computation of estimated hydraulic conductivity from standard interpretation records - Draft 3. National Soil Survey Laboratory, National Soil Survey Center, Lincoln, NE.

Busacca, A.J., M.J. Singer, and K.L. Verosub. 1989. Late Cenozoic stratigraphy of the Feather and Yuba rivers area, California, with a section on soil development in mixed alluvium at Honcut Creek. USGS Bull. 1590-G. U.S. Gov. Print. Office, Washington, DC.

Department of Water Resources. 1995. CIMIS online reference. Sacramento, CA.

Jackson, L.E., R.B. Strauss, M.K. Firestone and J.W. Bartolome. 1988. Plant and soil nitrogen dynamics in California annual grassland. Plant and Soil 110:9-17.

McFadden, L.D. 1988. Climatic influences on rates and processes of soil development in Quaternary deposits of southern California. In Paleosols and weathering through geologic time (W.R. Sigleo and J. Reinhardt eds.). Geological Society of America Special Paper 216:153-177.

Munk, L.P. 1993. Stratigraphy, geomorphology, soils and neotectonic interpretation of the Dunnigan Hills, California. Ph.D. thesis, Univ. of California, Davis.

National Oceanic and Atmospheric Administration. 1995. Climatological data: California. Available on CDROM distributed by Hydrosphere Data Products, Inc., Boulder, CO.

Ritter, E.W., and B.W. Hatoff. 1977. Late Pleistocene pollen and sediments: An analysis of a central California locality. The Texas Journal of Science 24:195-207.

Soil Survey Staff. 1968. Technical Note - Soils - 15: Table for computing available water-holding capacity. USDA-SCS, Berkeley, California.

Soil Survey Laboratory Staff. 1996. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, Version 3.0. USDA-NRCS. Lincoln, NE.

Snyder, R.L. and W.O. Pruitt. 1994. Eto: User's guide and program documentation. Land, Air and Water Resources, University of California, Davis.

Thomas, J. 1996. Predicting leaching potential of current and historic climates on three soils in the Dunnigan Hills, California. M.S. Thesis, University of California, Davis.