# Sensitivity of Ground-Water Recharge Estimates to Climate Variability and Change, Ellensburg Basin, Columbia Plateau, Washington

By J. J. Vaccaro

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# CONVERSION FACTORS AND VERTICAL DATUM

| *Multiply inch-pound units* | *By* | *To obtain metric units* |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| acre | 4,047 | square meter |
| | 0.4047 | hectare |
| square mile ($mi^2$) | 259.0 | hectare |
| | 2.590 | |
| inch per year (in/yr) | 2.54 | centimeter per year |

**Sea level:** In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

# SENSITIVITY OF GROUND-WATER RECHARGE ESTIMATES TO CLIMATE VARIABILITY AND CHANGE, ELLENSBURG BASIN, COLUMBIA PLATEAU, WASHINGTON

By J. J. Vaccaro


## *ABSTRACT*

*The sensitivity of ground-water-recharge estimates to observed, synthetic, and projected climatic regimes is investigated for the semiarid Ellensburg basin, located in west-central Washington on the Columbia Plateau. The recharge was estimated for predevelopment land-use conditions (native plant communities) and current (1980's) land-use conditions (irrigated agricultural crops) using a daily energy-soil-water balance model (a recharge-estimation model).*

*Results of a previous study, based on climatological data for three weather stations for the 22-year period 1956-77, were compared with values calculated by the recharge-estimation model using climatological data from a single weather station and from a stochastic synthetic daily-weather-data generation model. The parameters for the synthetic daily-weather-data generation model were based on the 1956-77 data from the single weather station. Long-term average annual recharge for predevelopment conditions was about 6 percent less for the single-station simulation, and about 20 percent less for the single-station synthetic data simulation, than the results of the previous study. Long-term annual average recharge for current conditions was about 3 percent less for the single-station simulation and about 7 percent less for the synthetic data simulation. The large difference produced by the synthetic data for the predevelopment simulation results from the inability of the generation model to approximate wet extremes; the results indicate that predevelopment recharge is sensitive to these extremes. Current conditions are not as sensitive because of the large quantity of applied irrigation waters.*

*The recharge-estimation model was operated under simulated predevelopment and current land-use conditions for 87 years (1901-87) using three sets of climatological data. The first set was 87 years of historical climatological data and the second two sets varied the historical data according to averages and maximums projected by three general circulation models (GCMs). Recharge for predevelopment conditions for the native plant communities was shown to increase under average GCM climate change. Recharge for current conditions for irrigated agricultural crops was reduced under the average GCM climate change. For the maximum GCM climate change, recharge for both land-use conditions was reduced from the 87-year average: 0.73 inch less per year for predevelopment conditions and 3.48 inches less per year for current conditions.*

# INTRODUCTION

Numerical ground-water flow models commonly are used to examine the potential effects of current and proposed water development. The potential effects of ground-water development and stresses commonly are projected 10 to 100 years into the future. Estimates of ground-water recharge used for defining the ground-water flow system during the construction of the model are generally based on current and (or) recent historical climatic conditions and commonly are assumed to be invariant during the model projection. However, simulation results for many ground-water models are sensitive to the distribution and rate of ground-water recharge. Additionally, the assumption of stationary climatic conditions is probably reasonable for projections of 10 to 20 years, but beyond that, errors could arise from such an assumption (Stockton and Boggess, 1979). Thus, a potential complicating factor in making long-term predictions of ground-water conditions is the uncertainty of recharge estimates when climate varies.

Ground-water recharge was estimated under predevelopment and current (1980's) land-use conditions for 53 drainage basins and zones in the Columbia Plateau in parts of Washington, Oregon, and Idaho (fig. 1) as part of the U.S. Geological Survey's Columbia Plateau Regional Aquifer-System Analysis (RASA) (Bauer and Vaccaro, 1990). Predevelopment land-use conditions represent the native plant communities that existed before the area was settled: forest, grasslands (annual and perennial), and sagebrush. Current land-use conditions represent the land-use conditions that exist today (1980's) in the basin, and were obtained from analysis of Landsat data for the Columbia Plateau (Wukelic and others, 1981) and field mapping of irrigated crops by RASA personnel. Generally, the current land uses represent the conversion of sagebrush-covered rangeland to irrigated croplands and to commercial and residential lands, and the conversion of grasslands to irrigated and dryland croplands.

The recharge estimates were derived from a deep-percolation model (DPM) of Bauer and Vaccaro (1987). This energy-soil-water balance model calculates, for each of any specified number of cells in a basin, daily quantities of water percolating to below the root zone. These estimates, averaged over the 1956-77 period, were assumed to be the constant ground-water recharge rate. They were used later as input to a regional ground-water flow model constructed to represent the aquifer system.

The estimated year-to-year variability in ground-water recharge for predevelopment conditions for the 53 basins, represented by the Ellensburg basin (fig. 2), raised the questions of the suitability of the length of, and variability in, the 1956-77 climatic period chosen for the analysis. Additionally, the sensitivity of the recharge estimates to both a different period of record and a different, but equally probable, sequence of climatological data, is believed important for understanding the sensitivity of recharge to climate variability. Last, the effect of climate change caused by global warming, or the "greenhouse effect", needed consideration because the ground-water model might be used for projection over long periods of time.

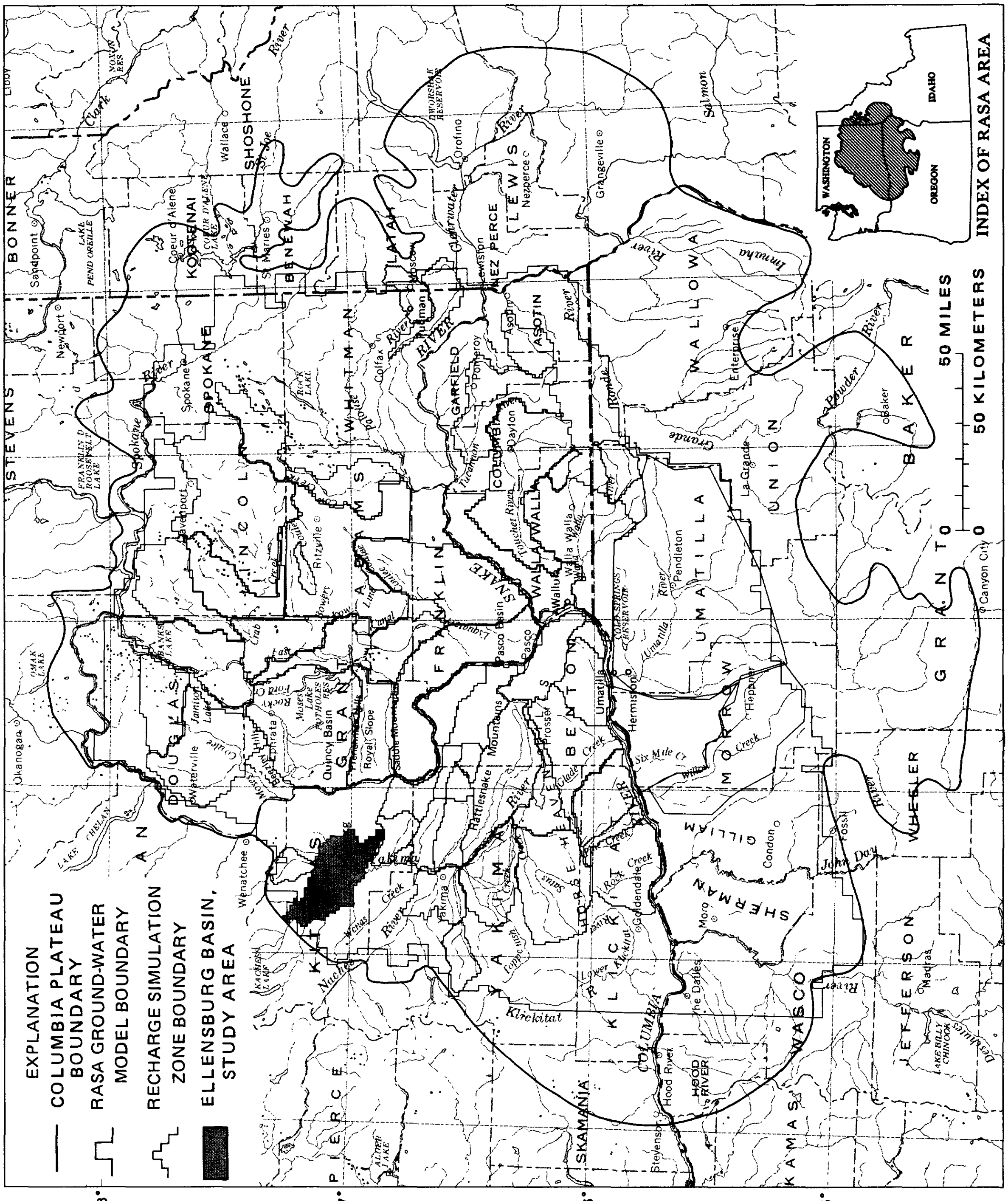


Figure 1.--Location of study area.

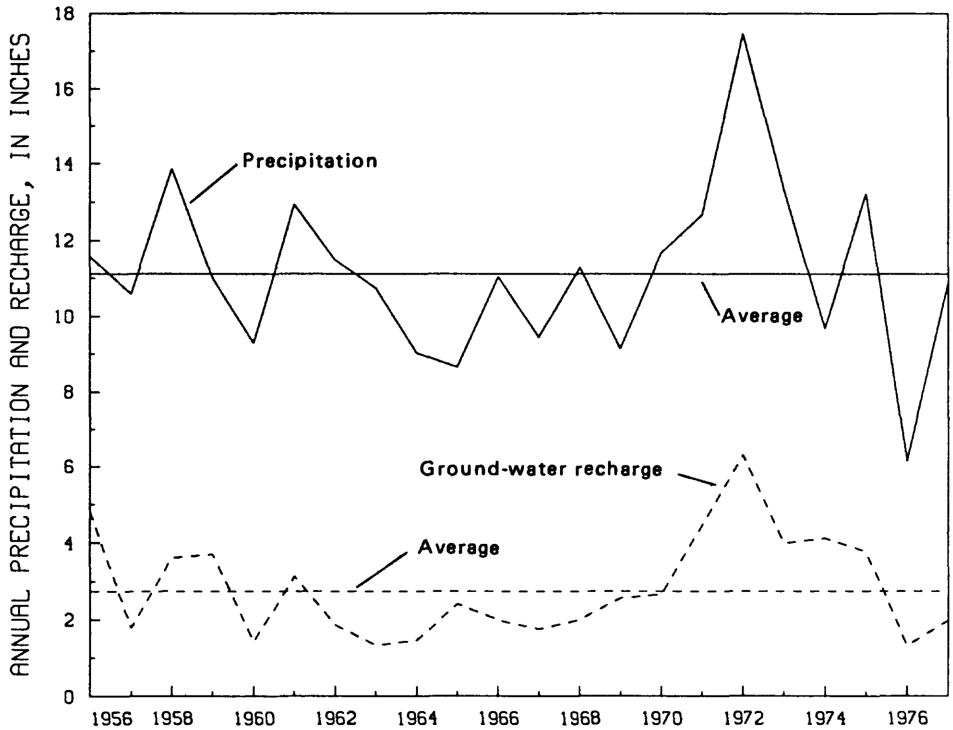


Figure 2.--Annual precipitation and recharge under predevelopment land-use conditions for the Ellensburg basin for the period 1956-77.

Several factors should be noted that relate to this investigation. Much of the area included by the study of Bauer and Vaccaro (1990) is arid to semiarid. Such areas encompass a large part of the economically important agricultural lands of the western United States. The assessment of the effect of climate variability on water resources, and in particular on ground-water recharge, needs to be studied at a reasonably fine scale because water use and allocation, soils, and crops vary greatly, both locally and regionally. For example, Bauer and Vaccaro (U.S. Geological Survey, written commun., 1986) found that discretizing arid and semiarid zones on the Columbia Plateau into cells greater than about 1 square mile resulted in gross underestimation of recharge. Using a larger cell size requires using average or statistically representative values for model input parameters for plant type, root depth, soil characteristics, irrigation application rates, foliar cover percentages, and plant interception capacities. However, these average values did not produce representative recharge computations, and the sensitivity of the net basin recharge to model parameters increased as cell size increased. Thus, for estimating recharge, plant community and soil properties can be spatially aggregated only to scales on the order of 1 mile. The sensitivity to aggregation probably will increase for analyses of lower latitude arid and semiarid regions, where potential evapotranspiration is larger and the importance of unique combinations of plants and soils increases.

In a complete analysis of ground-water recharge, surface-water runoff must be determined and subtracted from moisture that otherwise would enter the root zone. For this comparative sensitivity study, the surface-water runoff component of the water balance is assumed to be negligible. Using this assumption probably produces recharge estimates for current conditions that are better than those for predevelopment conditions. This is because during the summer, applied irrigation water generally exceeds potential evapotranspiration (PET), and actual evapotranspiration (AET) thus equals PET, eliminating other approximations that account for soil-moisture deficits. The latter is believed to be the reason that the estimates of recharge for current conditions are more robust than the predevelopment estimates, as shown later in this report.

## Background

Bauer and Vaccaro (1986) showed that, for at least part of the Columbia Plateau, the use of monthly values of precipitation cannot account for the estimated variability in the recharge and usually results in the underestimation of recharge. The latter factor concurs with the work of other investigators (Alley, 1984; Howard and Lloyd, 1979; Rushton and Ward, 1979; Giambelluca and Oki, 1987; Stephens and Knowlton, 1986; Gee and Kirkham, 1984). Thus, daily climate records are necessary for most analyses of ground-water recharge variability, and it is best to use the longest daily historical climate records within the Columbia Plateau. Only one relatively long climate record was available (near Ellensburg, Wash.) within one of the 53 basins previously analyzed (fig. 1). The climate record and ground-water recharge for this basin were analyzed in this study.

The part of the Ellensburg basin included in the model (fig. 1) covers about 362 $mi^2$. The basin slopes gradually to its axis, over which the Yakima River flows. Altitudes in the basin range from about 1,500 feet to slightly more than 3,000 feet above sea level. Most of the basin lies between 1,600 and 3,000 feet, and the 2,000-foot contour line generally defines the transition from the flat-lying lowlands to the bordering uplands and mountains. Long-term annual precipitation in the basin ranges from about 7 to 25 in/yr. Predevelopment land use in the basin was estimated to be about 326 $mi^2$ of sagebrush-covered rangeland, 19 $mi^2$ of mixed grasslands, and 17 $mi^2$ of forests. Under current land-use conditions, about 193 $mi^2$ of the sagebrush was converted to irrigated croplands. Surface-water-irrigation application rates for the croplands generally range between 22 and 46 in/yr. For this study, the irrigation application rates are assumed to be constant for all years, and on the basis of 1980's information, the estimated average application rate is 17.43 in/yr.

## Purpose and Scope

This report presents the results of an investigation to provide insight into the sensitivity of recharge estimates to historical and synthetic climate variability and projected climate change. In this study, the climatic variability in the 87-year Ellensburg historical record (1901-87) was first analyzed, and then ground-water recharge for the Ellensburg basin was simulated using the DPM model for the 22-year period (1956-77) and the 87-year period. Previously, data from three weather stations were used to interpolate daily temperature and precipitation to the cells of the basin (Bauer and Vaccaro, 1990). Because data from only one station were going to be used in this study, the previous results were compared with the results of the 22-year single-station simulation and results using a 22-year synthetic generated climate record. The object of comparing results of the one-station and three-station simulations was not to examine the effects of spatial climate variability. The comparison was done to determine the potential error in the estimated recharge caused by the loss of information on spatial climate variability when using climatological data from only one station. The results of 87-year simulations incorporating projected climatic change derived from three general circulation models were then compared with the 87-year results calculated using the historical record.

The scope of this investigation was, thus:

(1) Analysis of the climatic variability in the 87-year historical climatological data and comparison of the 1957-77 variability with the 1901-87 variability; the analysis was done through graphical procedures, comparison of descriptive statistics, use of a stochastic synthetic daily-weather-data generation model, and spectral analysis.

(2) Effects of potential climate change were analyzed using results from three general circulation models. The results of the models were used to modify the historical 87-year climatological data. The modifications resulted in two 87-year climate change data series: one for an average projected climate change and one for a maximum water-deficit climate change.

(3) Recharge estimates for predevelopment and current land-use conditions for the 22-year period were compared with estimates made using data from one weather station, data from a stochastic daily-weather-data generation model, and data from the generation model that was reordered.

(4) Recharge was estimated for both land-use conditions using the 87-year historical climatological data. Results of these two simulations were then compared.

(5) Using the two modified 87-year data climate change sets, recharge was estimated for both land-use conditions. The results of those four simulations were compared with each other and with the results from the two simulations in (4) above.

(6) The generation model was used to generate 87 years of climatological data. The parameters in the model were based on the 1928-37 drought period climate data. The generated data then were used in the deep-percolation model to calculate 87 years of recharge for current land-use conditions. The results from this simulation were compared with the other simulation results.

# HISTORICAL CLIMATE VARIATIONS

The averages of the climate data for the 22-year and the 87-year historical period are summarized in table 1. The 22-year period was slightly wetter and the mean annual maximum and minimum air temperatures were about the same for both periods. However, several differences between the periods are apparent when the mean monthly and annual values are compared (table 1 and figs. 3-5). The extremes, especially below-normal extremes, were not as well represented in the shorter record. The longer record appeared to have some periodicity, and different periods within the long record appeared to be associated with different climatic regimes.

The apparent periodicity in the 87-year record was analyzed using standard spectral analysis techniques (Box and Jenkins, 1976; IMSL, 1987). The results of the spectral analysis indicate that much of the variance in the annual precipitation record occurs in periods of about 11, 5, and 2.7 years, and in the annual winter (November-February) precipitation record in periods of 11, 2.7, and 2.2 years. The variance in the annual temperature record occurs with periods of about 6.9, 4.8, 3.2, and 2.2 years. The annual temperature record also has a strong signal at about 32 years, but the record is too short to verify that periodicity. The results of the spectral analysis indicate that temperature and precipitation distributions are linked in a highly complex manner, and that the difference in periodicity between the two variables might result in different climatic regimes over time scales as short as a decade.

Table 1.--Averages of climate data for the periods 1956-77 and 1901-87

| Averaging period | Precipitation (inches) | | Maximum temperature (degree Fahrenheit) | | Minimum temperature (degree Fahrenheit) | |
|---|---|---|---|---|---|---|
| | 1956-77 | 1901-87 | 1956-77 | 1901-87 | 1956-77 | 1901-87 |
| January | 1.44 | 1.33 | 34.3 | 33.4 | 19.6 | 18.2 |
| February | .85 | .96 | 43.0 | 41.2 | 24.8 | 22.9 |
| March | .83 | .66 | 51.2 | 52.7 | 28.3 | 28.3 |
| April | .64 | .46 | 59.6 | 61.7 | 34.1 | 33.8 |
| May | .60 | .57 | 61.1 | 69.6 | 41.8 | 41.6 |
| June | .61 | .67 | 76.1 | 75.8 | 48.9 | 48.1 |
| July | .17 | .23 | 82.7 | 81.0 | 53.2 | 52.8 |
| August | .39 | .27 | 81.0 | 82.1 | 52.0 | 51.3 |
| September | .39 | .49 | 74.8 | 74.5 | 43.4 | 43.2 |
| October | .63 | .60 | 61.4 | 62.2 | 34.4 | 34.2 |
| November | 1.29 | 1.34 | 45.3 | 45.4 | 27.7 | 28.9 |
| December | 1.63 | 1.48 | 36.6 | 35.6 | 22.8 | 21.2 |
| Annual | 9.47 | 9.06 | 59.6 | 59.6 | 35.9 | 35.2 |

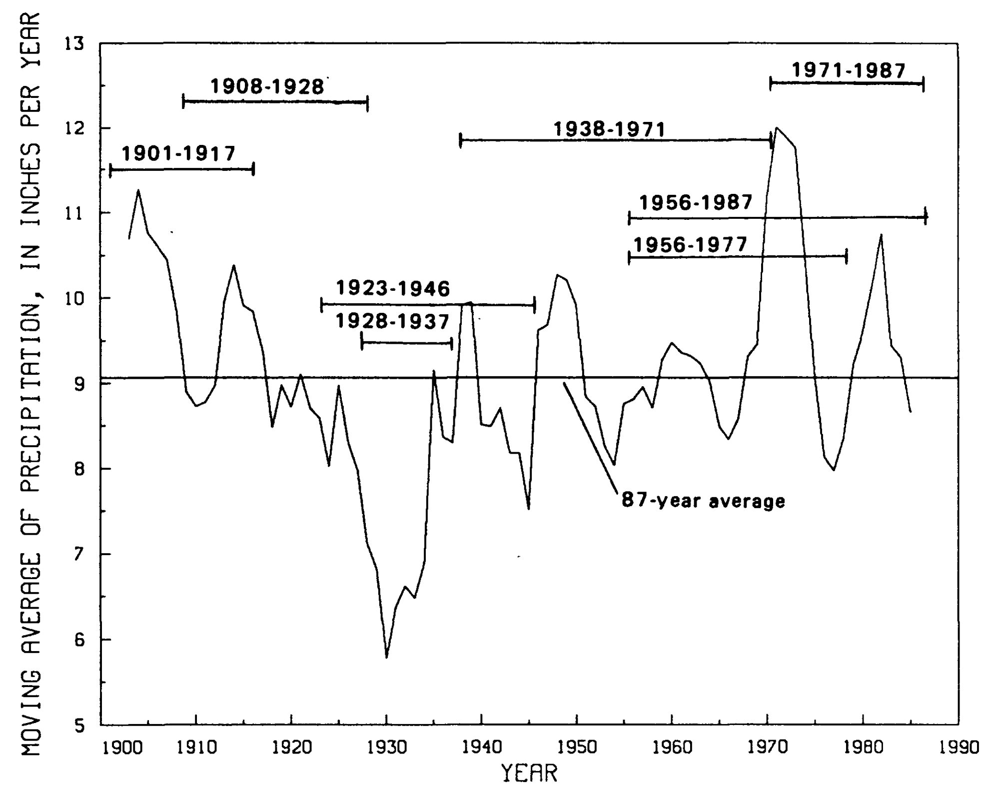


Figure 3.--Five-year moving average of annual precipitation and selected subsets of the historical record.

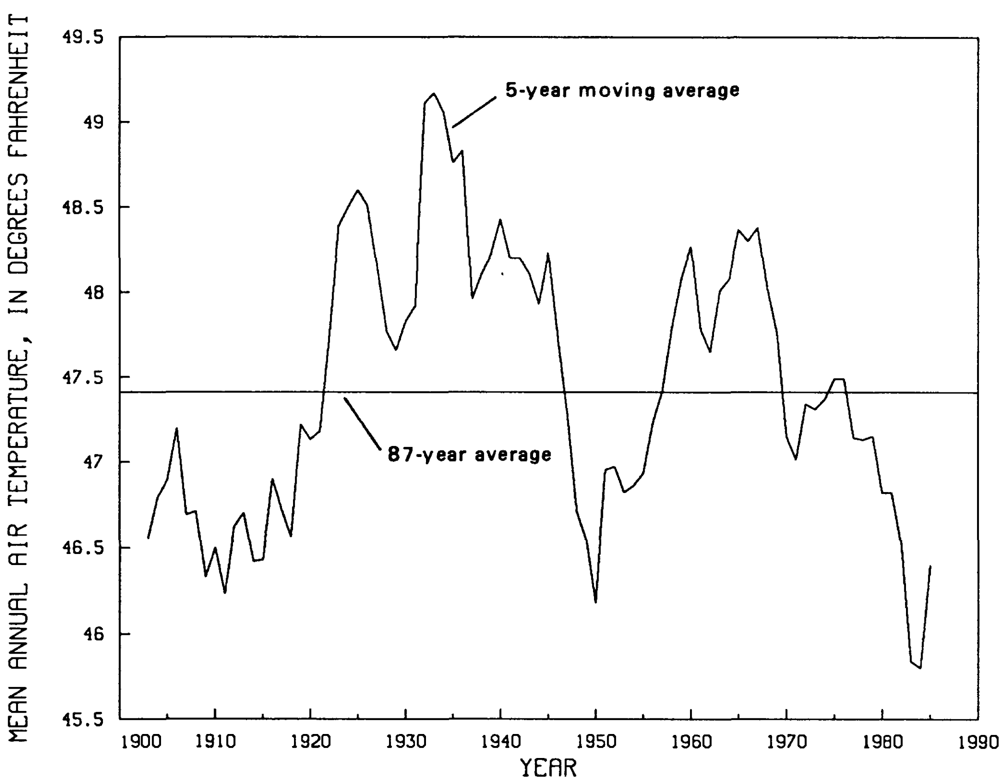


Figure 4.--Five-year moving average of mean annual air temperature.

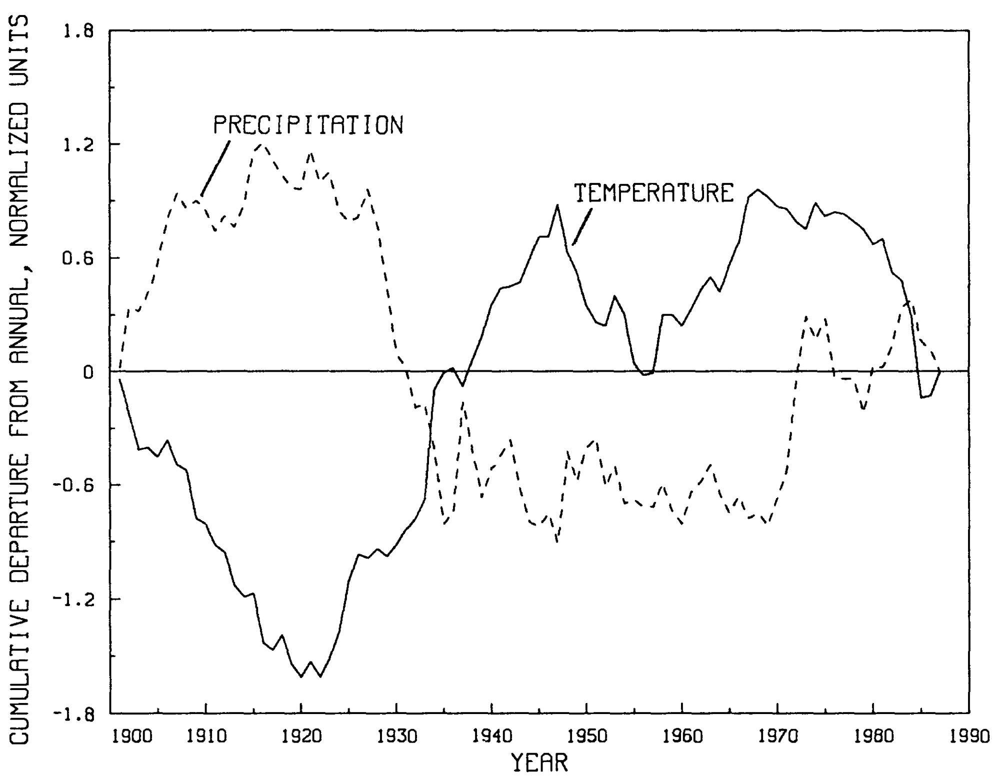


Figure 5.–Cumulative departure from average for precipitation and air temperature.

Eight selected subsets of the record and the complete record (shown in figure 3) were analyzed for the variability (different climate regimes) that occurred within the 87-year record. These subsets are periods for which the daily data are averaged. These same subsets are used as averaging periods for the analysis of ground-water recharge sensitivity. The delineation of subsets was based loosely on the annual precipitation distribution and on the concept of enveloping general climate trends. Variability within the historical record was analyzed using descriptive statistics (table 2), parameters generated from application of a stochastic synthetic daily-weather-generation model (Richardson and Wright, 1984), and simple graphical comparison.

The daily-weather-generation model (herein called the Richardson model) uses a first-order Markov chain with two states to define the occurrence of wet and dry days and a two-parameter gamma distribution to generate and describe the precipitation amounts on wet days. Daily maximum and minimum temperatures are conditioned on wet-dry day status. Seasonal variations in parameters are based on a single-component Fourier series.

The parameters of the Richardson model were fitted to the subset data, and the model preserved many statistical characteristics of the observed climate series for each subset. The probability of a wet day, given the previous day as either wet or dry for selected periods, shows that there were significant historical variations in the statistical characteristics describing the seasonality of the daily data (fig. 6). As another example, figure 7 shows the variation with time of phase and amplitude of the daily maximum air temperatures on wet and dry days, and daily minimum air temperatures on either wet or dry days. Although amplitude changes with time are represented by the mean values in table 2, the phase change (fig. 7) best shows the difference in temperature over the different subsets. The product of the temperature-phase coefficient and the number of days in the year defines when the maximum temperature occurs, and also approximates the average growing season; these values are given in table 2.

Table 2.--Descriptive statistics of the climate data for selected subsets of the historical record

| Years | Average annual precipitation (inches) | Maximum temperature: Average, Dry (degrees Fahrenheit) | Maximum temperature: Average, Wet (degrees Fahrenheit) | Maximum temperature: Growing season, Dry (days) | Maximum temperature: Growing season, Wet (days) | Minimum temperature: Average (degrees Fahrenheit) | Minimum temperature: Growing season (days) |
|---|---|---|---|---|---|---|---|
| 1901-1 | 10.0 | 60.1 | 55.7 | 174 | 165 | 33.9 | 187 |
| 1900-28 | 8.96 | 61.5 | 56.3 | 166 | 157 | 34.1 | 180 |
| 1928-37 | 7.47 | 61.8 | 55.9 | 189 | 190 | 35.8 | 186 |
| 1923-46 | 8.03 | 62.0 | 56.1 | 180 | 178 | 36.1 | 186 |
| 1938-71 | 8.92 | 60.6 | 55.6 | 186 | 185 | 35.9 | 197 |
| 1956-77 | 9.48 | 60.7 | 56.4 | 187 | 180 | 35.9 | 189 |
| 1956-87 | 9.37 | 60.5 | 56.5 | 181 | 174 | 35.4 | 178 |
| 1971-87 | 9.62 | 60.3 | 56.0 | 182 | 165 | 34.8 | 167 |
| 1901-87 | 9.07 | 60.8 | 55.9 | 180 | 175 | 35.2 | 186 |

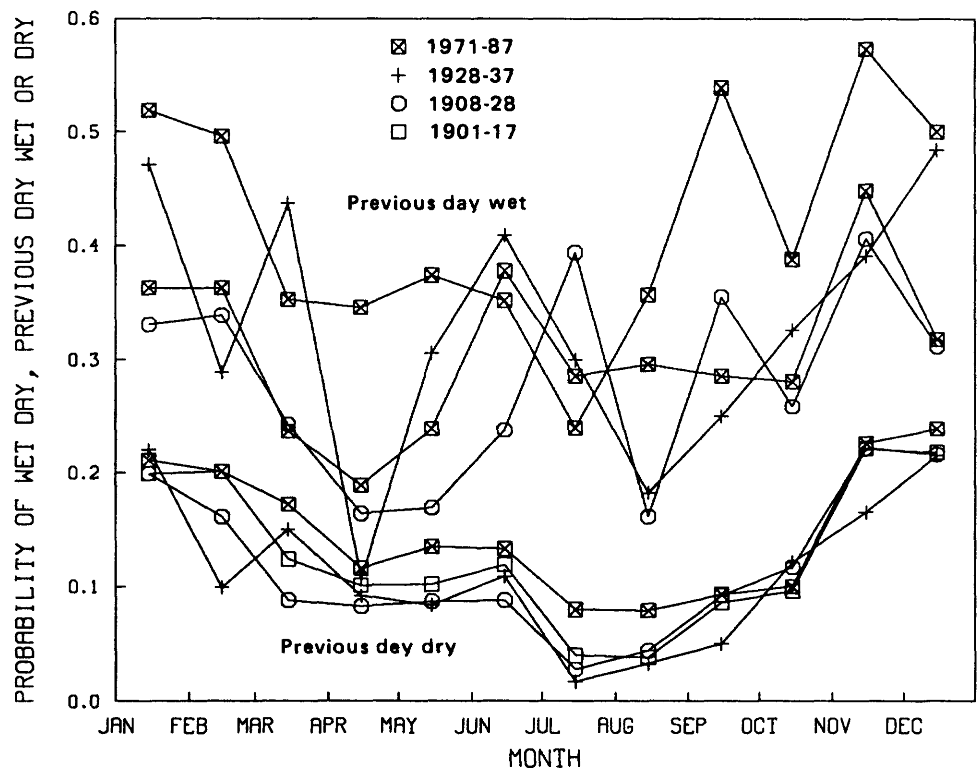


Figure 6.– Probability of a wet day, given the previous day as wet or dry, for selected periods.

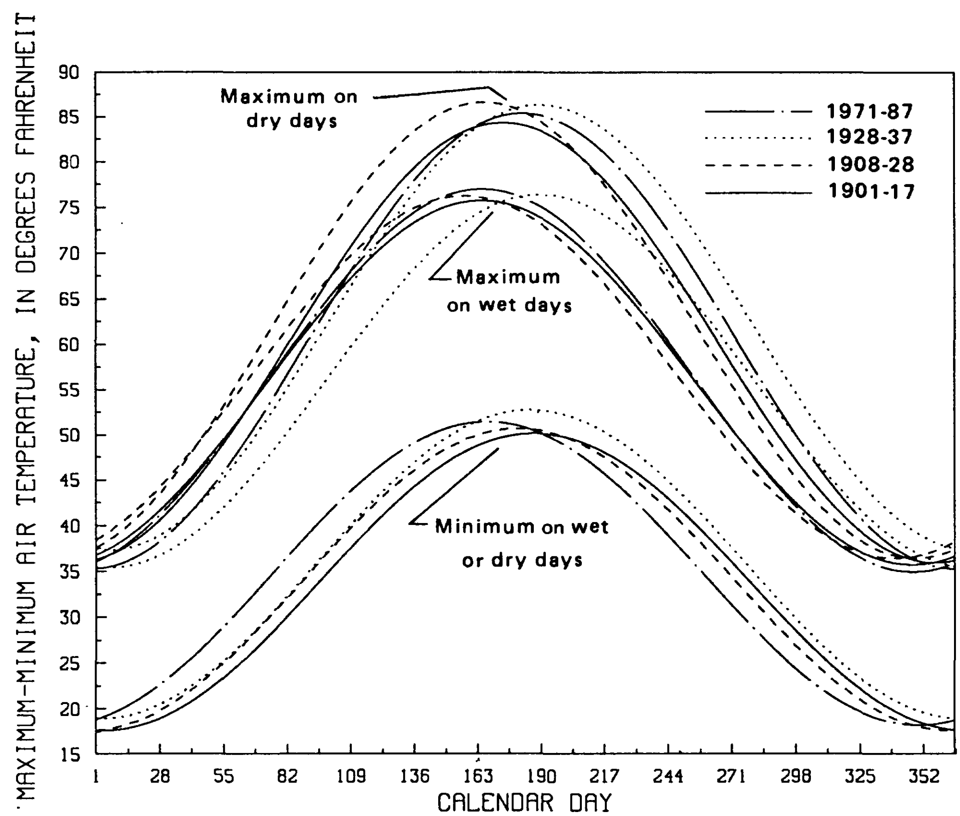


Figure 7.--Seasonal variation of daily maximum temperature on wet and dry days and daily minimum temperature on wet or dry days, for selected periods.

The cumulative departure of precipitation shows that net deficits have occurred over reasonably long periods; however, the 5-year moving averages (figs. 3 and 4) for both mean annual precipitation and temperature indicate that departures of temperature from average are generally more persistent than departures of precipitation. The analysis of historical climate data indicates the need to use long records to incorporate reasonable variability and persistence into recharge estimates, and the potential for incorrect interpretations of recharge estimated using subsets of the climatic record; for example, 1956-77 (fig. 5). For the Ellensburg basin, the climatic variability in the historical record indicates that about 20 years of historical record should be used for estimating recharge in order to encompass at least one climatic cycle; if there is a 32-year period in the annual temperature data, about 65 years of record should be used.

# SYNTHETIC CLIMATE VARIATIONS

The daily-weather-generation model of Richardson and Wright (1984) was used to estimate three sets of daily climate-model parameters from which three sequences of daily synthetic data were generated. The first set used data from 1956 to 1977 and was used to generate 22 years of synthetic data; the second used data from 1901 to 1987 and generated 87 years of synthetic data; and the third used data from 1928 to 1937 and generated 87 years of data. The first sequence was used to estimate recharge for comparison with recharge calculated by Bauer and Vaccaro (1990) using the 1956-77 data, and with recharge calculated in this study using only one station for the 1956-77 period. The second sequence was used to examine how well the Richardson model simulates relatively long records in order to estimate the suitability of long synthetic records. The last sequence was used as input to the DPM model as a first estimate of the potential effects of long-term persistence of the drought experienced during the 1928-37 period.

The Richardson model preserves many statistical characteristics of the historical data--means, number of wet days, runs of wet days, and lag-1, auto-, and cross-correlations. However, because it was not designed to preserve periodicity, spectral analysis was used to compare the spectral density and periodicity of the synthetic data and the historical data. The analysis confirmed that the occurrence of the variance of the record within certain periods was not preserved. Because the synthetic data would be used as an initial estimate of the sensitivity of recharge to an equally likely climatic sequence, they were ranked on the basis of the distribution of historical annual precipitation. For example, the ninth lowest annual precipitation for the period 1956-77 occurred in 1956, so the ninth lowest year of precipitation for the 22-year synthetic series was made to occur in 1956. Figure 8 shows cumulative departures from average precipitation for the 1956-77 period for historical, synthetic, and synthetic-ranked records (the latter two records being based on climate-model parameters derived from the data for 1956-77).

The 1901-87 synthetic record was also ranked. Spectral analysis showed that the ranked record reasonably preserved the periodicity of the precipitation data. However, both spectral analysis and the cumulative departures showed that ranking did not preserve the periodicity (or trends) for the 87-year synthetic air-temperature record as well as it did for the 22-year record. This was expected because air temperature is conditioned upon precipitation in the Richardson model and because periodicity of precipitation and temperature appear to be different. On the average, the model calculates cooler climate when it is wetter and warmer when it is drier, conditions that did not always happen in the historical climate record (fig. 5). This aspect of the historical record also is apparent from (1) the ranking of the year of occurrence of precipitation and temperature extremes (table 3), and (2) the relation between winter precipitation and summer temperature (fig. 9). Thus, the synthetic data set appears to be good if reordered and if its length is less than, or equal to, about twice the longest dominant period within the precipitation record. The 87-year record generated with the 1928-37 model parameters, and then reordered, was still believed to be suitable for studying the effects of a long-term drought.

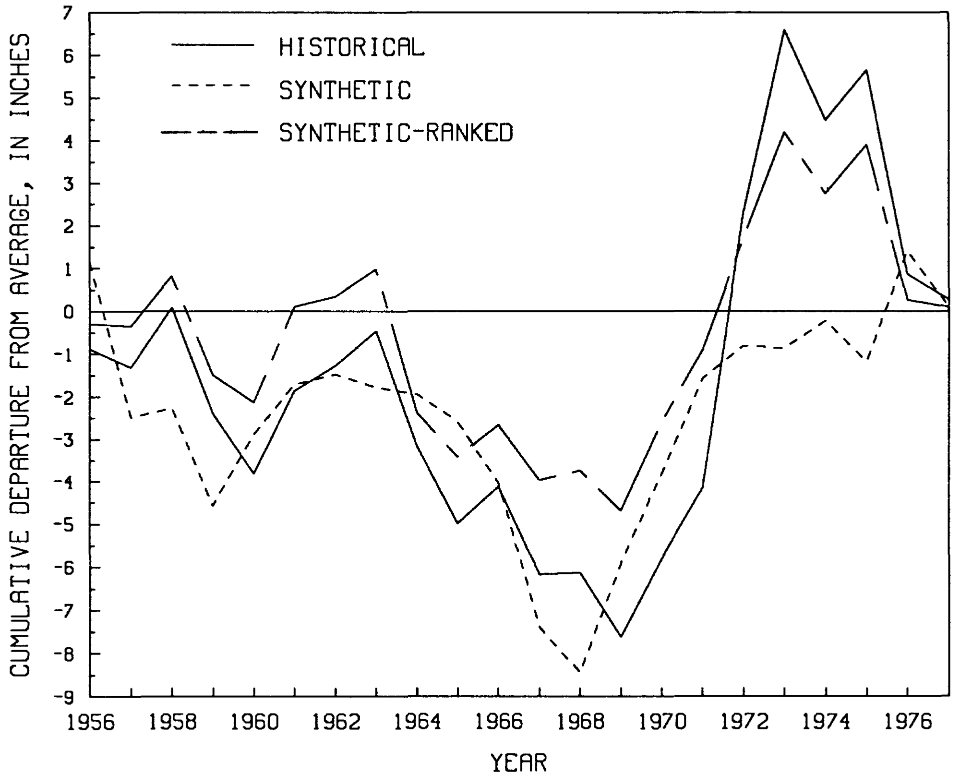


Figure 8.--Cumulative departure from average precipitation for historical, synthetic, and synthetic-ranked records, 1956-77.

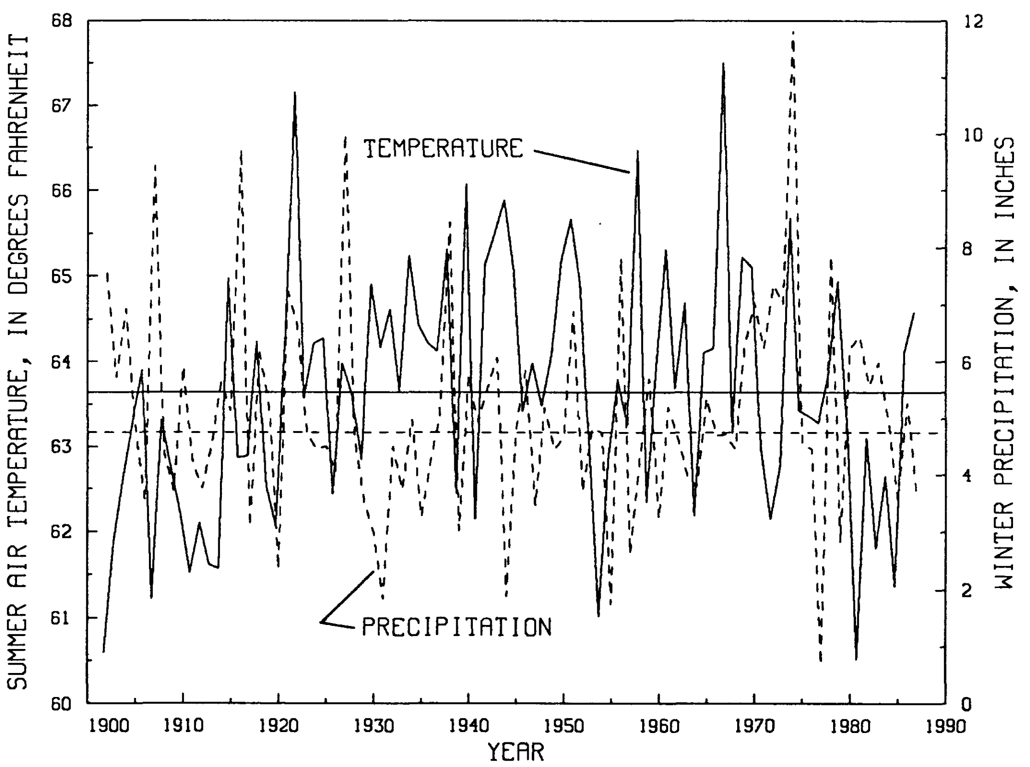


Figure 9.--Relation between winter precipitation and summer temperature.

Table 3.--Rank of year of occurrence of precipitation and temperature extremes

| Rank | Annual temperature | Annual precipitation | Summer temperature[1] | Winter precipitation[2] |
|---|---|---|---|---|
| | | A. Warmest-Driest | | |
| 1 | 1934 | 1935 | 1967 | 1976-77 |
| 2 | 1958 | 1930 | 1922 | 1954-55 |
| 3 | 1925 | 1929 | 1958 | 1930-31 |
| 4 | 1967 | 1976 | 1940 | 1943-44 |
| 5 | 1940 | 1939 | 1944 | 1919-20 |
| 6 | 1947 | 1952 | 1974 | 1956-57 |
| 7 | 1953 | 1943 | 1951 | 1978-79 |
| 8 | 1924 | 1938 | 1943 | 1929-30 |
| 9 | 1926 | 1934 | 1961 | 1938-39 |
| 10 | 1928 | 1985 | 1938 | 1916-17 |
| | | B. Coldest-Wettest | | |
| 78 | 1985 | 1983 | 1903 | 1920-21 |
| 79 | 1909 | 1921 | 1983 | 1971-72 |
| 80 | 1916 | 1906 | 1913 | 1901-02 |
| 81 | 1955 | 1980 | 1914 | 1955-56 |
| 82 | 1948 | 1915 | 1911 | 1977-78 |
| 83 | 1984 | 1902 | 1985 | 1937-38 |
| 84 | 1903 | 1973 | 1907 | 1906-07 |
| 85 | 1982 | 1972 | 1954 | 1915-16 |
| 86 | 1902 | 1948 | 1902 | 1926-27 |
| 87 | 1950 | 1937 | 1981 | 1973-74 |

[1] Average temperature for the period June through August.
[2] Precipitation for the period November through February.

# CLIMATIC VARIABILITY AND PROJECTED CLIMATIC CHANGES

Three methods are used in this study to investigate the sensitivity of ground-water recharge estimates to climatic variability and projected climatic change. The first uses the historical climate record and analyzes the effects of observed climatic variability on recharge estimates. The estimates of recharge calculated using the historical data are assumed to represent the range in recharge values that can be expected to occur in the future. Several problems exist with this method: the length of historical record, sequence of climatic variations, lack of information on the probability of reoccurrence of the historical climate, and the potential effects of global warming due to increased concentrations of radiactively active atmospheric gases (the greenhouse effect).

The second method uses climatic-change projections based on a doubling of $CO_2$ calculated by general circulation models (GCMs) (Lettenmaier and others, 1988; Singh, 1987). Although the GCMs cannot account for small-scale (regional and local) processes, their projections at least can be used for testing hydrologic sensitivities to climate change. That is, the GCMs provide perhaps the best available initial estimate of projected climate change due to increasing $CO_2$. Thus, GCM projections were used to evaluate the sensitivity of recharge due to potential climatic change.

The results from the GCMs, based on the doubling of $CO_2$ (D.G. Lettenmaier, University of Washington, written commun., 1988), were used to calculate changes in monthly values of precipitation and temperature (table 4). The changes in monthly values were based on average monthly changes in temperature and average monthly multiplying (scaling) factors for precipitation, and were applied to the observed daily data for each month of the 87-year record in order to modify the historical record for two scenarios. The three GCMs were the Goddard Institute for Space Studies model (GISS), the Geophysical Fluid Dynamics Laboratory model (GFDL), and the Oregon State University model (OSU). The first simulation was based on the average change projected by the three models (AVE-GCM). The second used the monthly changes from whichever model predicted the maximum 'water-deficit' effect; that is, the largest increase in monthly temperature and the largest percentage decrease in monthly precipitation (MAX-GCM).

The third method was 87 years of climatological data that were generated using the stochastic daily-weather-generation model. The generation model used parameters that were based on the 1928-37 drought period. This method investigates the possible long-term effects of the persistence of drought.

Table 4.--Projected monthly temperature changes and monthly precipitation multiplying factors calculated from three general circulation models for a doubling of atmosphere carbon dioxide

[GISS, Goddard Institute for Space Studies; GFDL, Geophysical Fluid Dynamics Laboratory; OSU, Oregon State University; Temp., projected monthly temperature change, in degrees Fahrenheit; Precip., projected monthly change in precipitation, as multiplying factor]

| | | Model[1] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | GISS.1 | GISS.2 | GISS.AV | GFDL | OSU | Average[2] | Maximum[3] |
| Jan. | Temp. | 11.92 | 10.24 | 11.08 | 7.63 | 1.40 | 6.70 | 11.08 |
| | Precip. | 1.42 | 1.23 | 1.33 | .92 | .95 | 1.07 | .92 |
| Feb. | Temp. | 8.86 | 9.11 | 8.59 | 7.99 | 4.39 | 7.12 | 8.59 |
| | Precip. | 1.46 | 1.16 | 1.31 | .80 | 1.18 | 1.10 | .80 |
| Mar. | Temp. | 12.69 | 8.60 | 10.78 | 9.76 | 2.34 | 7.63 | 10.78 |
| | Precip. | 1.22 | 1.52 | 1.37 | 1.32 | 1.22 | 1.30 | 1.22 |
| Apr. | Temp. | 6.64 | 9.27 | 7.96 | 9.83 | 4.79 | 7.53 | 9.83 |
| | Precip. | 1.34 | 1.02 | 1.18 | 1.06 | 1.36 | 1.20 | 1.06 |
| May | Temp. | 4.99 | 5.67 | 5.33 | 8.05 | 3.96 | 5.78 | 8.05 |
| | Precip. | 1.17 | 1.11 | 1.14 | 1.08 | .96 | 1.06 | .96 |
| June | Temp. | 5.99 | 7.20 | 6.60 | 9.47 | 6.28 | 7.45 | 9.47 |
| | Precip. | 1.34 | 1.44 | 1.39 | .57 | 1.37 | 1.11 | .57 |
| July | Temp. | 3.73 | 5.96 | 4.85 | 11.32 | 3.80 | 6.66 | 11.32 |
| | Precip. | 1.14 | 1.06 | 1.10 | 1.33 | 1.28 | 1.24 | 1.10 |
| Aug. | Temp. | 7.51 | 10.78 | 9.15 | 8.71 | 3.74 | 7.20 | 9.15 |
| | Precip. | 1.13 | 1.29 | 1.21 | 1.07 | 1.06 | 1.11 | 1.06 |
| Sept. | Temp. | 7.69 | 15.39 | 11.54 | 9.81 | 4.48 | 8.61 | 11.54 |
| | Precip. | .86 | .62 | .74 | 1.00 | 1.01 | .92 | .74 |
| Oct. | Temp. | 6.44 | 9.59 | 8.02 | 6.59 | 3.58 | 6.08 | 8.02 |
| | Precip. | 1.18 | 1.37 | 1.27 | .96 | .68 | .97 | .68 |
| Nov. | Temp. | 5.99 | 6.25 | 6.12 | 8.91 | 6.28 | 7.10 | 8.91 |
| | Precip. | 1.11 | 1.40 | 1.25 | 1.12 | .83 | 1.07 | .83 |
| Dec. | Temp. | 7.74 | 8.44 | 8.09 | 8.24 | 3.87 | 6.73 | 8.24 |
| | Precip. | 1.36 | 1.11 | 1.23 | 1.23 | 1.02 | 1.16 | 1.02 |

[1]

| Model | | Latitude | Longitude |
|---|---|---|---|
| | | (decimal degrees) | |
| GISS | (.1) | 50.87 | 120.00 |
| | (.2) | 43.04 | 120.00 |
| | (.AV) | 46.96 | 120.00 |
| GFDL | | 46.66 | 120.00 |
| OSU | | 46.00 | 120.00 |

[2] Used for AVE-GCM simulation.
[3] Used for MAX-GCM simulation.

# GROUND-WATER RECHARGE ESTIMATES AND SENSITIVITY

The estimates of recharge for three groupings of simulations are discussed in this section. The first grouping (1956-77 simulations) compares the estimates of Bauer and Vaccaro (1990; calculated using data for three stations) with estimates calculated using (1) data from one station; (2) the synthetic record that is based on the climatological data for the single station; and (3) the same synthetic record that has been ranked. The second grouping are the simulations for the 87-year period 1901-87 that used the long record climatological data. The third grouping is for the two climate change scenarios. All three groupings include simulations for both predevelopment and current land-use conditions.

## Estimates for 1956-77 from Single-Station and Synthetic Climate Records

The recharge estimated by the simulations using climatological data from three weather stations (Bauer and Vaccaro, 1990) and data from a single station for the 1956-77 period of record are presented in table 5. The 22-year average annual recharge for the single-station simulation was about 0.17 in/yr less (6 percent) for predevelopment conditions and was 0.3 in/yr less (3 percent) for current conditions. Even though total precipitation was slightly greater using the single-station record, there was a decrease in recharge. This appears to be because higher-intensity or longer-duration precipitation events are missed when data from only a single station are used. The tendency of the single-station simulation to underestimate precipitation and recharge during dry years and overestimate them during wet years, compared with the three-station simulation, is also demonstrated by the years during which maximum and minimum recharge occur. The single-station simulation appears to underestimate the 22-year average annual recharge because of a greater persistence of drier years in the single-station record.

The two simulations using the synthetic and synthetic-ranked climate data gave reasonable estimates of the average recharge (table 5). The predevelopment recharge estimates based on the synthetic data were about 20 percent less than the Bauer and Vaccaro (1990) estimates, whereas the current estimates were only about 7 percent less. The synthetic record simulation estimates the large recharge events more accurately than the synthetic-ranked record, and the synthetic-ranked record simulation estimates the dry-year recharge more accurately. However, because the ranked record preserves the sequencing (although probably statistically random) and Hurst coefficient of the historical climate series, it can be assumed to be a better estimate than the unranked record of an equally probable climate series for the 1956-77 period.

The results of the single-station simulations suggest that both average and deficit period recharge estimates discussed in the next sections may be slightly biased (downward) by using the single-station record, and that recharge is sensitive to the temporal and spatial distribution of precipitation and temperature. The results for current conditions are less sensitive to precipitation because irrigation, which is assumed to be constant, is added to precipitation, and thus, the total precipitation not only increases, but also becomes more evenly distributed throughout the year.

Table 5.--Recharge estimates simulated using four different climate inputs, 1956-77, and associated information

[All values are reported in inches per year; P, predevelopment land use; C, current land use]

| Simulations | Average | | | | Minimum | | | | | | Maximum | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Recharge | | Precipitation | | Recharge | | Precipitation | | Year | | Recharge | | Precipitation | | Year | |
| | P | C | P | C | P | C | P | C | P | C | P | C | P | C | P | C |
| Bauer and Vaccaro (1990) | 2.74 | 9.72 | 11.12 | 28.55 | 1.32 [1](1.33) | 7.38 | 6.15 [1](10.74) | 26.88 | 1976 1963 | 1967 | 6.30 | 15.20 | 17.46 | 34.88 | 1972 | 1972 |
| Single-Station | 2.57 | 9.42 | 11.20 | 28.63 | 0.77 (0.78) | 6.24 | 5.50 (8.72) | 26.15 | 1976 1967 | 1967 | 6.62 | 15.26 | 18.70 | 36.12 | 1972 | 1970 |
| Synthetic Record | 2.19 | 9.07 | 11.21 | 28.64 | 0.48 | 5.93 | 7.36 | 24.79 | 1967 | 1967 | 4.66 | 11.86 | 13.95 | 31.37 | 1971 | --- |
| Synthetic-Ranked Record | 2.12 | --- | 11.21 | --- | 0.87 | --- | 7.36 | --- | 1964 | --- | 3.98 | --- | 13.95 | --- | 1961 | --- |

[1] Information in parentheses is for the year with the second smallest annual recharge.

## Estimates for 1901-87 from Historical Climate Records

Results of the 1901-87 simulations using the historical climate record (table 6; figs. 10 and 11) indicate that long-term average recharge estimates are sensitive to the period of record chosen for simulation. This is especially true for predevelopment land use. For example, the multiyear average of the estimates of daily recharge for the selected subsets of the 87-year period varied as much as 43 percent (1.62 to 2.86 in/yr) for predevelopment conditions and as much as 23 percent (7.47 to 9.71 in/yr) for current conditions. Similarly, departures of the annual recharge from the 87-year average (fig. 10) varied from about 30 percent less to 25 percent more under predevelopment conditions, and 20 percent less to 15 percent more under current conditions (variations of more than 10 in/yr). The above also indicates that the estimates for current conditions are more robust than the estimates for predevelopment conditions.

The cumulative departure for estimated predevelopment recharge (fig. 11) shows the long-term trends and the time-dependence of deficit periods. The precipitation oscillated about the mean from about 1940 to about 1969 (figs. 5 and 12), whereas the net deficit in recharge (downward trend) continued until about 1970, suggesting a winter precipitation season time-lag of about a year relative to recharge events. The upward trend of precipitation from about 1970 to 1975 (fig. 5) apparently represented enough water to keep a large part of the basin's soil-moisture reservoir full and, thus, allow for recharge events. Since that time, the deficits (quantity and duration) in precipitation have not been persistent or large enough to trigger another long-term downward recharge trend. For example, although 1974 was a dry year (the 22nd driest), it occurred during an average period of precipitation so that recharge for 1974 was above average (the 15th wettest).

Recharge appears to be sensitive to a 'threshold' of accumulated precipitation that controls the quantity of recharge and initiates periods of deficits and excesses. This aspect can be seen by the information on predevelopment recharge for selected dry and wet years (table 7). This interannual variability (time-dependence) of predevelopment recharge is further illustrated in fig. 13, where the annual values of precipitation have been ranked and then plotted together with the annual recharge value for the ranked precipitation year. Although there is a large degree of correlation between precipitation and recharge (correlation coefficient of 0.75), the variable recharge departures are obvious. The interannual variability also can be seen in table 5 in the column labeled "Minimum" for predevelopment land use for the Bauer and Vaccaro (1990) and single-station simulations. Although precipitation varied between the 2 minimum years by as much as 43 percent, the recharge estimates were about the same. This is partly because the storage capacity of the soil root zone (the available water capacity of the root zone multiplied by area) is limited, and 1 or 2 consecutive dry years can deplete that reservoir over large parts of the basin. This is important for much of the basin because the average soil storage capacity is 4.76 inches and annual precipitation can be less than that quantity (1935, for example). Additionally, more than 20 percent of the basin has a root-zone soil storage capacity of more than 8.8 inches. Thus, accumulated precipitation must be at least equal to the storage capacity plus AET to refill the reservoir during the winter to allow for recharge events. The effects of interannual variations in precipitation, combined with the areal variability of the soil storage capacity, is illustrated by the variation in the number of cells with non-zero recharge for selected years (table 7).

The interannual variation in precipitation does not have as much control on recharge under current conditions because of the availability of irrigation water to supplement the precipitation deficits. That is, the irrigation waters fill the soil-moisture reservoir before the onset of winter, so a large part of winter precipitation becomes recharge.

Under both land-use conditions, recharge is sensitive to the past climate regime. For example, the 5-year moving averages and cumulative departures of recharge under both land-use conditions (figs. 10 and 11) show the downward trend in recharge from the early 1900's to about 1935 and correspond to the trend in precipitation (figs. 3 and 5). However, the current recharge trends upward to average, whereas the predevelopment recharge trends downward to about 1970 (fig. 11). Therefore, it appears that current recharge is less sensitive than predevelopment recharge to short-term dry cycles due to excess irrigation in the summer, whereas the predevelopment recharge is sensitive to both trends and cycles in precipitation.

Table 6.--Estimates of recharge for predevelopment and current land-use conditions for three simulations

| Averaging period | Recharge (in inches per year) | | | | | |
|---|---|---|---|---|---|---|
| | Historical simulation | | AVE-GCM[1] simulation | | MAX-GCM[2] simulation | |
| | Predevelopment | Current | Predevelopment | Current | Predevelopment | Current |
| 1901-17 | 2.68 | 9.71 | 2.94 | 8.20 | 1.80 | 5.92 |
| 1908-28 | 2.30 | 8.08 | 2.48 | 7.20 | 1.53 | 5.12 |
| 1923-46 | 1.93 | 7.97 | 2.12 | 6.50 | 1.27 | 4.76 |
| 1928-37 | 1.62 | 7.47 | 1.88 | 6.12 | 1.10 | 4.46 |
| 1938-71 | 2.14 | 8.93 | 2.35 | 7.25 | 1.45 | 5.44 |
| 1956-77 | 2.65 | 9.51 | 2.87 | 8.02 | 1.87 | 5.96 |
| 1956-77[1] | 2.57 | 9.42 | | | | |
| 1956-87 | 2.54 | 9.28 | 2.77 | 7.81 | 1.78 | 5.76 |
| 1971-87 | 2.86 | 9.60 | 3.15 | 7.25 | 2.07 | 6.07 |
| 1901-87 | 2.33 | 8.96 | 2.57 | 7.49 | 1.60 | 5.48 |

[1]Climate change from the historical record used in these simulations are defined in table 4.

[2]Same 22-year period of simulation as Bauer and Vaccaro (1990), but climate data input from only one climatological station.

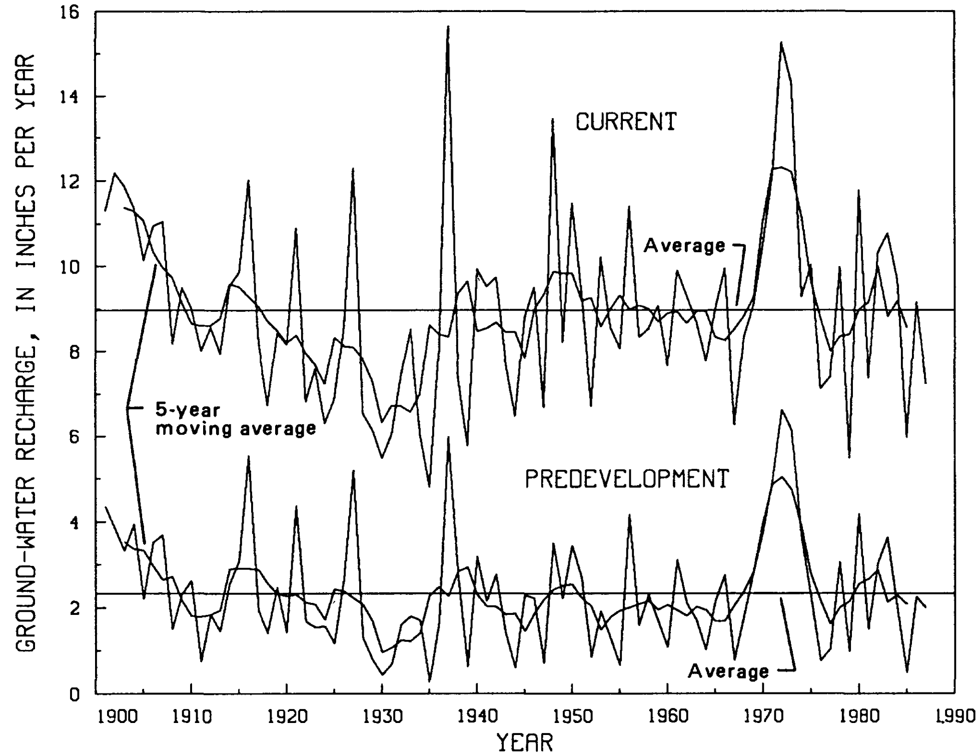


**Figure 10.--Annual ground-water recharge estimated using historical climate record for predevelopment and current land-use conditions, 1901-87.**

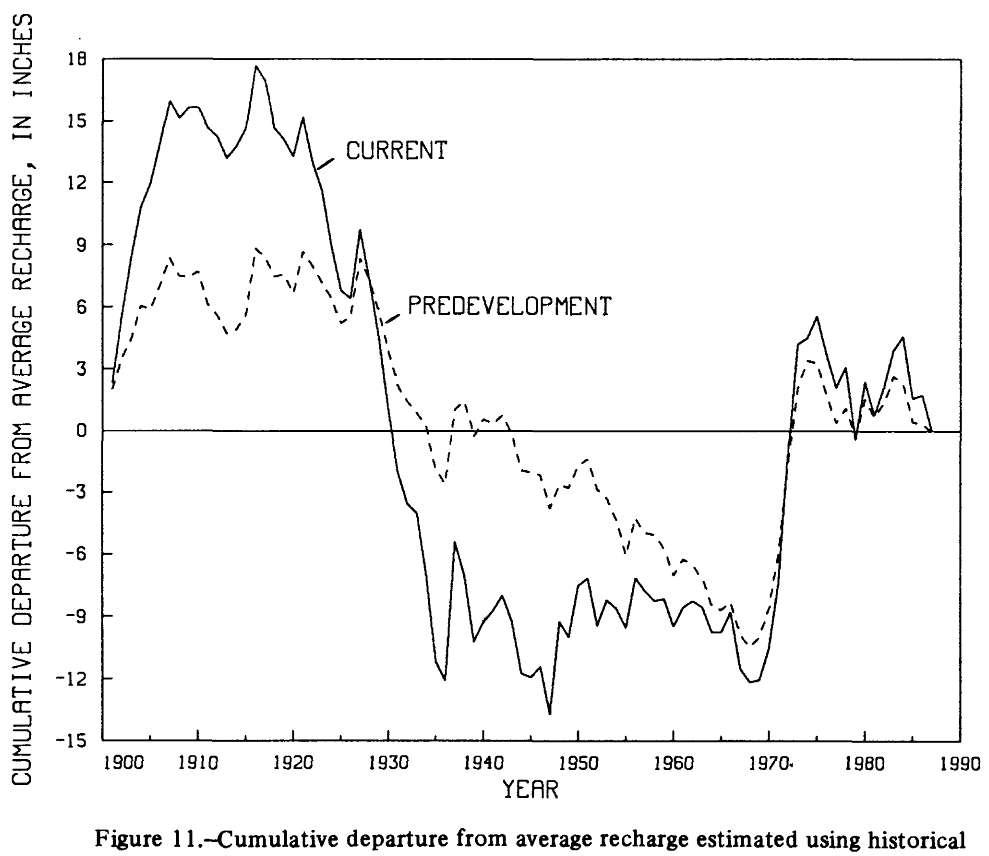


**Figure 11.--Cumulative departure from average recharge estimated using historical climate record for predevelopment and current land-use conditions, 1901-87.**

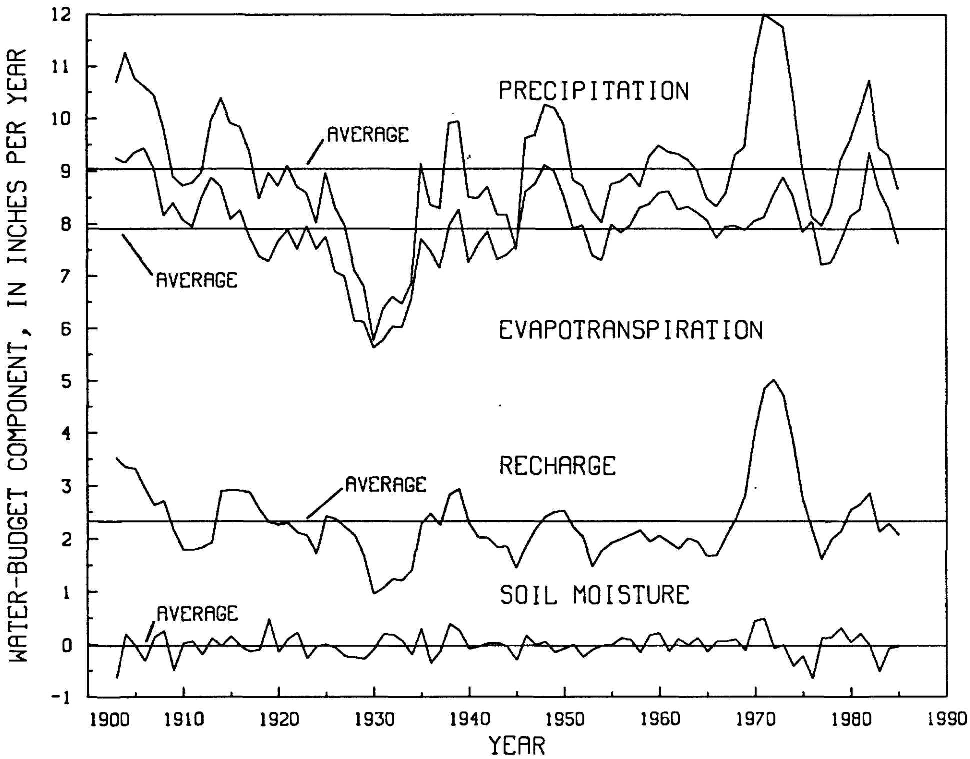


**Figure 12.--Five-year moving average of the water-budget components for predevelopment land-use conditions.**

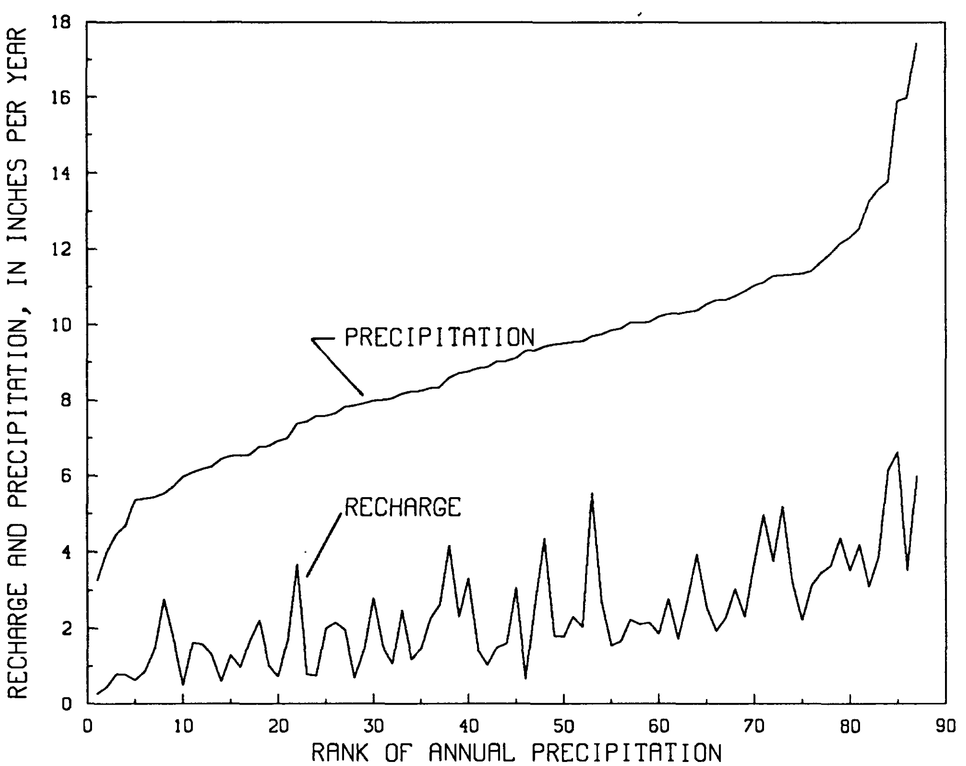


**Figure 13.--Ranked annual precipitation and estimate of associated annual recharge for predevelopment land-use conditions.**

Table 7.--Predevelopment recharge information for selected dry and wet years

[Values in inches per year, unless otherwise noted.]

| | Dry year[1] | | | Wet year[2] | | |
|---|---|---|---|---|---|---|
| Year | 1935 | 1939 | 1943 | 1905 | 1972 | 1973 |
| Previous[3] | D | D | A | A | W | W |
| Average precipitation at weather station | 3.25 | 5.36 | 5.43 | 11.35 | 15.90 | 13.78 |
| Average basin recharge | 0.27 | 0.44 | 1.41 | 2.20 | 6.62 | 6.14 |
| Minimum cell recharge | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Maximum cell recharge | 2.6 | 7.7 | 8.1 | 17.9 | 32.3 | 26.0 |
| Number of cells in basin with recharge[4] | 124 | 93 | 219 | 173 | 255 | 302 |
| Change in basin soil moisture | -1.55 | 0.72 | -2.29 | -0.72 | 1.47 | 0.56 |

[1]Within lowest quartile of annual precipitation quartiles.

[2]Within highest quartile of annual precipitation quartiles.

[3]Previous year dry (D), wet (W), or average annual precipitation within middle quartiles (A).

[4]362 one-square-mile cells

## Estimates for 1901-87 from Projected Climate Records

The recharge under predevelopment conditions is robust to the AVE-GCM climatic projections; most changes in the recharge estimates between the subsets for the historical and AVE-GCM simulations were less than 10 percent (table 6). Thus, recharge under predevelopment condition is more sensitive to the historical climate variability than to the AVE-GCM change. Correspondingly, the 87-year average recharge for current conditions was about 16 percent (1.47 in/yr) less than those derived from the historical climate, suggesting they are more sensitive to the AVE-GCM projected changes (table 6).

The difference between results for the two land-use conditions is due partly to the seasonality of temperature and precipitation. The increase in precipitation (10.66 to 11.77 in/yr, or 1.11 in/yr) under the AVE-GCM change for predevelopment conditions is offset by the increase in AET (7.9 to 9.05 in/yr, or 1.15 in/yr) due to increased air temperatures. For current conditions, abundant irrigation waters applied during the dry season, combined with increased temperatures, result in even more AET during the summer months (an additional 1.73 in/yr of AET more than the increase in precipitation). For all but two of the averaging periods chosen, the recharge estimated for current conditions using the AVE-GCM simulation is less than the average for the 1928-37 drought in the historical record, and the 87-year average for the AVE-GCM simulation is essentially the same as the

1928-37 average for the historical simulation. Similarly, the MAX-GCM current-recharge estimates for all averaging periods are less than all the historical and AVE-GCM estimates (table 6 and fig. 14). The 87-year average recharge for the MAX-GCM simulation for both land-use conditions was 0.73 and 3.48 cm/yr, respectively, less than the 87-year average historical estimates.

## Discussion

Box plots of the annual average recharge estimates under current conditions for the historical and the two GCM simulations (fig. 15) show that 75 percent of the estimates for the historical simulations were greater than the median of the AVE-GCM estimates, and 75 percent of the AVE-GCM estimates were greater than the median of the MAX-GCM estimates. The distribution of the annual estimates (fig. 15) shows that as the sensitivity of recharge estimates to climatic variability increases, the interannual variability/sensitivity weakens. For example, the range of annual recharge estimates between the 10th and 50th percentile values for the three simulations is 5.7, 5.3, and 3.8 in/yr, respectively. The decrease in interannual variability is especially clear in figure 14 for the MAX-GCM. Additionally, the mean difference in annual recharge from one year to the previous year is -1.42, 1.43, and 0.0 in/yr for the three simulations, respectively. Thus, these differences tend to be more negative (less recharge from the previous year) for the historical simulation, more positive (more recharge) for the AVE-GCM, and about normally distributed around 0.0 for the MAX-GCM. These interannual recharge dependencies are attributable to the feedback between AET and soil moisture.

Recharge for current conditions appears to be more sensitive to temperature changes than recharge for predevelopment conditions because of the availability of irrigation water; the correlation coefficients between annual temperature and recharge for current and predevelopment conditions are 0.35 and 0.20, respectively. The increase in the precipitation (1.11 in/yr) for the AVE-GCM simulation under current conditions is more than offset by increases in PET (6.75 in/yr) and AET (2.84 in/yr). For the MAX-GCM simulation under current conditions, a 1-inch average decrease in precipitation and large increases in PET (9.31 in/yr) and AET (2.73 in/yr) resulted in a 3.5-inch average decrease in recharge. Correspondingly, AET under current conditions changed from 66 percent of precipitation plus irrigation for the historical simulation to 79 percent for the MAX-GCM simulation.

Operation of the DPM model for 87 years with reordered daily synthetic data (generated from the Richardson model using the 1928-37 model parameters) resulted in an average recharge of 7.1 in/yr for current conditions. This value approximates both the 1928-37 average recharge for the historical simulation and the 87-year average recharge for the AVE-GCM simulation (table 6). For the above three simulations and averaging periods, AET was about 72 percent of precipitation plus irrigation. Thus, for current conditions, the 87-year average recharge for the AVE-GCM simulation is about equivalent to the 1928-37 year period. However, if 1937 (a wet year) is not included in the 1928-37 average for the historical simulation, the AET still remains about the same percentage of precipitation plus irrigation, and average recharge is reduced by about 0.9 in/yr for this 1928-36 period. Therefore, recharge for the historical simulation drought period is smaller than the 87-year average for the AVE-GCM simulation, and sensitivity of recharge to the long-term effect of the AVE-GCM projected climate change would not be as large as the historical drought period. Note that the 1928-37 recharge for the AVE-GCM simulation is still less than all the subset averages for the historical simulation (table 6). Therefore, because different subsets of climatological data have certain distributions and averages for which AET

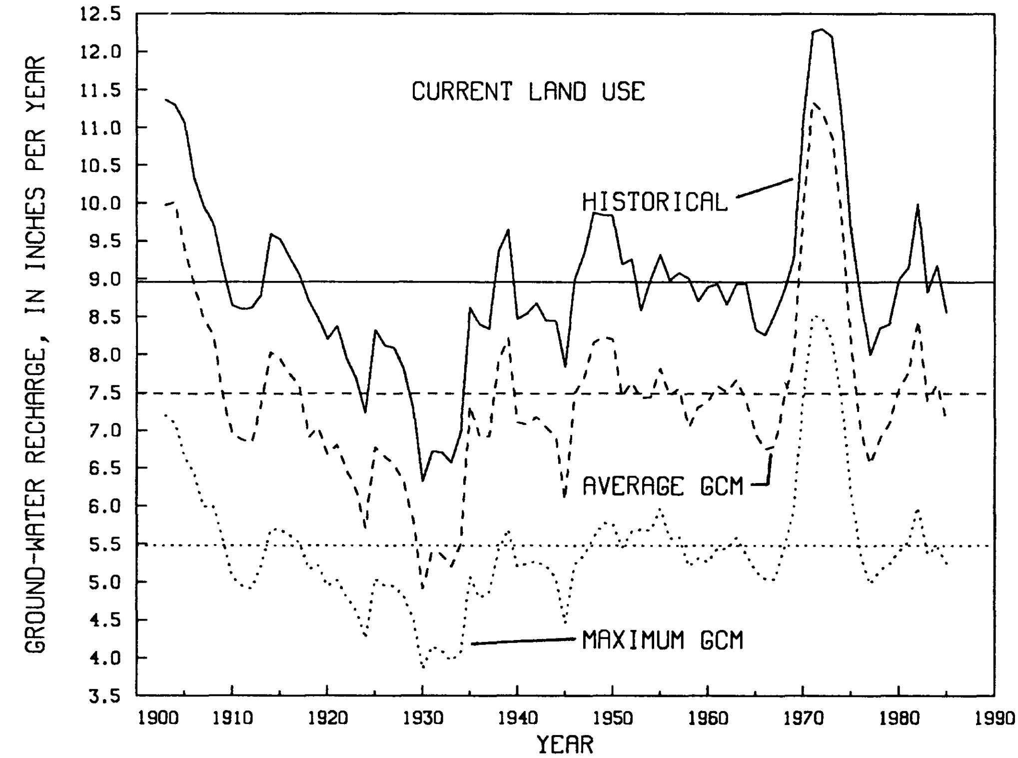


Figure 14.--Five-year moving average of annual ground-water recharge for current land-use conditions for the historical and projected climate regimes. (GCM, global climate model.)

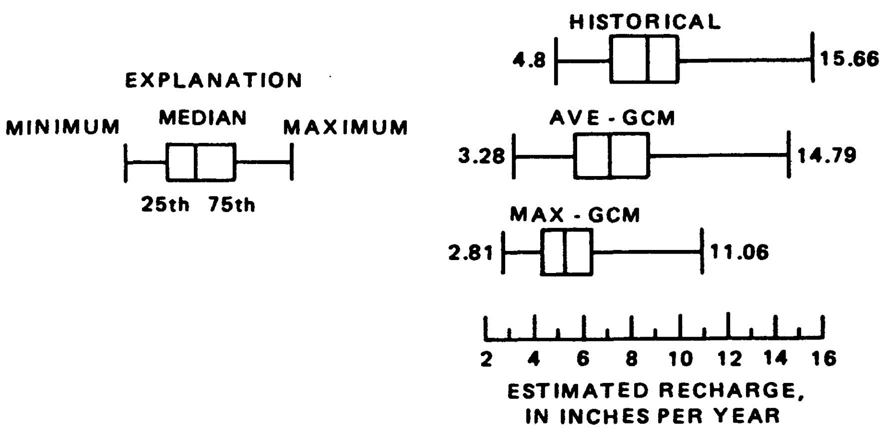


Figure 15.--Box plots showing quartiles of annual recharge for current land-use conditions. (AVE-GCM, average change projected by the three global climate models; MAX-GCM, monthly changes from whichever global climate model predicted the maximum 'water-deficit' effect.)

remains a nearly constant percentage of precipitation plus irrigation, the average of annual recharge estimates over subsets of the historical record can approximate an average recharge for a longer period of time under those same climatological conditions or regimes. The average of recharge values over subsets, thus, imparts useful information.

The AVE-GCM results translate into a decrease in return flow of about 39 $ft^3/s$, which could reduce the availability of water to downstream or junior water users. The 87-year average recharge estimate for the AVE-GCM simulation is only 0.1 in/yr larger than the annual recharge estimated for the historical simulation for 1977, when junior users within the basin were denied water. The AVE-GCM results also indicate that the lower 20 percent of the recharge estimates for the historical simulation can become more persistent. The difference between the 87-year average for the MAX-GCM and historical simulation represents a decrease in return flow of about 90 $ft^3/s$, or a loss of irrigation water to between 15,000 and 30,000 acres, depending on the annual application rate of irrigation water.

The study of Bauer and Vaccaro (1990) was designed to estimate the long-term average recharge; for areas with deep water tables and deep soils, this recharge rate would tend to be constant and was approximated using the average of the annual recharge values. Therefore, on the basis of this approximation, the spatial distribution of long-term averages of minimum and maximum current recharge that potentially can occur under either historical or projected climate regimes is estimated as the average of annual values for selected subsets (fig. 16). The maximum distribution is based on the average of the annual values for the 1971-87 period for the historical simulation and the minimum distribution for the 1928-37 period for the MAX-GCM simulations. These distributions show the potential range in long-term average recharge and illustrate the sensitivity of recharge to climate variability and climate change.

Several factors that were not analyzed in this study also could effect the sensitivity discussed in this report. For example, the crop-growth curves used in DPM (Bauer and Vaccaro, 1987) were not altered for the GCM simulations. For native plant communities, the length or start of the growing season can affect the recharge estimates and, thus, possibly change the interpretations of the predevelopment simulation results. The changes in the growing season could be adjusted through an analysis based on both the projected temperature changes and the phase coefficient in the Richardson model. These numbers then would need to be factored into the various crop-growth curves used in the DPM. For the irrigated plant communities now cultivated, the length of the growing season probably would not change much, but the onset might vary. The effects of earlier or later planting and growth of irrigated crops on the estimated recharge would be difficult to assess, especially because of the variety of agricultural practices.

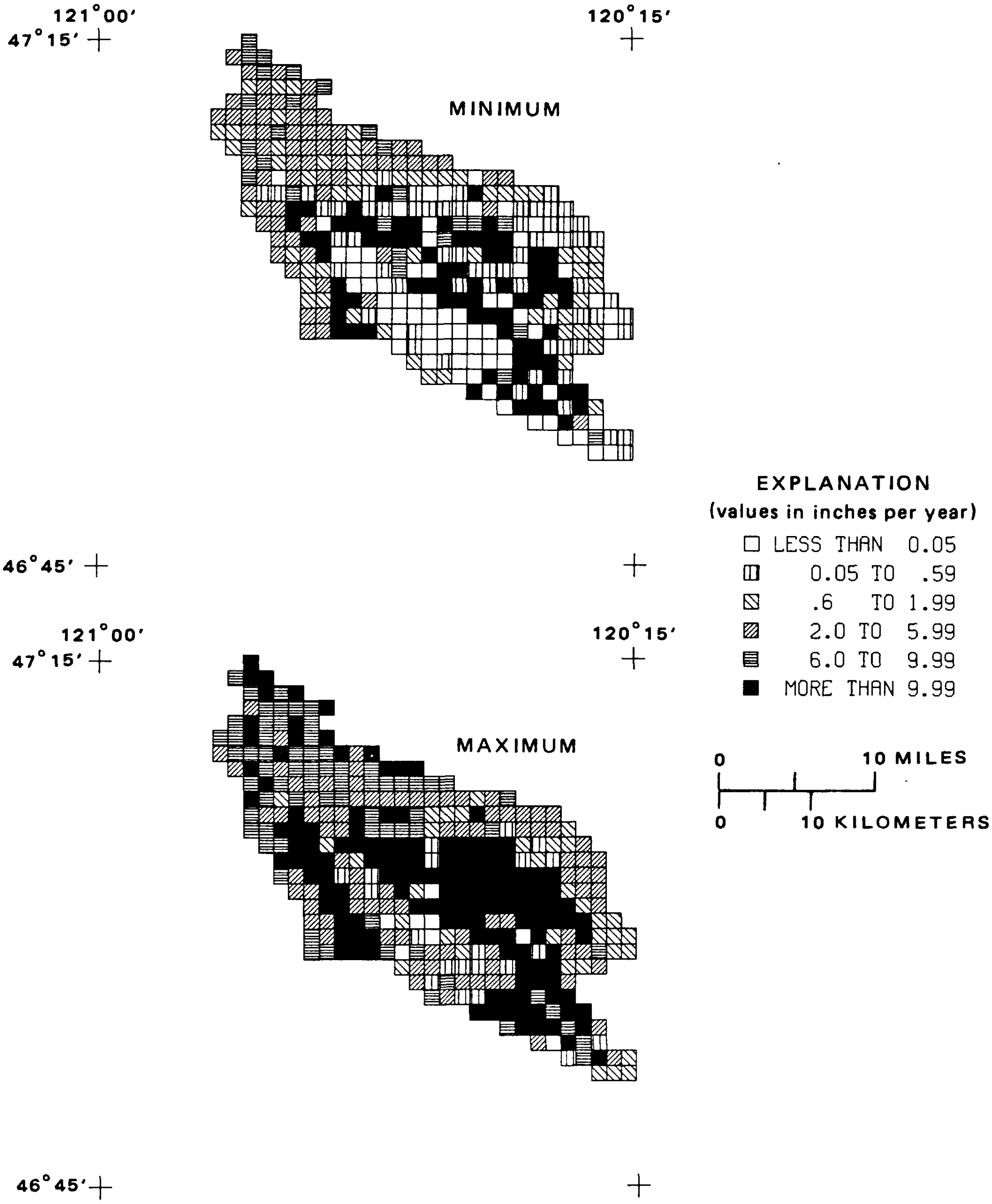


Figure 16.–Long-term average of minimum and maximum recharge for current land-use conditions that potentially can occur under historical or projected climatic regimes in the Ellensburg basin. See figure 1 for location.

# SUMMARY

This study investigated, as a first estimate, the sensitivity of ground-water recharge estimates for the semiarid Ellensburg basin of the Columbia Plateau to historical, synthetic, and projected climatic variations, including global warming. The historical climate data show some periodicity, but no discernible trends.

The Richardson model adequately generated equally probable synthetic daily climate data for periods of as much as 20 to 25 years. Longer periods of equally probable synthetic data could be reordered to preserve the Hurst coefficient and periodicity. Shorter length periods also could benefit from reordering to preserve a particular sequence of departures from average data values, although such a sequence probably would be statistically random.

The estimation for semiarid areas and especially for arid areas is highly dependent on the discretization size used in models, the dominant plant community, and the availability of climatological data. Daily modeling methods for estimating recharge improve on monthly or annual methods, and the calculated daily recharge values probably should be time-averaged over at least 10 years. The use of climatic-change projections calculated by general circulation models (GCMs) for modifying the historical climate record for input to hydrologic models is probably the best available initial estimate for assessing sensitivity to potential climate change. However, historical climate data are useful for estimating past recharge variations (that can be of importance for planning purposes), although GCM climate-change projections indicate that these climate data may not be applicable for defining the full range of recharge sensitivity for the doubling of $CO_2$.

Estimated recharge was found to be sensitive to the climatic variability in the historical record; recharge was more sensitive to precipitation variability than to temperature variability. The difference in annual recharge values for current conditions was greater than 10 in/yr. When the historical record was adjusted with GCM-projected climate changes, the estimated annual recharge was still variable, but the range of the annual recharge values and the interannual variability decreased. The median annual recharge values for the simulation that was based on the average change projected by the three general circulation models (AVE-GCM) were less than 75 percent of the annual values for the historical simulation and were greater than the smallest of the historical estimates. The median annual recharge for the MAX-GCM simulation (which used the monthly changes from whichever general circulation model predicted the maximum 'water deficit' effect) was less than 75 percent of the annual values for the AVE-GCM simulation.

The sensitivity of the recharge estimates provides managers with information of potential use for long-term planning. The sensitivity of, and variability in, recharge indicate that predictions from ground-water models of the flow system within the Columbia Plateau probably become more uncertain with the length of projection. Using several distributions of recharge (small-average-large) that address potential climate regimes that might cause long-term average recharge to change in a ground-water flow model can identify a range of uncertainties in projections. These latter two findings agree with those of Stockton and Boggess (1979).

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