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PAST CLIMATE RECONSTRUCTION: A TOOL FOR ASSESSING SITE SUITABILITY

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FOREWORD

This paper presents the most recent information regarding the reconstruction of past climate. Its purpose, as part of the Waste Management Program, is to aid in the evaluation of different regions of the U.S. as potential nuclear waste repositories.

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CONTENTS

Foreword	iii
Abstract	vii
Introduction	1
Regional Precipitation Changes in the Near Future (0 to 350 Years)	2
Future Work With The Near-Term Climate Estimates	13
Longer-Term Climate Variations	17
References	19

LIST OF ILLUSTRATIONS

1. Computer-generated map of the conterminous United States, showing the 11 regions adopted for study and the 96 stations from which meteorological data were gathered	4
2. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 1 (Columbia Basin) for the period 1602-1900, using 1901-1960 as a control period	5
3. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 3 (Intermountain Basins) for the period 1602-1900, using 1901-1960 as a control period	6
4. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 4 (Southwest Deserts) for the period 1602-1900, using 1901-1960 as a control period	8
5. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 6 (Southern High Plains) for the period 1602-1900, using 1901-1960 as a control period	9
6. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 9 (Great Lakes and Midwest) for the period 1602-1900, using 1901-1960 as a control period	10
7. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 10 (Southeast) for the period 1602-1900, using 1901-1960 as a control period	11
8. Crop-specific soil model (adapted from Terjung and O'Rourke, 1978), showing the flow of water through the model	16

ABSTRACT

Reconstructing past climatic variations can lead to a better understanding of possible future precipitation and groundwater recharge patterns. Work so far has led to several new insights into past climate variability and will provide input into the hydrologic modeling effort in progress for the Waste Management Program. Short-term reconstructions (0 to 350 y) suggest that the basin and range and the southwestern United States have the driest, least variable precipitation record. The Pacific Northwest shows higher variability and several trends lasting for more than 25 y. The Southern High Plains have even more variability, but the upper Midwest and Southeast vary most and have with the highest precipitation amounts. Future work will investigate the connection between precipitation variability and groundwater recharge.

Longer-term estimates of precipitation and groundwater will provide information about the warm hypsithermal period (6000 y ago). Pollen and lake level data from the literature suggest that the Southwest was wetter during at least part of the last glacial maximum than it is today.

INTRODUCTION

Detailed reconstruction of past regional climate variations is subject to much uncertainty, as is the extrapolation of this information to provide groundwater recharge values for studies of waste management site suitability. Nonetheless, during the past year, we have managed to piece together a fascinating view of the climate change in the continental United States that has occurred during the past 10 000 y. We also are beginning to understand how to assess the effects these changes might have on underground water flow in the source regions.

To date, two approaches have been used to reconstruct past precipitation amounts. Both are site independent and contain the type of variation that is representative of the past 18 000 y. Potter (1978) demonstrated that, for all practical purposes, the past 18 000 y contained most of the climatic variability that could be expected to occur in the next 10^6 y. We can expect wet and dry periods, as well as glaciations, throughout this time span. Using past climates to predict the magnitude of these future variations, their duration, and their regional distribution (and effect on recharge) is the object of this subtask. The choice of two time scales has been controlled primarily by the availability of data. The first method discussed below predicts the near-term climate change (0 to 350 y, 1-y resolution), whereas the second concerns longer-term climate change (1000 to 20 000 y, 500- to 1000-y resolution).

REGIONAL PRECIPITATION CHANGES IN THE NEAR FUTURE (0 to 350 YEARS)

Fortunately, tree rings provide a reliable source of data for reconstructing the climate of the past 350 y. They provide information about seasonal variations, and they are available for all regions of interest (Fritts, 1976; Fritts and Lofgren, 1978). As noted by Potter (1978), the past 350 y encompass a cool period called "the little ice age." Although no new continental glaciers developed, many existing glaciers advanced, and the civilized regions of the world apparently experienced a cooling trend that lasted several hundred years. Of the various proxy methods of determining past climates, the most detailed is the record obtained from tree rings. Ring widths respond in size and structure to environmental conditions; therefore, by sampling numerous rings in a region and determining the similar synchronous growth features in a large number of trees, investigators can date the rings and construct time series that correspond to climate fluctuations for that region. By comparing these time series to meteorological data from the 20th century, we obtain a transfer function that can then be applied to past and present yearly values of tree growth to reconstruct climatic variations. The reconstructions for the past can be compared to those for the present to obtain a measure of past anomalies in the climate.

One important variable in using tree ring estimates of climate is the choice of the control period. Since the earth has experienced minor changes in climate throughout the past 60 y, the choice of the control period (the period with which we compare the past climate variation) will influence the comparative magnitude of the past deviations of various climatic parameters. For instance, the period 1900-1930 was wet, with a warming trend, whereas 1930-1960 was dry and warm, with a cooling trend. The control period used for comparisons in this report (1900-1960) tends to be biased toward a warm climate.

The University of Arizona Laboratory for Tree Ring Research, under subcontract to the Waste Management Program, has provided regional estimates for 25- and 100-y precipitation averages for the past 350 y. Figure 1 shows the regional boundaries adopted in this study, together with the location of the meteorological data sources. The data for the areas west of the dashed line are somewhat more reliable than those for areas to the east.

For each of the regions of interest to the program (in terms of possible repository location), we now have estimates of the annual precipitation averaged for 25-y periods, the maximum annual precipitation during each period, the minimum annual precipitation during each period, and the probabilities of these occurrences based on the distribution of the control period and the reconstructed period. Figure 2 shows the precipitation data for Region 1 (Columbia Basin). Generally, the mean precipitation shows a slight downward trend from a considerably wetter period (1602-1625 to 1676-1700). One interesting feature is that the wettest single year (the maximum) appears to be during the most recent reconstructed interval (1876-1900). For the control period, the mean was 631 mm/y, the maximum was 975 mm/y, and the minimum was 332 mm/y. This emphasizes again that the period 1876-1900 had much more precipitation than periods before or after. The largest anomaly in the mean (for 1626-1650), which is 18% greater than the mean of the control period, could be described as a positive pulse with a duration of 25 y, for the hydrologic modeling effort in Task II. The data also suggest that the Columbia Basin was generally wetter in the past. One should keep in mind, however, that this region includes the humid western Washington area.

Figure 3 shows the reconstructed precipitation for Region 3 (Intermountain Basins, which includes the Nevada Test Site area). The most interesting feature of these data is the absence of large variations during the reconstructed period. On the average, the past 300 y were 6% drier than the present (1901-1960), and no significant positive pulses are obvious in the data. This arid land precipitation distribution (of 25-y averages) does not have the wide oscillations we often think of as characteristic of arid regions. However, if we were to examine more carefully the yearly variations in precipitation, the data would likely show considerably more year-to-year

FIG. 2. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 1 (Columbia Basin) for the period 1602-1900, using 1901-1960 as a control period.

FIG. 3. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 3 (Intermountain Basins) for the period 1602-1900, using 1901-1960 as a control period.

variation. Dry regions tend to have years with anomalous precipitation amounts, but when averaged over a somewhat longer period, these variations tend to be obscured. For the Intermountain Basins, the standard deviation for the control period is about 50 mm/y, and for the reconstructed period, it is 44 mm/y. This suggests somewhat less variation in the past than during the present period.

Data for Region 4 (Southwest Deserts) are shown in Fig. 4. The variations and amounts appear to be much the same as presented in Fig. 3 (Intermountain Basins), although the past 100 y seem to have somewhat more variation than the Intermountain Basins. Although the mean precipitation for the Southwest Deserts during the reconstructed period is less than that for the Intermountain Basins, the standard deviation is 65 mm/y, whereas for the control period, it is 60 mm/y. If we were interested in an arid region with minimum short-term climate variation (350 y), the Intermountain Basins would seem to be more suitable than the other arid and semiarid regions discussed so far. Assuming that groundwater flow is somewhat responsive to 25- to 50-y changes in precipitation, a repository location based on the present hydrologic situation in the Southwest Deserts would have a relatively high probability of less, not more, groundwater flow in the near future.

The Southern High Plains (Fig. 5) show somewhat more variation than Regions 1, 3, or 4, and the mean precipitation during the past appears to be less than that during the present period (1901-1960).

Moving away from the arid regions to the Great Lakes and Midwest (Fig. 6), we find much greater precipitation amounts, but the amounts average only 1% greater than present-day precipitation. However, the standard deviation of the reconstructed period is higher than that of the control period. Therefore, for the upper Midwest region, the mean of the control period is a relative good estimator of past precipitation amounts, but the control period provides a poor estimate of the year-to-year variability in the past.

Figure 7 shows the precipitation estimates for the Southeast (including the Gulf Coast). Large variations were reconstructed, averaging 7% higher than the mean for the control period. Year-to-year variations were 9% greater in the past.

FIG. 4. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 4 (Southwest Deserts) for the period 1602-1900, using 1901-1960 as a control period.

FIG. 5. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 6 (Southern High Plains) for the period 1602-1900, using 1901-1960 as a control period.

FIG. 6. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 9 (Great Lakes and Midwest) for the period 1602-1900, using 1901-1960 as a control period.

FIG. 7. Twenty-five-year maximum, mean, and minimum reconstructed precipitation (mm/y) for Region 10 (Southeast) for the period 1602-1900, using 1901-1960 as a control period.

These precipitation reconstructions, developed by the Tree Ring Laboratory, should be viewed as tentative indications of past variation and not as absolute indicators. The main purpose here is to explore the possible variations of precipitation in the recent past and to use these numbers as scenario inputs for the hydrologic models developed and used by the Waste Management Program. Fritts and Lofgren (1978) discuss the detailed methods of data collection and the statistical techniques, and the regional time series code is given by DeWitt (1979).

FUTURE WORK WITH THE NEAR-TERM CLIMATE ESTIMATES

The Laboratory for Tree Ring Research will continue with recalibration and verification of precipitation models. This will provide the Waste Management Program with a second, improved estimate of climate, allowing a measure of the variation due to differences in modeling procedures.

In addition to the improvements currently underway, we have been considering methods of extending the precipitation estimates to actual recharge amounts. One suggestion by the Tree Ring Laboratory is to use the methods described by Palmer (1965). The Palmer drought index was designed to "develop a general methodology for evaluating the meteorological anomaly (drought) in terms of an index which permits time and space comparisons of drought severity." The data needed to assess the drought and all of the associated parameters (including recharge) consist of temperature, precipitation, and the available water capacity of the soils in the area under consideration. The entire technique appears to be a simplistic approach, but given the type of data we have for the reconstructed climates, this is probably the most rewarding methodology.

To calculate the desired recharge values we start with:

$$PE = 1.6 (10t_i/I)^a,$$

where

- PE = potential evapotranspiration, in cm: transfer of water vapor from the surface under ideal conditions of soil moisture and vegetation (Landsberg, 1969).
- t_i = monthly temperature in $^{\circ}\text{C}$.
- I = heat index: $(t_i/5)^{1.514}$.
- a = characteristic of region.

By using the standard temperature values in the determination of PE, we can begin to calculate a hydrologic budget:

$$L_s = S'_s \text{ or } (PE - P), \text{ whichever is smaller,}$$

and

$$L_u = (PE - P - L_s) \frac{S'_u}{AWC} \text{ (thus, } L_u \leq S'_u \text{) ,}$$

where

L_s = moisture loss from surface layer.

S'_s = available moisture stored in surface layer at start of month (or any time period).

P = precipitation for the period.

L_u = loss from underlying levels.

S'_u = available moisture stored in underlying levels at start of period.

AWC = combined available capacity of both levels.

The AWC term varies markedly from soil to soil but can be taken for our purposes to be a value that is more or less representative of a given region.

We can now compute three potential values. First,

$$PR = AWC - S' ,$$

where

PR = potential recharge: the amount of moisture required to bring the soil to field capacity.

S' = amount of available moisture in both layers of the soil at the beginning of the period.

Second,

$$PRO = AWC - PR ,$$

where

PRO = potential runoff (when the soil becomes saturated, yet precipitation is low--i.e., runoff is not as large as expected).

Finally,

$$PL = PL_S + PL_U ,$$

where

PL = potential loss: the amount of moisture that could be lost from the soil provided the precipitation during the period is zero.

$PL_S = PE$ or S'_s , whichever is smaller.

$PL_U = (PE - PL_S)S'_u/AWC$.

Another approach might be to use a more complete model of water movement through soil, as discussed by Terjung and O'Rourke (1978). Figure 8 shows the flow of water through the system. With appropriate choices for the type of vegetation in the catchment basin (much simpler than shown in Fig. 8), it would be possible to trace the effect of large changes in precipitation on the groundwater.

FIG. 8. Crop-specific soil model (adapted from Terjung and O'Rourke, 1978), showing the flow of water through the model.

LONGER-TERM CLIMATE VARIATIONS

Under contract with the Waste Management Program, Brown University will help provide estimates of precipitation and groundwater variations for the past 20 000 y at 1000-y intervals. Brown University plans to review the literature on pollen variation and lake level variations in terms of their response to past climate changes. Methods will also be reviewed that will help with the reconstruction of past precipitation and groundwater recharge patterns. These methods are similar to those developed by Fritts (1976), but considerably fewer data are available. The contract also calls for both improved estimates of reconstructed precipitation patterns for the past 10 000 y and more complete water balance information for the reconstructed period.

The longer-term reconstruction of climate is actually built around three related approaches. The first is the estimation of past groundwater changes for the western United States that were associated with Lake Bonneville and Lake Lahontan between 10 000 and 20 000 y ago. The sizes of these lakes in the past indicate dramatic changes in groundwater since then. Brown University and others are developing techniques to use these lake level variations as indicators of past precipitation, although calibration with the detail used by the University of Arizona is not possible.

The second type of reconstruction uses tested and established methods (Webb and Bryson, 1972; Webb and Clark, 1977; Howe and Webb, 1977). Pollen taken from lake cores can be used as indications of past vegetation assemblages, allowing reconstructions of precipitation in Minnesota and Michigan, along the lines developed at the University of Arizona Laboratory for Tree Ring Research. Much of the work will involve refining and testing these techniques to improve the estimates and to provide new estimates as new data become available.

The third approach is a literature survey of existing pollen and lake level estimates that will give us insights regarding the possible range of

precipitation in regions of interest to the Waste Management Program. An evaluation of this sort, dealing with pollen data from eastern Washington, is currently underway and will be incorporated into a future update of this report.

Dr. T. Webb of Brown University has provided the program with new estimates of precipitation 18 000 y ago. This estimate will be published soon (Peterson et al., 1979). It suggests that, during the last glacial maximum, much of the western and southwestern United States was wetter than it is today. This is contrary to the modeling results shown in the summary by Potter (1978) and suggests that more effort should be directed toward the maximum glacial precipitation patterns.

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