AN ABSTRACT OF THE THESIS OF

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Characterizing the distribution of precipitation at regional scales is a requirement for the development of regional scale, spatially distributed hydrologic water balance models. This study performs a preliminary assessment of the utility and limitations of historical hydro-meteorological data for providing spatially distributed precipitation estimates over large areas. The historical data are used in a spatial analysis to characterize regional patterns of precipitation and runoff across the conterminous United States. Precipitation and runoff "surfaces" generated from interpolation of point measurements capture broad regional patterns. A distributed water balance is calculated over the continent using long-term (1948 -1988) and seven-year (1982 -1988) annual average values to check the reliability of precipitation estimates. The resulting "input-output surfaces" illustrate the deficiency (low elevation bias) of historical precipitation measurements in the mountainous western United States where snowmelt is an important component of the annual runoff. The incorporation of high elevation snow measurements into the precipitation record for the seven-year average significantly improves the water budget estimates in these regions and enhances the utility of historical data for providing spatially distributed precipitation estimates at regional and continental scales.

An Analysis of the Distribution of Precipitation and Runoff from the Historical Record for the Continental United States

by

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Thesis presented by Jayne Ellen Dolph

To my Mother and Father

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An Analysis of the Distribution of Precipitation and Runoff from the Historical Record for the Continental United States

Introduction

Spatially distributed hydrological and ecological analyses are required to assess the effects of climate change on water resources and vegetation (Eagleson, 1986; Dooge, 1986; Neilson et al., 1989). The development of spatially distributed models requires spatially distributed precipitation estimates at regional to continental scales, with regional referring to areas on the order of roughly 50,000 to 500,000 km^2. What is not well understood is whether historical data can be used effectively to characterize precipitation patterns over large areas and thereby provide the necessary input to spatially distributed models.

This study provides a preliminary assessment of the utility of historical data for providing spatially distributed precipitation estimates over large regions, and is the first step in characterizing surface hydrology at scales compatible with climate change research.

The global hydrologic cycle is an important component of the coupled ocean-atmosphere-land surface system. It contributes to atmospheric circulation and exerts a strong influence on weather and climate. Global climate change, which is predicted to occur due to increasing concentrations of green-house gases in the atmosphere, would cause changes in the earth's hydrologic cycle (Smith and Tirpak, 1989). These changes may significantly alter physical processes of the terrestrial biosphere, because changes in hydrologic regimes directly affect land surface properties such as soil moisture, vegetative health and distribution, and surface albedo (Rasmusson et al., 1990; Hall et al., 1988; Hansen et al., 1984; Rind, 1984; Shugart and West, 1977).

A major uncertainty at this time is the effect that climate change will have on regional hydrology and the distribution of biomes (e.g. Dooge, 1990; Neilson et al., 1989). In particular, it is not well understood how the spatial patterns and seasonality of precipitation may change. While much research has been directed toward understanding historical temperature records (eg. Hanson and Lebedeff, 1987; Jones et al., 1986; Wigley et al., 1985), relatively little attention has been given to large-area precipitation patterns.

Presently, the only tool for predicting the effects of climate change on physical processes across large geographic areas is the General Circulation Model (GCM). GCMs are global scale numerical models of atmospheric circulation that simulate the fundamental physical relationships of the ocean-atmosphere-land surface system (Manabe and Wetherald, 1975; Hansen et al., 1988; Dickinson and Cicerone, 1986). GCMs predict that global precipitation is likely to increase (e.g. Smith and Tirpak, 1989), but it is not clear how regional precipitation patterns will be affected. Furthermore, the geographical distribution of predicted change differs from model to model (Schlesinger and Mitchell, 1987; Rind 1988). These inconsistencies are due, in part, to the unrealistic parameterization of land surface processes in the models which is a function of their coarse resolution (Eagleson, 1986; Rind et al., 1990). The GCM distributes precipitation uniformly over one grid cell, tens to hundreds of thousands of km^2 in size. However, precipitation is a highly variable process, particularly at large spatial scales, and in topographically diverse regions. Given the simplified treatment of precipitation distribution in these models, their predictions of hydrologic sensitivity to climate change are unreliable. A more realistic representation of the global hydrologic cycle in the models would improve the reliability of precipitation estimates. This improvement requires a better understanding of basic hydrologic phenomena at regional scales (e.g., Eagleson, 1986).

An important step towards improving precipitation estimates for large area modeling and climate change research, is the characterization of past and present spatial distributions of precipitation at regional scales using historical data. This will better link surface hydrology to climatic processes by providing spatially distributed precipitation estimates at resolutions which are ecologically and hydrologically meaningful.

Objectives

The objectives of this study are:

1) the development of a comprehensive database of historical precipitation and runoff data for analyses at regional to continental scales;

2) a preliminary assessment of the utility of historical precipitation data for characterizing the spatial distribution of precipitation at regional and continental scales using water balance techniques;

3) the identification of those regions where the use of historical precipitation data may be most limited;

4) the recommendation of improvements to the historical data, and alternatives to its use for precipitation estimation across large areas.

Related Research

Historical hydro-meteorological data are an important source of information on past and present hydrologic conditions (e.g. Karl and Riebsame, 1989). In the United States, extensive networks of precipitation and runoff measurement sites have been established, and historical data are becoming widely available in digital form. The development of comprehensive national information bases and data bases has substantially increased the amount of observational information available on hydro-climatic dynamics. The goal of these efforts is primarily inventory-oriented, aimed at data collection and the identification and projection of water resource problems. Thus far, a high-quality geographic database, combining the historical hydro-meteorological data into a single usable form for spatial analysis and modeling at the continental scale has not been developed.

Several studies in recent years have investigated the utility of historical data for describing hydrologic parameters across large areas. Rasmusson (1985) and Ropelewski et al. (1986,1987) have analyzed global precipitation patterns associated with anomalous climate events such as the El Nino Southern Oscillation cycle. Trends in precipitation fluctuations over the northern and southern hemisphere have been studied with the objective of assessing the significance of projected climate change from GCMs as compared with the variability evident in precipitation and temperature records (e.g. Diaz, et al., 1989, Bradley, et al., 1987). Additionally, multi-year fluctuations in temperature and precipitation at the continental scale have been investigated in sensitivity studies to assess the utility of historical data for detecting secular climate change (Karl 1987; Karl and Riebsame, 1989).

These studies have emphasized the need for improved estimates of precipitation at regional scales, and a better understanding of the spatial and temporal variability of land surface processes at resolutions which are hydrologically and ecologically meaningful. As Bradley (1987) points out, the "magnitude of observed trends, their geographic distribution, and differences between seasons need to be examined in more detail." Initially, this will involve determining the utility and limitations of the historical data for adequately characterizing physical processes at a variety of spatial scales. Past correlations and empirical relationships describing the spatial distribution and variability of precipitation may be inadequate with climate change conditions because changes are predicted to be more severe and rapid than the historical record indicates (e.g., Hansen et al. 1988). By using historical data to characterize precipitation and runoff patterns at regional to continental scales, we can begin to identify those regions and conditions where historical data are most limited, and where better data networks and more focused research efforts are required.

Methods

The approach taken in this study was to utilize Geographic Information System (GIS) technology and historical data to generate "surfaces" that represent the spatial distribution of precipitation and runoff across the continental United States. Distributed water balance techniques were developed using these surfaces to make a preliminary assessment of the utility of historical data to account for the spatial variability of precipitation at the continental scale. The output is spatially distributed, long-term annual average precipitation estimates for the United States.

Data

Synthesizing the immense volume of historical data at the continental scale is a formidable task, due both to the quantity of data available and data quality uncertainties. Analyzing patterns of precipitation and runoff at this scale requires a substantial amount of data aggregation, manipulation, and quality control. The conterminous United States was chosen as the study area for this research because the historical data are abundant, readily available in digital form, and are generally of higher quality than in many other parts of the world. The analysis techniques developed here may later be used to characterize precipitation patterns in other regions of the world, where data may be less reliable.

Historical data were aggregated from existing digital databases and synthesized into a single, geographically-referenced database. Such an effort has only become possible recently with the advent of mass storage devices such as CD-

ROM for data collection and storage, improvements in computing efficiency, and the growing availability of GIS technology. These advances have provided the mechanisms necessary to synthesize and analyze historical data in a spatial context.

Runoff Data

Monthly time-series runoff data were obtained from a newly-created hydro-meteorological database for the United States (Wallace et al., in review). The database consists of 1014 unregulated or minimally regulated gauging sites with streamflow data that have been corrected for station moves and missing values. The database was compiled from the EarthInfo (EarthInfo, 1990) database of daily runoff values on CD-ROM which is a digital compilation of the USGS daily and peak values files. Runoff measurements from this database are for the period 1948 to 1988. Figure 1. is a map of gauging station locations and illustrates the spatial distribution of measurement sites across the country.

The historical runoff data used in this analysis had to meet several criteria. The first criterion was a representative range of drainage area sizes so that runoff contributed from large drainage basins and tributary flow from smaller basins

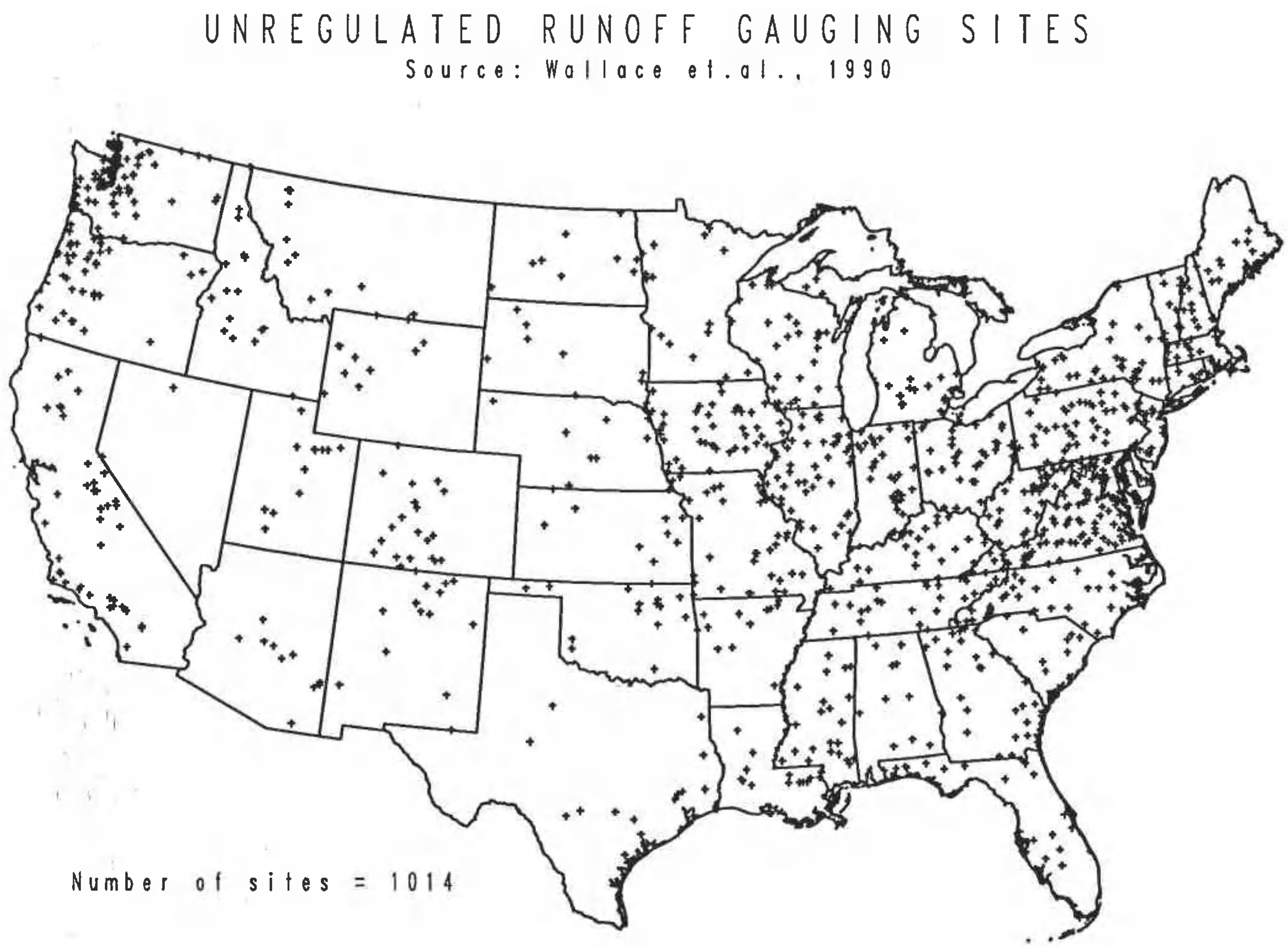

Figure 1 Runoff gauging station location map

would be represented. While the drainage areas exhibit a small drainage area bias, sizes range from 4.14 km^2 to 35,224 km^2. Figure 2. is a histogram showing the distribution of drainage area sizes.

The second criterion was that each runoff gauge be operational for a substantial number of years and have a continuous measurement record so that average conditions could be represented. Where discontinuities in runoff records did arise, data filling techniques were used and are described by Wallace, et al. (in review).

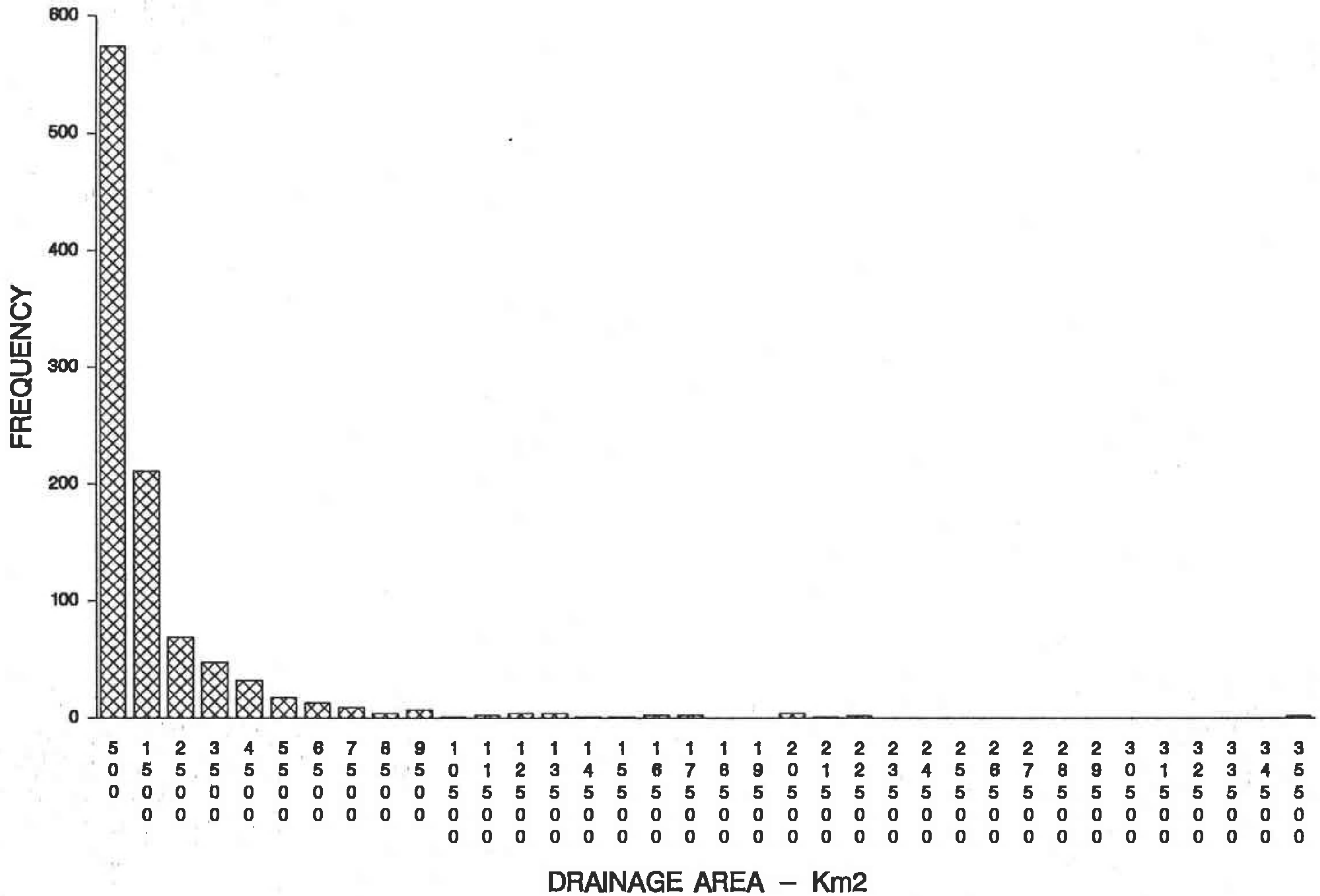

Figure 2 Distribution of gauging station drainage areas

<u>Precipitation Data</u>

Precipitation measurements were obtained from the Carbon Dioxide Research Division of the United States Department of Energy and the National Climatic Data Center of NOAA's Historical Climatology Network (HCN) (Quinlan et al., 1987). The HCN data represent a high-quality dataset of monthly precipitation measurements for 1211 stations which are free from anthropogenic and localized effects on precipitation. Each station has a continuous eighty year record and is quality-controlled to account for missing data. The dataset was specifically designed for analyses of climate change at the regional scale (Quinlan et al., 1987).

Figure 3. is a map of station locations showing the spatial distribution of HCN measurement sites across the country. The spatial distribution of HCN stations is adequate across much of the United States, except for the southwest. A greater density of measurement sites in mountainous regions is

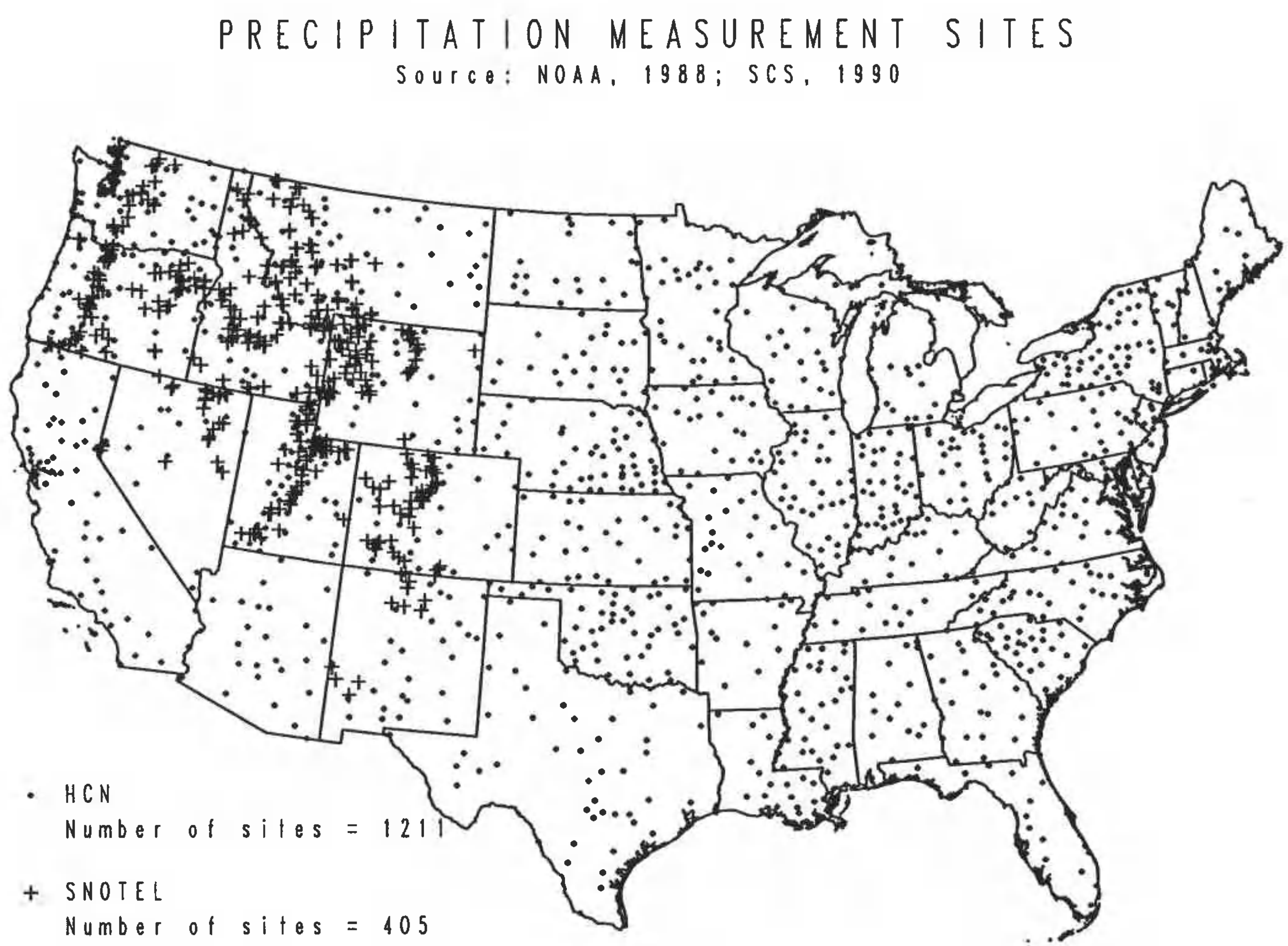

Figure 3 HCN and Snotel station location map

desirable for characterizing precipitation, because in topographically diverse areas precipitation is highly variable due to orographic influences. Unfortunately most precipitation gauges in the United States are located in low-lying areas. Therefore, mountainous regions are not well represented by the historical data and the density of measurement sites is actually lowest in high elevation areas. HCN data from 1948 - 1987 were used for near-compatibility with the runoff data, as 1988 data were not yet available at the time of this analysis.

Monthly precipitation measurements were also obtained from the Soil Conservation Service's Snotel database (USDA-SCS, 1988) to increase the elevational range of precipitation measurement sites. Snotel measurements are available for twelve states in the western United States and represent snow water equivalent measured at snow course locations. These stations are located in mountainous regions and measure precipitation (rainfall and snowfall) at high elevations on a year-round daily basis. A limitation of these data is their relatively short period of record. Measurements are only available in digital form for about a ten year period, on average. In several states (California and Arizona), the data are unavailable before 1989 and could not be used for this analysis. Monthly values from 1982 through 1987 for 405 stations were used for this study. Figure 3. shows the locations of the Snotel measurement sites.

Figure 4. illustrates the low elevational range of HCN stations as compared with the Snotel sites. The majority of HCN sites are located below 1,300 meters with several sites located at 2,700 meters. The inclusion of 405 Snotel sites increases the elevational range to 3,500 meters.

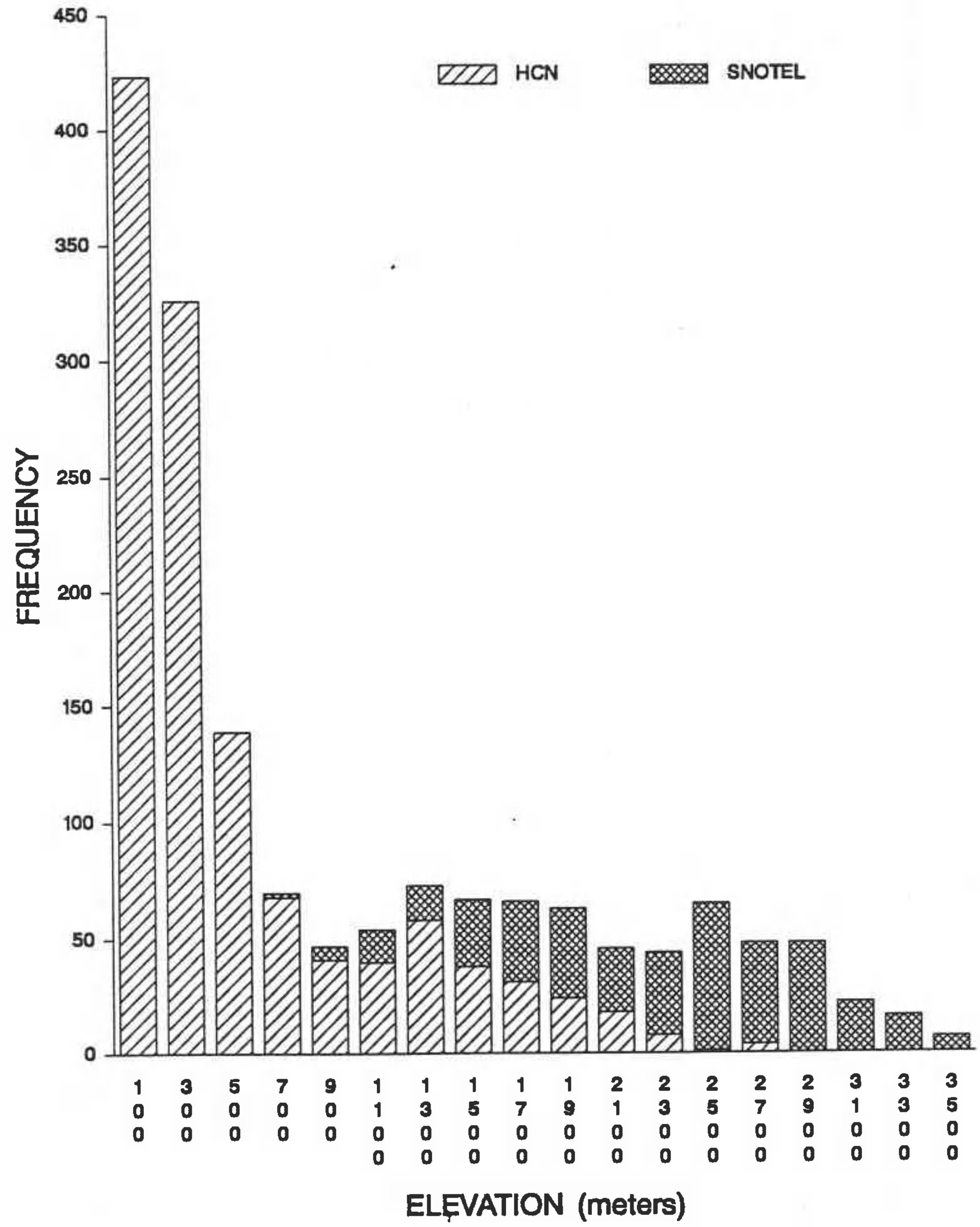

Figure 4 Distribution of HCN and Snotel station elevations

Continental Data Surfaces

Continental surfaces were generated using these data to characterize general spatial patterns of precipitation and runoff across the country and to illustrate precipitation-runoff relationships at the continental scale. Monthly runoff values for the 1014 gauging stations were normalized by converting values of cfs-days to unit runoff for comparability with precipitation data. This resulted in an average volume of flow, or depth, at each gauge relative to that gauge's drainage area. Average annual values of runoff were computed for each gauge for a 41-year time period, from 1948 through 1988. Monthly precipitation measurements from the 1211 HCN stations were aggregated to annual precipitation averages for the period 1948 through 1987.

A raster-based GIS (USACE, 1988) was used to distribute the point values of precipitation and runoff to a 5 minute digital elevation grid (approximately 10km X 10km resolution)

(NOAA, 1989) for the conterminous United States. An inverse distance-squared algorithm (Isaaks and Srivastava, 1989) was used to interpolate the point values of precipitation and runoff to annual precipitation and runoff surfaces. The interpolation algorithm fills the grid cell matrix with interpolated values generated from the input data points (eg. precipitation or runoff measurement sites), keeping the original data values. The twelve nearest data points are used to determine the interpolated value of each cell in the surface. The boundary of the continental United States was used as a mask so that only those cells falling within the study area were assigned interpolated values. Numerical approximation techniques such as weighted-averaging interpolation provide a mechanism for representing complex, irregular surfaces by employing restrictions to the spatial influence of measurement errors that may otherwise bias results (Isaaks and Srivastava, 1989). Figure 5. shows the 41-year average annual runoff and precipitation surfaces.

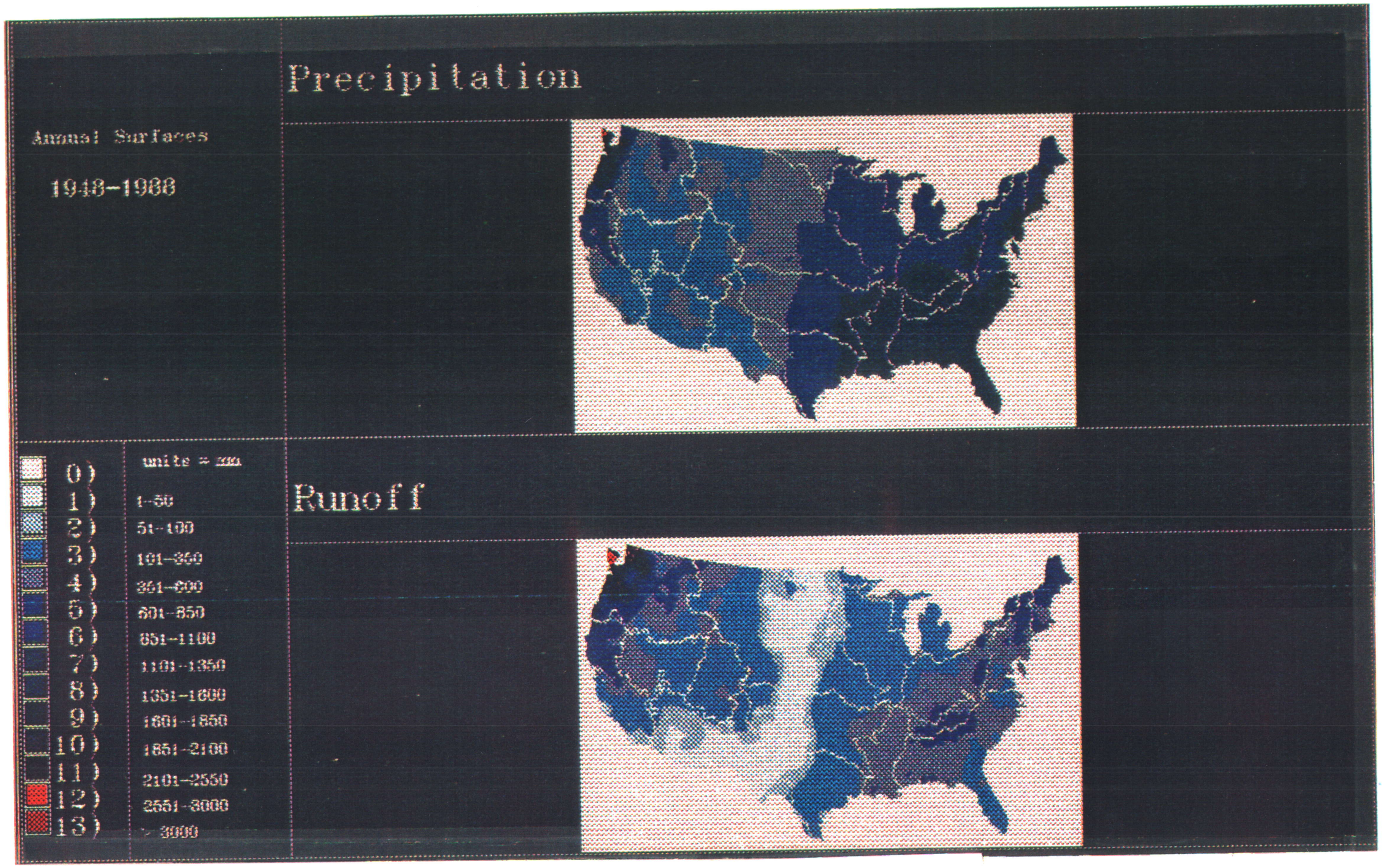

Figure 5 Average annual runoff and precipitation surfaces

The continental surfaces illustrate the general spatial extent of runoff and precipitation across the United States. The use of long-term average values tends to smooth out the influence of extreme hydrologic events. What is readily apparent from viewing the surfaces is the magnitude of spatial variability of runoff and precipitation at the continental scale, and the steep gradients which exist between major hydrologic regions.

Additionally, figures 4. and 5. strongly suggest that precipitation in the western United States is under represented by the HCN historical data, due to the poor spatial distribution of measurement sites in mountainous regions. With limited precipitation measurements at high elevations, the interpolation of precipitation can not capture orographic influences on precipitation variability. Furthermore, the elevational range of measurement sites in the West can not account for the substantial portion of precipitation deposited as snow.

Distributed Water Balance Calculation

A spatially distributed water balance was calculated over the continent using the long-term average annual runoff and precipitation surfaces to provide a general idea of areas where obvious inconsistencies exist and where better precipitation estimation techniques beyond simple linear interpolation algorithms, better data, or a combination of both are needed.

The water balance equation (Linsley et al., 1982) is:

$$P = Q + ET + \Delta S + R$$

where

P = Precipitation

Q = Runoff

ET = Evapotranspiration

ΔS = Change in storage

R = Data measurement error and model error

The water balance calculation used for this analysis is a variation on this equation. When a long-term average is used, changes in storage can be assumed negligible (Linsley et al., 1982) and are unaccounted for here. Evapo-transpiration (ET) represents a significant portion of water movement through the hydrologic cycle and is an important component of the annual water balance. ET has been estimated to be 50% or more of the annual precipitation at continental to global scales (Budyko, 1974; Brutsaert, 1986). Rind et al. (1990) have reported that transpiration alone may account for as much as 70% of precipitation in some regions of the United States. The remaining percentage appears as streamflow, as indicated in the water balance equation. The difference, then, between measured precipitation and measured runoff over sufficiently long periods of time is a measure of losses primarily by ET (Chow, 1964). Given these assumptions, the continental water balance equation simplifies to:

$$P = Q + R$$

where R is now a residual term which includes ET, data measurement error, and model measurement error.

The terms (P and Q) of the water balance equation were represented by the average annual precipitation and runoff surfaces. Precipitation (P) should exceed runoff (Q) across the continent if the historical data adequately account for the spatial distribution and total amount of precipitation input. Theoretically, the residual (R) should be positive or zero. For this analysis however, I did not expect that the water budgets would actually 'balance' because: 1) measurement errors are inherent in the historical data; 2) the interpolation of point values to a surface has limitations; and 3) precipitation measurement sites in mountainous regions are poorly distributed, spatially and topographically. I did expect the water balance to indicate broad regions where measured runoff is substantially greater than measured precipitation, and thus point out those areas where the historical data may poorly characterize the spatial distribution of precipitation.

Results

Using the 1948-1988 long-term average precipitation and runoff surfaces, a distributed water balance was calculated over the continent by subtracting the values of the annual runoff surface from those of the annual precipitation surface. Figure 6. illustrates the resulting annual "input-output surface". The blue areas represent regions where the water balance calculation produced residuals which are positive (measured precipitation exceeds runoff), with light blue representing those regions having residual values falling within 20 cm of balance and dark blue representing regions with larger positive residuals. These regions occur consistently throughout the eastern and midwestern states and to a much lesser extent in the mountainous west. Red areas depict regions of the country where the water balance calculation produced residuals which are negative (measured runoff exceeds measured precipitation), with lighter red representing regions with residuals falling within 20 cm of

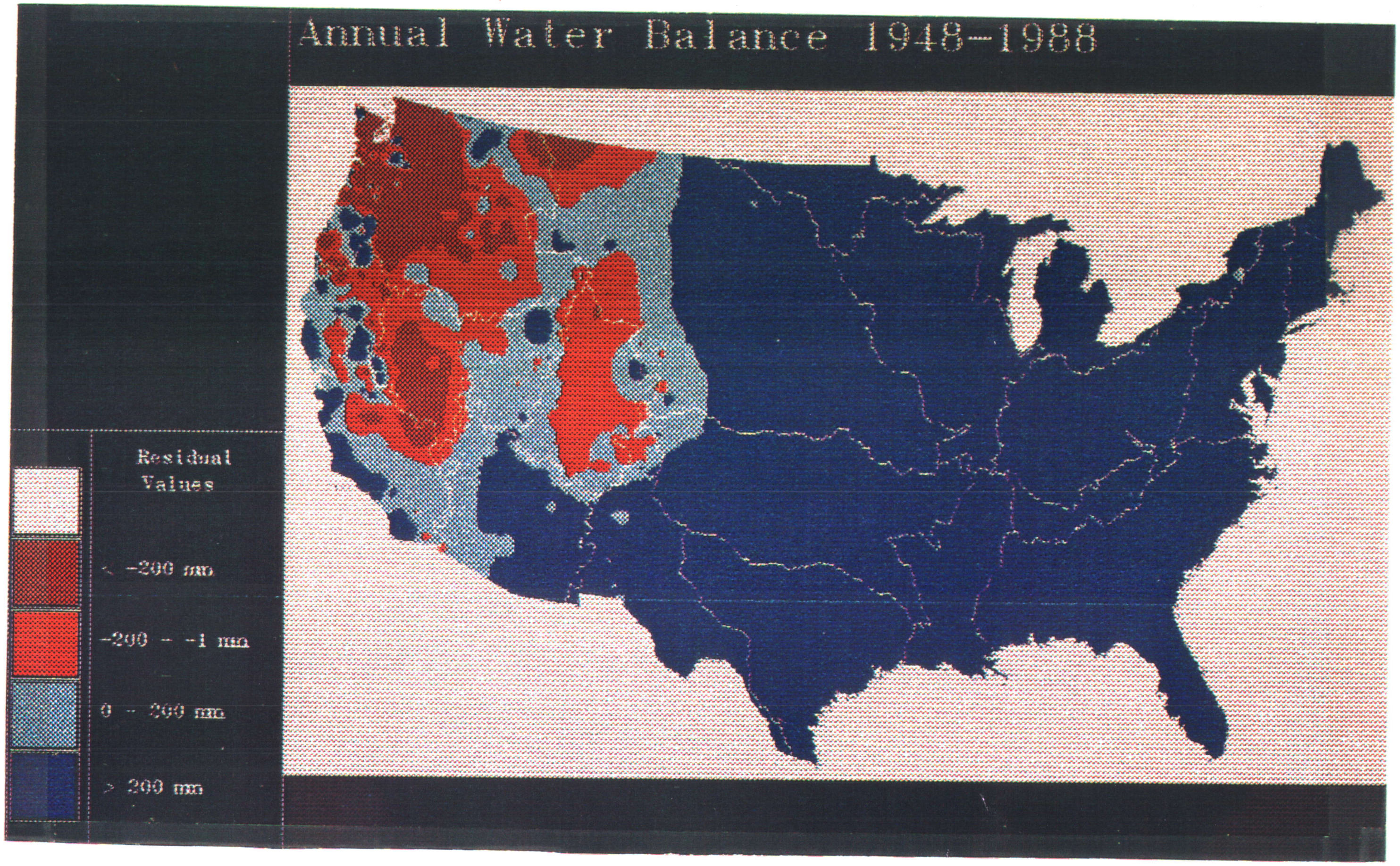

Figure 6 Annual Input-output surface

balance (negative), and dark red representing those regions with large negative residuals. These dark red regions are areas where inconsistencies in the measured data are most severe. This occurs almost exclusively in the mountainous west, most notably in the Pacific Northwest, the Great Basin, and to a lesser extent in parts of California. The input-output surface illustrates the inadequacy of HCN historical data to account for the amount and spatial distribution of precipitation in the mountainous western United States.

Snotel data were incorporated into the precipitation record to increase the elevational range and spatial density of precipitation observations and to improve the distributed water balance calculations. Average annual precipitation values were calculated from monthly HCN and Snotel site data for the period 1982 to 1988. Monthly runoff values for 1982 to 1988 were aggregated to annual averages. These values were interpolated using the procedure described earlier to create new annual precipitation-snow and runoff surfaces.

Additionally, precipitation surfaces were generated using only the HCN data for the period 1982 to 1987 to compare the spatial distribution of precipitation with and without the incorporation of snow data in the precipitation record (Figure 7.).

The spatial patterns of the short-term surfaces were visually compared to the 41-year surfaces and found to be highly similar. While average annual precipitation values are greater during the 1948 to 1988 period, particularly in parts of the west, the general patterns of precipitation and runoff across the country do not vary significantly when short-term average values are used rather than the 41-year average values. However, comparing the short-term precipitation-snow surfaces to the short-term precipitation surfaces calculated using only the HCN data, illustrates a significant increase in measured precipitation input in the mountainous West with the inclusion of the Snotel data, most notably in the Pacific Northwest, Great Basin, and Upper Colorado regions.

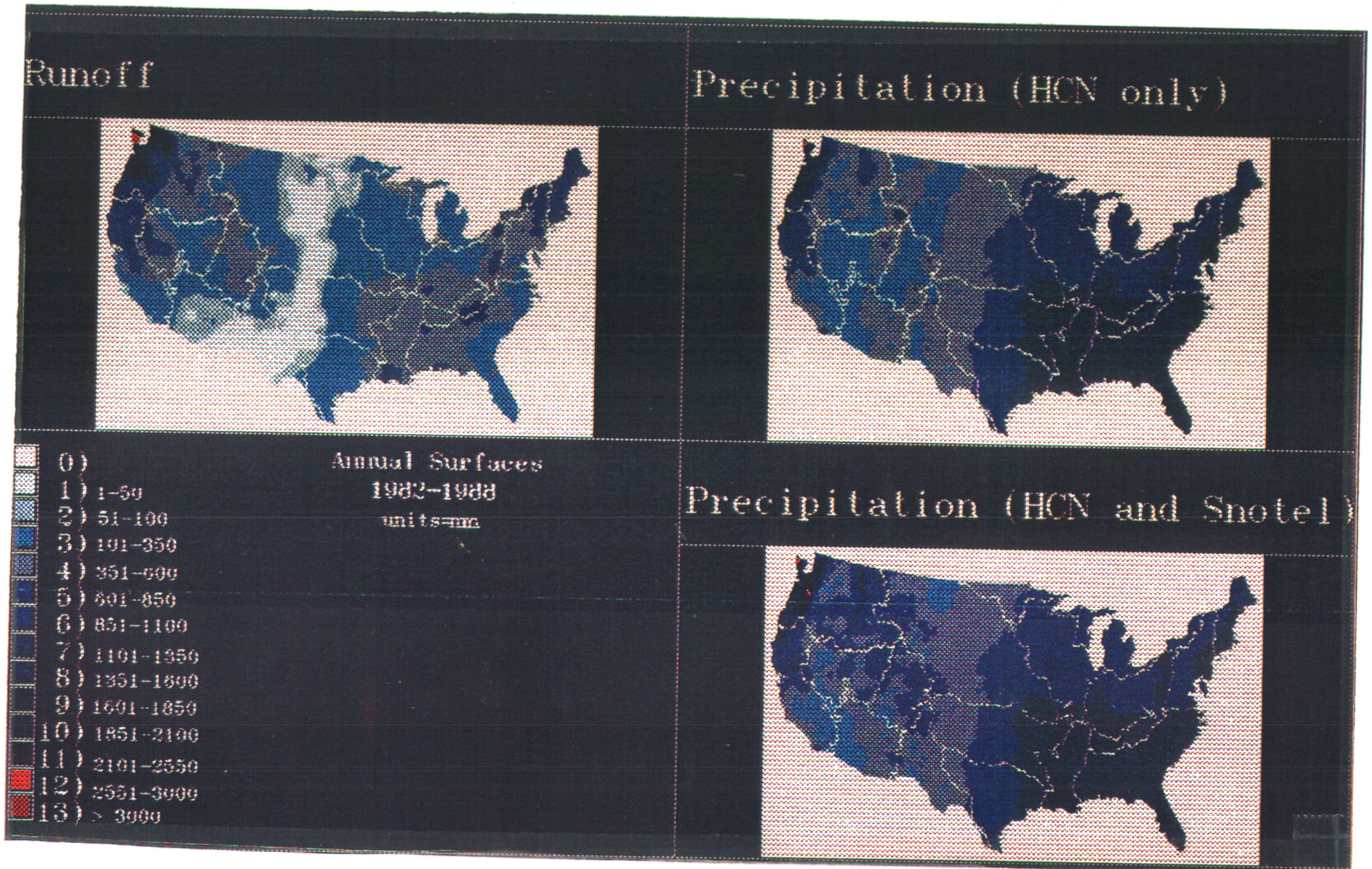

Figure 7 Average annual runoff, precipitation, and precipitation - snow surfaces

The short-term precipitation-snow and runoff surfaces were used to calculate a new distributed water balance across the continent. An annual water balance was also calculated using the short-term precipitation surfaces generated using only the HCN data to compare and quantify the improvement when including snow in the calculations (Figure 8). The input-output surfaces calculated with the incorporation of Snotel data illustrate a substantial improvement in the distributed water balance. As compared with the input-output surfaces calculated using only the HCN data, a greater portion of the mountainous west, particularly large regions of the Pacific Northwest, Great Basin, and Upper Colorado have positive rather than negative residuals. This analysis illustrates that care must be taken in the use of historical precipitation estimates to avoid under-estimation in mountainous regions, and that the inclusion of snow into the precipitation record enhances the utility of the historical data for characterizing the spatial distribution of precipitation by increasing the elevational range and spatial density of measurement sites. It

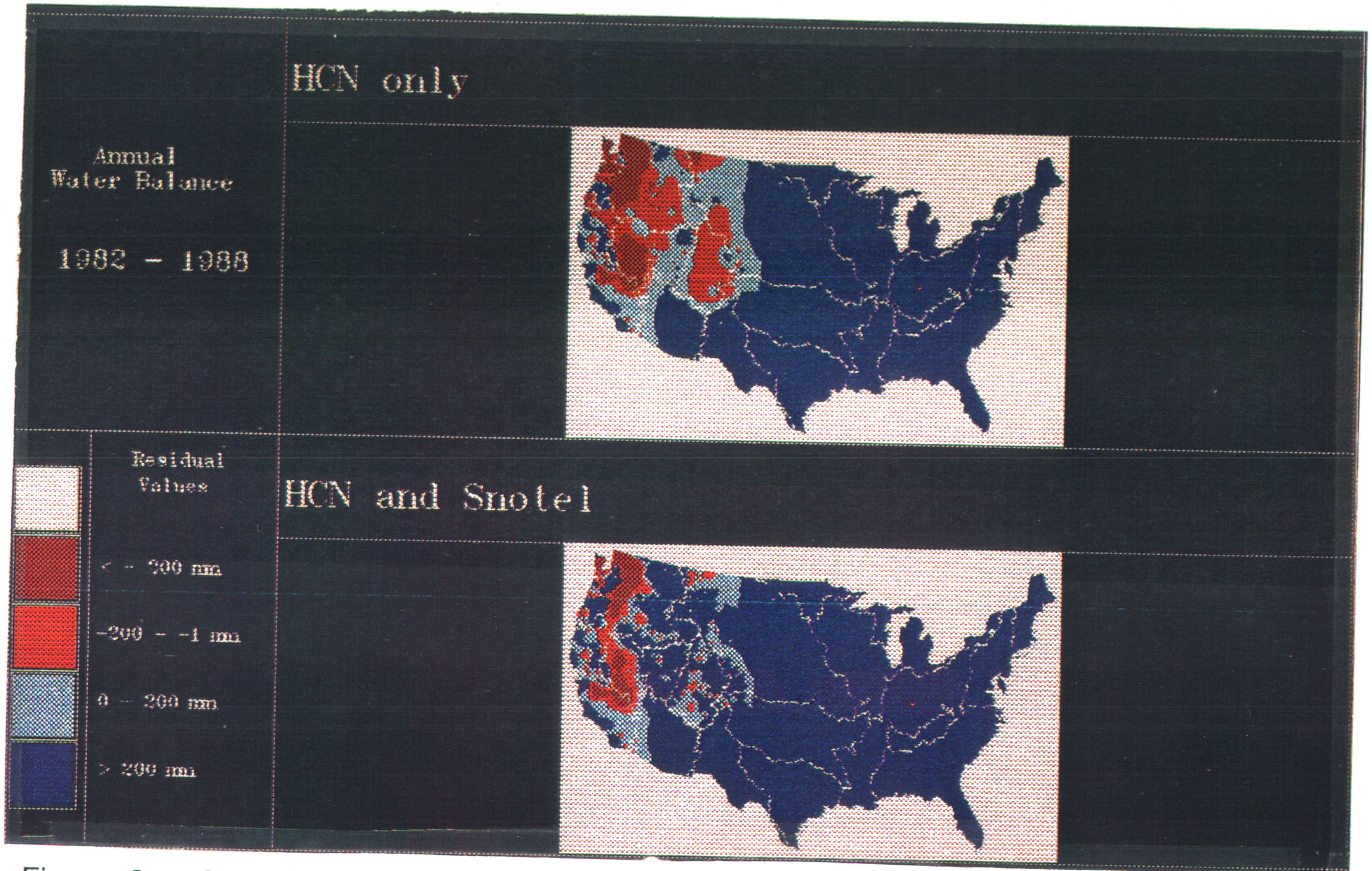

Figure 8 Annual input-output surfaces with and without Snotel data

also emphasizes the need to consider orographic effects on the spatial distribution of precipitation in mountainous regions.

Annual average runoff, precipitation, and precipitation-snow values from the short-term surfaces were calculated for four major hydrologic regions in the western United States to quantify the improvement in measured precipitation volume with the inclusion of snow deposition data in the precipitation record. The size of this region is approximately 1.3 million km^2 and includes the Pacific Northwest, the Great Basin, the Upper Colorado and the Lower Colorado water resource regions as defined by the Water Resources Council (1978). These values (in depths of water) are shown in Figure 9. The average annual runoff value for this region is 50.6 cm. The average annual precipitation value using only HCN data, at 46.5 cm, does not even equal the measured runoff. With the inclusion of Snotel data, this value increases to 68 cm, accounting for the total measured runoff plus a positive residual of 17.4 cm.

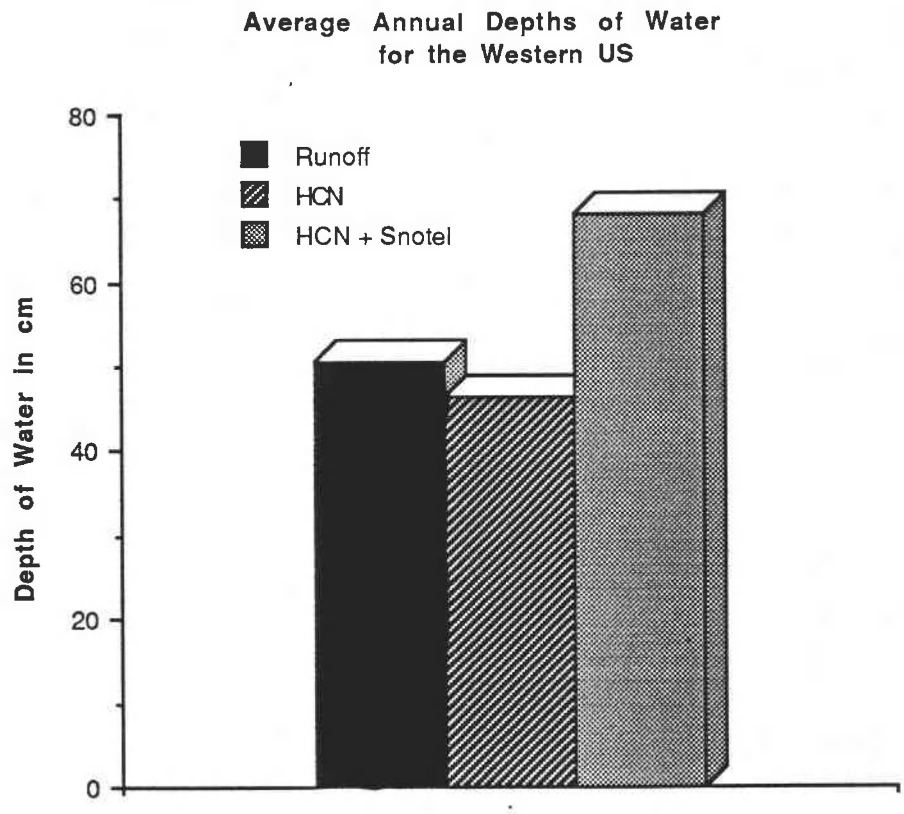

Figure 9 Water balance estimates - western U.S.

Limitations

The analysis presented is exploratory in nature, and part of a larger effort aimed at the development of ecological, hydrological, and biogeochemical models for climate change research. It is important to note the limitations associated with the data and the techniques which were used.

The use of unregulated gauges rather than the entire gauging network limits the spatial density of point measurements, particularly in areas of the western United States. Additionally, the extrapolation of runoff from one drainage to another possibly quite distant drainage, has obvious limitations. However, at the continental scale, detailed basin information is difficult to consider and the use of a time-consistent, quality-controlled data set of unregulated flow measurements was the natural place to begin. In some areas, more measurement sites will need to be incorporated for future work, and flow records from regulated basins will need to be included (for example, in the southwest where regulated flow comprises a substantial portion of the measured runoff, data measurements are sparse). The use of regulated flow exclusively will become particularly critical for regional scale, seasonal analyses using monthly time series data rather than long-term averages. The point here is that while augmentation of the precipitation-runoff database with additional data is required, better techniques for distributing these data both spatially and temporally in topographically diverse regions must be developed.

The use of unregulated gauging stations exclusively for this study, introduced a small drainage area bias. This bias may actually tend to over-estimate runoff, as smaller basins yield greater depth of flow per unit area. Conversely, unregulated gauging stations having large drainage areas typically produce less runoff. In any event, I do not feel that by using unregulated flow exclusively, the runoff estimates are off by an order of magnitude, or any substantial amount for the purposes of this analysis. The emphasis in this study was not to attempt to simulate runoff distribution or predict runoff at a point, but rather to use the runoff surfaces as a check on the precipitation estimates in a general sense, to identify those regions where severe inconsistencies exist in the measured values of precipitation and runoff.

The procedure used to generate the precipitation and runoff surfaces is a simple, linear interpolation algorithm. As such, it may introduce estimate bias in areas of high topographic relief. Geostatistical techniques such as kriging and co-kriging have been applied across smaller geographic areas to interpolate precipitation based on precipitation-elevation relationships (e.g., Dingman et al., 1988, Istok et al., 1990a,b; Tabios and Salas, 1985). Phillips et al. (in review) showed that while co-kriging was effective in estimating precipitation distribution over a small river basin, the method could not be applied over a larger, more hydrologically diverse region. Furthermore, while other interpolation algorithms may yield precipitation and runoff estimates which are different, I do not feel that they would contradict the conclusions from this analysis - that precipitation is underestimated in regions of the western United States by the historical data, and that the inclusion of snow data into the historical record improves the precipitation estimates in mountainous regions.

This analysis is a first-cut effort at spatially distributing precipitation at the continental scale for the identification of regions where more detailed analyses should be directed. Other models and interpolation algorithms which can include elevation and other variables as factors to better simulate the spatial distribution of precipitation-elevation relationships should be considered in future work, at a variety of spatial scales.

An uncertainty analysis is beyond the scope of this study. However, estimates of uncertainty for both the distributed precipitation and runoff surfaces should be addressed in future work. One way to address this issue would be to utilize a 'jack-knife' procedure whereby each original point measurement of precipitation (or runoff) is removed and the interpolation algorithm re-run over the entire grid. The estimate of precipitation (or runoff) at that point given by the interpolation algorithm could then be compared to the actual measured value to obtain an estimate of uncertainty. This procedure could be performed for each of the original measurment points separately to produce a surface of uncertainty associated with the distributed estimates of precipitation and runoff.

Conclusions

The development of ecological and hydrological models for analyses across large areas requires spatially distributed estimates of precipitation. While historical hydro-meteorological data may be used to characterize the spatial distribution of precipitation across large regions, geographic scale and topographic variability must be considered. In the United States, historical data characterize precipitation best in regions with minimal topographic variability, namely the eastern and mid-western regions. However, the historical data may be severely limiting in mountainous regions of the West, in part, because the data do not account for precipitation inputs at high elevations.

This study has illustrated that the integration of snow measurements into the HCN precipitation record is essential for improving precipitation estimates. The incorporation of snow data into the precipitation record for four major hydrologic regions of the western United States improved the precipitation input by roughly 40%. While the addition of snow data significantly improves the spatial distribution and elevational range of measurement sites, these data have a limited geographical extent and period of record. Additionally, the inclusion of these data will not, in itself, resolve the temporal variability of precipitation-runoff relationships. Resolving the seasonal cycle of winter snow deposition followed by spring snowmelt runoff is a more complex issue which is critical for predicting runoff under both current and predicted $2XCO_2$ climate conditions in water-stressed areas of the western United States. Ultimately, techniques must be developed to use these and other sources of data to account for snow depletion and runoff timing in mountainous regions.

This research has established a database for precipitation and runoff analyses at regional and continental scales and has produced spatially distributed precipitation estimates for the conterminous United States at a resolution which is ecologically meaningful. Most importantly, it has demonstrated that it is insufficient to simply use historical data to characterize precipitation across large areas, particularly in mountainous regions where dramatic precipitation gradients exist. Spatially distributed precipitation estimates that account for the spatial arrangement of measurement sites, precipitation-elevation relationships, and topographic constraints on precipitation distribution are needed.

Bibliography

Bradley, R.S., H.F. Diaz, J.K. Eischeid, P.D. Jones, P.M. Kelly and C.M. Goodess, Precipitation fluctuations over northern hemisphere land areas since the mid-19th century, *Science*, 1987.

Brutsaert, W., Catchment scale evaporation and the atmospheric boundary layer, *Water Resources Research*, 22, 39S-45S, 1986.

Budyko, M.I., *Climate and Life*, pp. 508, Academic Press, New York, 1974.

Chow, Ven Te, *Handbook of Applied Hydrology*, McGraw-Hill, New York, 1964.

Diaz, H.F., R.S. Bradley, and J.K. Eischeid, Precipitation fluctuations over global land areas since the late 1800's, *Journal of Geophysical Research*, vol. 94, 1989.

Dickinson, R.E. and R.J. Cicerone, Future global warming from atmospheric trace gases, *Nature*, 319, 109-115, 1986.

Dingman, S.L., D.M. Seely-Reynolds, and R.C. Reynolds III, Application of driging to estimateing mean annual precipitation in a region of orographic influence, *Water Resources Bulletin*, 24, pp.329-339, 1988.

Dooge, James, C.I., Looking for hydrologic laws, in *Trends and Directions in Hydrology*, ed. Stephen J. Burges, pp. 46S-58S, American Geophysical Union, Washington, D.C., 1986.

Dooge, James, C.I., Hydrologic models and climate change, keynote address *Chapman Conference on Hydrologic Aspects of Global Climate Change*, 1990.

Eagleson, P.S., Land Surface Processes in Atmospheric General Circulation Models, in *Proceedings of Greenbelt Study Conference,* p. 560, Cambridge University Press, New York, 1982.

Eagleson, P.S., The emergence of global-scale hydrology, *Water Resources Research*, 22,6S 14S, 1986.

EarthInfo, *Hydrodata User's Manual - Daily and Peak Values*, Denver, CO, 1988.

Hall, F.G., D.E. Strebel, and P.J. Sellers, Linking knowledge among spatial and temporal scales: vegetation, atmosphere, climate, and remote sensing, *Landscape Ecology*, vol. 2, 1988.

Hansen, J., I. Fung, A. Lacis, D. Rind, S. Lebedeff, R. Ruedy, and G. Russell, Global climate changes as forecast by Goddard Institute for Space Studies three dimensional model, *Journal of Geophysical Research*, 93D, 9341-9364, 1988.

Hansen, J., and S.Lebedeff, Global trends of measured surface air temperature, *Journal of Geophysical Research*, 92, 13345-13372, 1987.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner, Climate sensitivity, analysis of feedback mechanisms, in *Climate Processes and Climate Sensitivity*, edited by J.E. Hansen and T. Takahashi, Geophysical Monograph, vol. 5, pp. 130-163, American Geophysical Union, Washington, D.C., 1984.

Isaaks, E.H. and R.M. Srivastava, *Applied Geostatistics*, pp. 561, Oxford University Press, New York, 1989.

Istok, J.D., J.A. Hevesi, and A.L. Flint, Precipitation estimation in mountainous terrain using multivariate geosttistics: 1. Structural analysis. Unpublished manuscript, 1990a.

Istok, J.D., J.A. Hevesi, and A.L. Flint, Precipitation estimation in mountainous terrain using multivariate geosttistics: 2. Isohyetal maps. Unpublished manuscript, 1990b.

Jones, P.D., T.M.L. Wigley, and P.B. Wright, Global temperature variations between 1861 and 1984, *Nature*, 322, 430-434, 1986.

Karl, T.R., Multi-year fluctuations of temperature and precipitation: the gray area of climate change, *Climatic Change*, vol. 12, 1987.

Karl, T.R. and W.E. Riebsame, The impact of decadal fluctuations in mean precipitation and temperature on runoff: a sensitivity study over the United States, *Climatic Change*, vol. 15, 1989.

Linsley, R.K., M.A. Kohler, and L.H. Paulhus, *Hydrology for Engineers*, McGraw Hill, 1982.

Manabe, S. and R.T. Wetherald, On the distribution of climate change resulting from an increase in CO_2 concentration on the climate of a general circulation model, *Journal of Atmospheric Sciences*, 32, 3-15, 1975.

National Oceanographic and Atmospheric Administration, National Geophysical Data Center, *Geophysics of North America: Users Guide*, U.S. Department of Commerce, Boulder, Colorado, 1989.

Neilson, R.P., G.A. King, R.L. DeVelice, J. Lenihan, D. Marks, J. Dolph, B. Campbell, and G. Glick. Sensitivity of ecological landscapes and regions to global climate change. *U.S. Environmental Protection Agency*, Environmental Research Laboratory, Corvallis, Oregon, 1989.

Phillips, D.L., J. Dolph, and D. Marks, A Comparison of Geostatistical Procedures for Spatial Analysis of Precipitation in Mountainous Terrain, *Biospheric Feedbacks to Climate Change: The Sensitivity of Regional Trace Gas Emissions, Evapotranspiration, and Energy Balance to Vegetation Redistribution*, Chapter V, EPA Report, ERL-Corvallis, 1990.

Quinlan, F.T., T.R. Karl, and C.N. Williams, *United States Historical Climatology Network (HCN) Serial Temperature and Precipitation Data*, U.S. Department of Energy, Carbon Dioxide Information Analysis Center, Oak Ridge, TN, 1987.

Rasmusson, E.M., El Nino and variations in climate, *American Scientist*, 73, 168-177, 1985.

Rasmusson, E.M. and P.A. Arkin, Measuring and understanding global precipitation variability, *in Symposium on Global Change Systems - Special Sessions on Climate Variations and Hydrology*, Anaheim, CA, 1990.

Rind, D., The influence of vegetation on the hydrologic cycle in a global climate model, in *Climate Processes and Climate Sensitivity*, edited by J.E. Hansen and T. Takahashi, Geophysical Monograph, vol. 5, pp. 73-92, American Geophysical Union, Washington, D.C., 1984

Rind, C., The doubled CO_2 climate and the sensitivity of the modeled hydrologic cycle, *Journal of Geophysical Research*, 93, 5385-5412, 1988.

Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy, Potential evapotranspiration and the likelihood of future drought, *Journal of Geophysical Research*, 95, 9983-10005, 1990.

Ropelewski, D.F.and M.S. Halpert, North American precipitation and temperature patterns associated with the El Nino Southern Oscillation Cycle, *Monthly Weather Review*, 1986.

Ropelewski, D.F. and M.S. Halpert, Global and regional scale precipitation patterns associated with the El Nino Souther Oscillation Cycle, *Monthly Weather Review*, 1987.

Schlesinger, M.E. and J.F.B. Mitchell, Climate model simulations of the equilibrium climatic response to increasing carbon dioxide, *Reviews of Geophysics*, 25, 760-798,1987.

Shugart, H.H. and D.C. West, Development of an appalachian deciduous forest succession model and its application to assessment of the impact of the chestnut blight, *Journal of Environmental Management*, 5, 161-179, 1977.

Smith, J.B. and D.A. Tirpak, *The Potential Effects of Global Climate Change on the United States*, Report to Congress, vol. PM-221, United States Environmental Protection Agency, Washington, D.C. 1989

Tabios, G.Q. and J.D. Salas, A comparative analysis of techniques for spatial interpolation of precipitation, *Water Resources Bulletin*, 21, pp 365-380, 1985.

U.S. Army Corps of Engineers, *GRASS Users and Programmers Manual*, U.S. Army Corps of Engineers, Construction Engineering Research Laboratory, Champagne, IL, 1988.

U.S. Water Resources Council, *The Nation's Water Resources 1975-2000*, Volume3 Analytical Data Summary, Washington, D.C. 1978

U.S.D.A. Soil Conservation Service, *Snow Survey and Water Supply Products Reference*, West National Technical Center, Portland, OR, 1988.

Wallace, J.R., D.P. Lettenmaier, and E.F. Wood, A daily hydro-climatological data set for the continental United States, *Water Resources Research*, (in review), 1990.

Wigley, T.M.L., J.Angell, and P.D. Jones, Analysis of the temperature record, in *Detecting the Climatic Effects of Increasing Carbon Dioxide*, DOE/ER-0235, pp. 198, Dept. of Energy, Washington, D.C., 1985.