# The Influence of Climatic Change on Watershed Yield in the Sierra Nevada

John H. Humphrey, PhD, Hydmet Inc.

## INTRODUCTION

The purpose of this study was to provide a practical procedure for evaluating the influence of climatic change on watershed yield for the west slope Sierra Nevada.

## LITERATURE REVIEW

### Climatic Change Scenarios

Worldwide concern for the influence of climatic change on all aspects of society has resulted in research efforts by many national governments in developing Global Climate Models (GCMs). Some of the internationally accepted GCMs (IPCC, 2001) are those of the Hadley Center in Britain (UK Hadley, 2002), Canada (CCC, 2003), U.S. (GFDL, 2003) and U.S. (NCAR, 2003). All of the GCMs are undergoing continual modification and producing new results every few years. The United States effort is currently combining and improving the GCMs of NCAR and GFDL, eventually resulting in one official United States position (U.S. CLSP, 2004). All of these models and others GCMs of countries such as, Japan, Germany, Australia, and France agreed that increased greenhouse gases have caused and will continue to cause significant climatic warming, especially at high latitudes.

Serious concerns have been raised on the specific influence of climatic warming on agricultural regions and the ocean water level. However, the GCM forecasts, for typical time frames of 50 and 100 years into the future, disagree significantly. There is a general consensus that man-caused climatic warming through 2002 is in the range of 0.5 deg. C to 1.0 deg. C. Additional climatic warming through the year 2050 is expected to be in the range of an additional 1 deg C to 4 deg C, with most models predicting in the middle of that range. These GCM differences can be attributed to both model algorithm differences and differing forecasts of greenhouse gases concentrations. This range of estimates of climatic warming is also applicable to California.

There are more serious differences between GCMs on the influence of climatic warming on precipitation. For example, for California, the Hadley GCM forecasted increasing El Nino tropical moisture influx into southern and central California, and increased annual precipitation up to 100%. In contrast, the Parallel Climate Model (Dettinger, 2004) showed little change in precipitation in California. Recent trends show significantly decreasing precipitation for southern and central California, and little change or a slight increase in northern California. Further obscuring the predictions, natural fluctuations of wet and drought periods, derived from hundreds of years of long-term proxy records, are greater than any of the GCM forecasts (Redmond, 2002). Until there is better GCM agreement, or at least an official United States position, it seemed reasonable to have scenarios of both increasing and decreasing precipitation for the Sierra Nevada.

Schneider (2004) had a good discussion of GCM uncertainty, which indicated that such an approach was acceptable.

For the purposes of this study, wet season (October-March) precipitation scenarios, for the Sierra Nevada, in the range of minus 25% to plus 25% were used. Increased temperature scenarios, with a range of 0 deg. C. to 4 deg. C., combined with the above precipitation range, include all reasonable GCM predictions made for the Sierra Nevada, and those likely to be made in the future.

## California Research Studies

There have been a number of recent studies on the potential influence of climatic change on flow from river basins in the Sierra Nevada (U.S. GCRP, 2002). This assessment report by GCRP ("Our Changing Planet") found an actual increase of 1.0 to 1.5 deg C air temperature generally in California, and a decrease in precipitation in Southern California. Their review of Global Climate Models showed a range of increases in air temperature of 1.5 deg C to 5 deg C through 2100, and precipitation increases, especially for central and southern California up to 100%. Numerous other publications discussed similar findings, such as: Michael D. Dettinger at U.S. Geological Survey and Daniel R. Cayan at Scripps Institute of Oceanography (Stewart, 2004 and Dettinger, 2004) and Lisa C. Sloan at U.C. Santa Cruz (Snyder, 2004). Research work for the Sierra Nevada has also been sponsored by the National Park Service and by the California Department of Water Resources (USDI, 2002), (Scripps, 2004).

Most published studies of California GCM applications relied on the UK Hadley Center and Canadian forecasts, which were basically a warmer and wetter scenario for the Sierra Nevada (for example, Jeton, 1999). However, a wetter scenario for southern and central California seems quite unlikely considering existing trends. The Scripps Institute of Oceanography is partnering with California Department of Water Resources and the California Energy Commission to improve regional climatic modeling and reduce uncertainty regarding changes in precipitation patterns. All of the studies reviewed above found that, regardless of GCM predictions of wet or dry, climatic warming had adverse consequences on watershed yield from the Sierra Nevada.

# METHODOLOGY

## Study Area

The geographic study area was defined as the west slope Sierra Nevada. Figure 1 shows river basins included in this definition. The study area was divided into north, central and south regions to incorporate significant differences in climatology. Moving from south to north in the Sierra Nevada, at a given elevation, air temperatures decrease, precipitation increases, and snowmelt season solar radiation is greater.

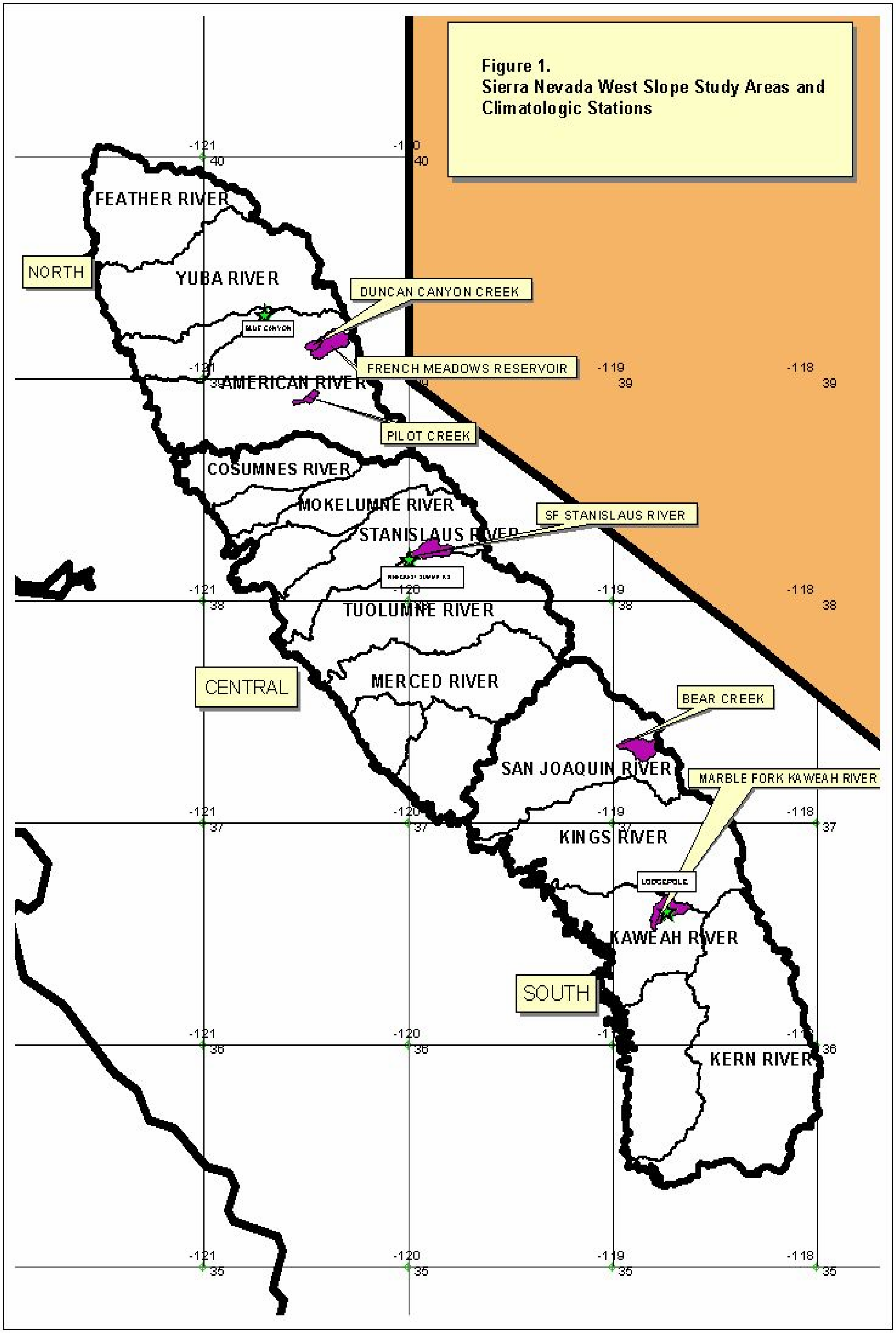


**Figure 1.**
**Sierra Nevada West Slope Study Areas and Climatologic Stations**

## Description of HSPF Model

The U.S. Environmental Protection Agency Hydrologic Simulation Program-Fortran (HSPF) model was selected to model watershed yield (USEPA, 2001, 2003). This model is widely accepted by the scientific community, and possesses the capability of long-term continuous simulations, including snow cover.

## WDM – Watershed Climatic Data Management Files.

The HSPF model uses climatic data in a time series management system operating with direct access to a Watershed Data Management (WDM) file. The time period for model simulations was October 1948 to December 2003 (55 years). From 1948 until 1989, there were a limited number of long-term hourly precipitation stations in or near the Sierra Nevada. Before 1989, with the exception of the weather station at Blue Canyon, only precipitation and maximum/minimum daily air temperatures were available at high-elevation sites. Since 1989, continuous recorded and telemetered climatologic stations have been installed at numerous locations in the Sierra Nevada.

### *Hourly and Daily Precipitation*

Precipitation data were published by the National Weather Service, in hourly and daily form. Missing data for precipitation were obtained from a number of nearby stations. A considerable work effort was required to compile an accurate hourly record for the three index stations at Blue Canyon, Pinecrest and Lodgepole (see Figure 1 for locations). Precipitation totals, for the index and other stations, and April 1st snowpack water content, are shown on Figures 3-5. A relationship is shown for October-March (wet season) between accumulated precipitation (and snowpack water content) with elevation. Precipitation catch efficiency in the snow zone above 5000 ft is severely influenced by wind speed, with a catch deficiency of approximately 1% for every mile per hour of wind speed. April 1st snowpack water content, below 8,000 ft, represented a minimum index to precipitation, since rain and melt water are generally lost to the soil, and evaporation is significant. For these reasons, envelope curves were drawn for the data. These curves were later found to be appropriate for the calibration watersheds

**Figure 2.**

NORTH SIERRA NEVADA PRECIPITATION STATIONS

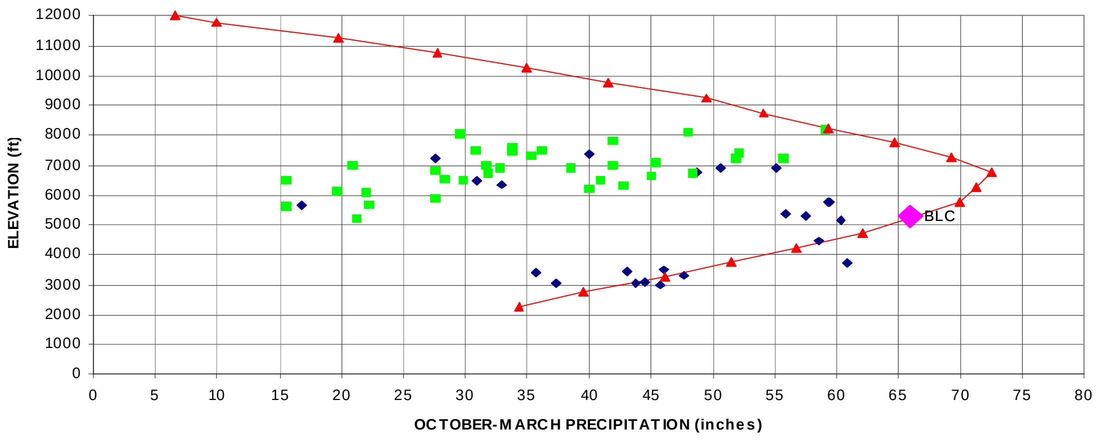


**Figure 3.**

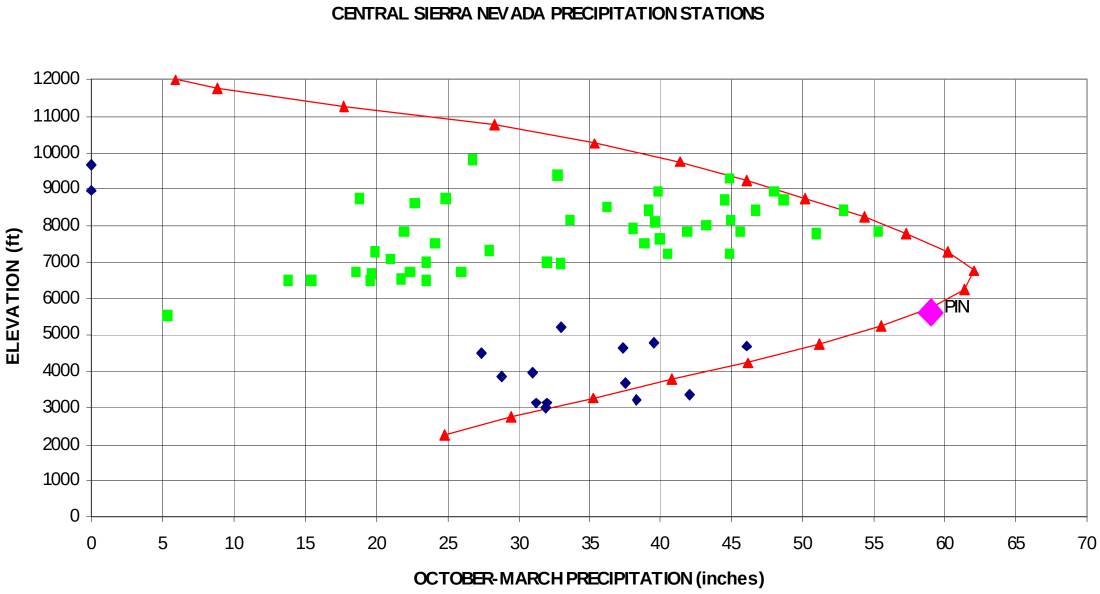
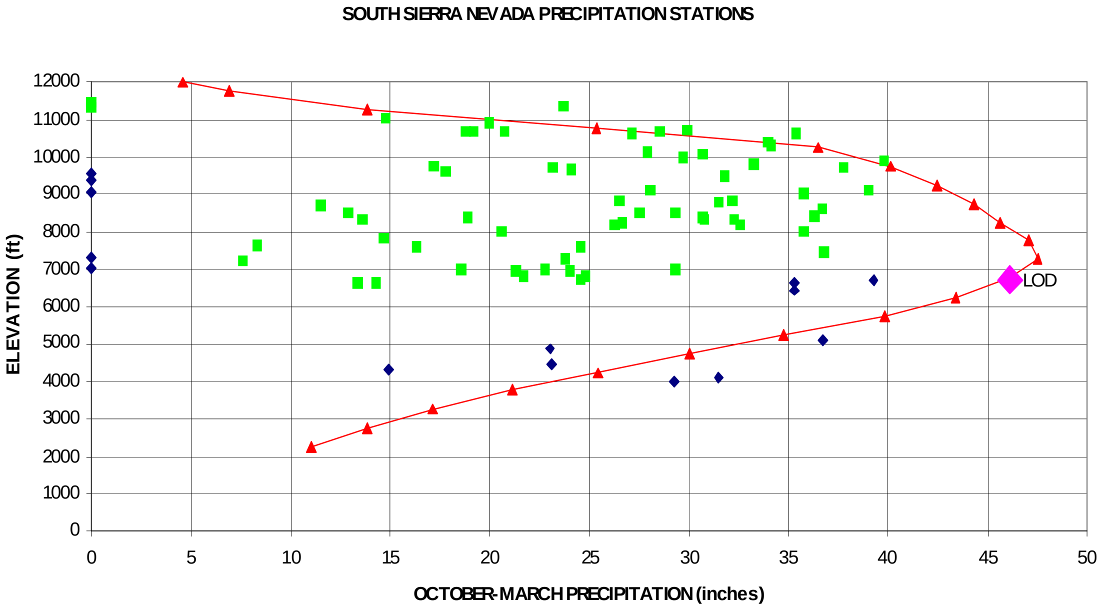


**Figure 4.**



### *Hourly Air Temperature*

The primary recording station for hourly air temperature data was Blue Canyon. Hourly air temperature data were available at other stations after 1989. Daily maximum and minimum air temperature were available at many other locations, during the 1948-1989 time period. An algorithm was written to convert maximum and minimum air temperature data to hourly air temperature using a sine wave function with minimum temperature at hour 0600 and maximum temperature at hour 1500.

### *Hourly Dewpoint*

When observed data were not available from recording weather stations, hourly dewpoint data were estimated from air temperature. The dewpoint was set one degree C. below the minimum air temperature for the day. When precipitation was occurring, dewpoint was made equal to air temperature.

### *Hourly Solar Radiation*

Solar radiation data were estimated from hourly theoretical clear sky radiation (Bird, 1991) for the latitude and elevation of the index climatologic stations (Blue Canyon, Pinecrest and Lodgepole), and adjusted for precipitation days. On precipitation days, a reduction factor was used for the influence of cloud cover on direct solar radiation. Annual averages were further adjusted to be consistent with short-term records at Soda Springs and Reno (California DWR, 1978).

### *Hourly Wind Speed*

Hourly data were available for Blue Canyon and numerous other stations after 1989. However, wind speed is only important for calculating convective-condensation snowmelt. This process is significant for flood forecasting, during unusual winter storms, when air temperatures are warm and rain is falling on snow cover. For years without data, average values for precipitation and non-precipitation days were used.

### *Daily Evaporation*

HSPF uses pan evaporation to estimate evapotranspiration. Short-term pan evaporation data were obtained from several high elevation locations, including: Long Valley Reservoir and Tahoe City, California and Grant Lake, New Mexico. (California DWR, 1978 and US NCDC, 2003). A comparison to long-term records at New Melones Reservoir, California, showed that an annual multiplier coefficient could be used to adjust low-elevation New Melones pan evaporation data to higher elevations.

### *Hydrology*

For calibration purposes, daily streamflow records were obtained from the U.S. Geological Survey for Duncan Canyon Creek, South Fork Stanislaus River and Bear Creek. The South Fork Stanislaus River data were adjusted for storage in Pinecrest Lake.

## HSPF Model Setup

Parameters in the HSPF model were set to values consistent with the hydrology of the watersheds being modeled. The Sierra Nevada region was divided into pervious runoff types to facilitate runoff modeling. Geographic Information System (GIS) mapping was used (ESRI, 2004) to define areas of unique combinations of vegetation, soil type, elevation and aspect.

### *Topography*

To facilitate modeling of snow accumulation and snowmelt, the west slope Sierra Nevada was divided into elevation zones and aspect zones. Aspect was divided into north (300-060 deg.), south (120-240 deg.) and east-west/flat (060-120 deg. and 240-300 deg, less than 10% slope). The average slope used for north and south aspects was 30 degrees.

### *Vegetation*

Land use maps were obtained from the National Land Cover Dataset (USGS, 2003), available from the U.S. Geological Survey EROS Data Center. Defined vegetation cover categories were forest, shrub/grassland, rockland (bare) and water. Impervious area urban land uses were included in the bare category.

### *Soil Moisture Capacity*

Soil types and descriptions were obtained from STATSGO (State Soil Geographic Database of the National Resource Conservation Service, USDA, 2003). The HSPF model required a physically meaningful index to soil moisture capacity for the lower moisture accounting zone (LZSN). This LZSN parameter depended on soil thickness above bedrock and primarily sets evapotranspiration losses for the period following spring snowmelt. Soil types were divided into three soil moisture capacity zones: ***low***-rock or urban (5 cm), ***moderate***-shrub or grass (15 cm) and ***high***-forest (30 cm).

## CALIBRATION OF HSPF MODELS

HSPF input parameters were required for pervious land surfaces. For runoff from pervious surfaces, land use, topography and soils defined unique sets of parameters. There were potentially a combination of 25 elevation zones, 3 aspects, 3 vegetation types and 3 soil types or 675 types. Many of these combinations were not needed: elevation zones without significant snowcover, redundant vegetation and soil types, and some combinations with small areas. 189 pervious land types were sufficient to define all combinations of these types.

### Elevation Adjustments to Climatologic Database

The HSPF model internally adjusted air temperature and dewpoint temperature to elevation change (from the index climatologic station) using the wet adiabatic lapse rate (5 deg C. per 1,000 m). Windspeed was adjusted using a relationship between vegetative cover and the condensation-convective heat transfer coefficient. (U.S. Army, 1957). Solar radiation increases with elevation were estimated using the theoretical relationships of Bird (1991). Evapotranspiration decreases with elevation were estimated using the Penman (1948) equation.

### Description of Calibration Watersheds.

Duncan Canyon Creek is located in the North Sierra Nevada region in the American River basin (see Figure 1). It has a drainage area of 9.9 sq. mi. (25.6 sq. km) and had nearly complete forest cover (most burned in the 2002 Star Fire) and limited areas of bare rock and old selective logging. It has an elevation range of 5500 to 7200 ft, and is typical of the primary runoff-producing zone of the northern Sierra Nevada. Figure 5 shows elevation zones; figure 6 shows aspect zones; figure 7 shows vegetation zones.

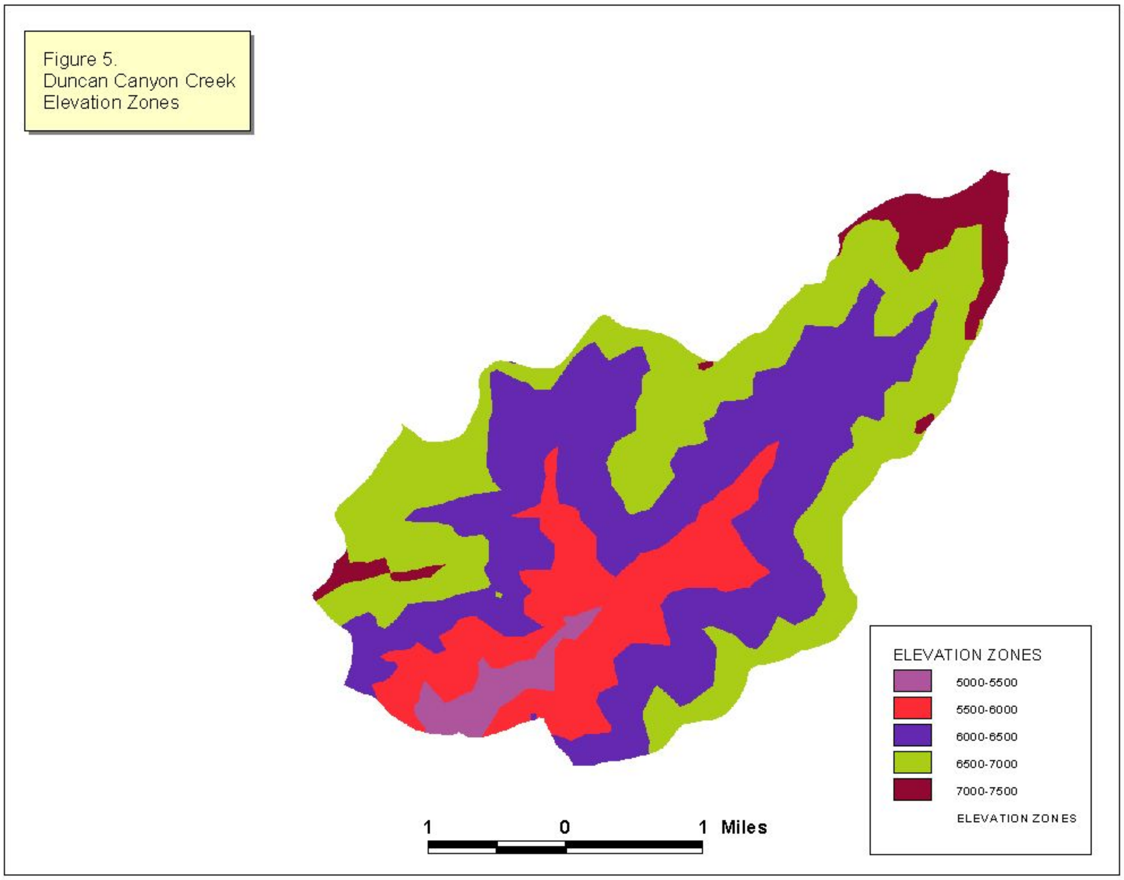


Figure 5.
Duncan Canyon Creek
Elevation Zones

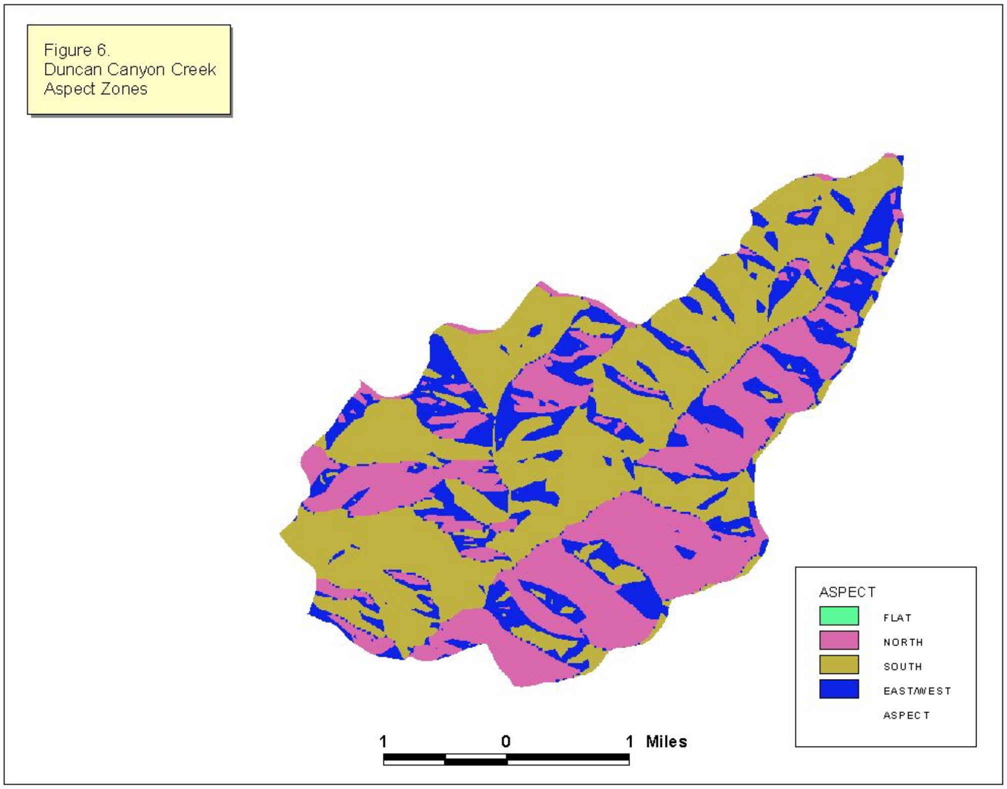


Figure 6.
Duncan Canyon Creek
Aspect Zones

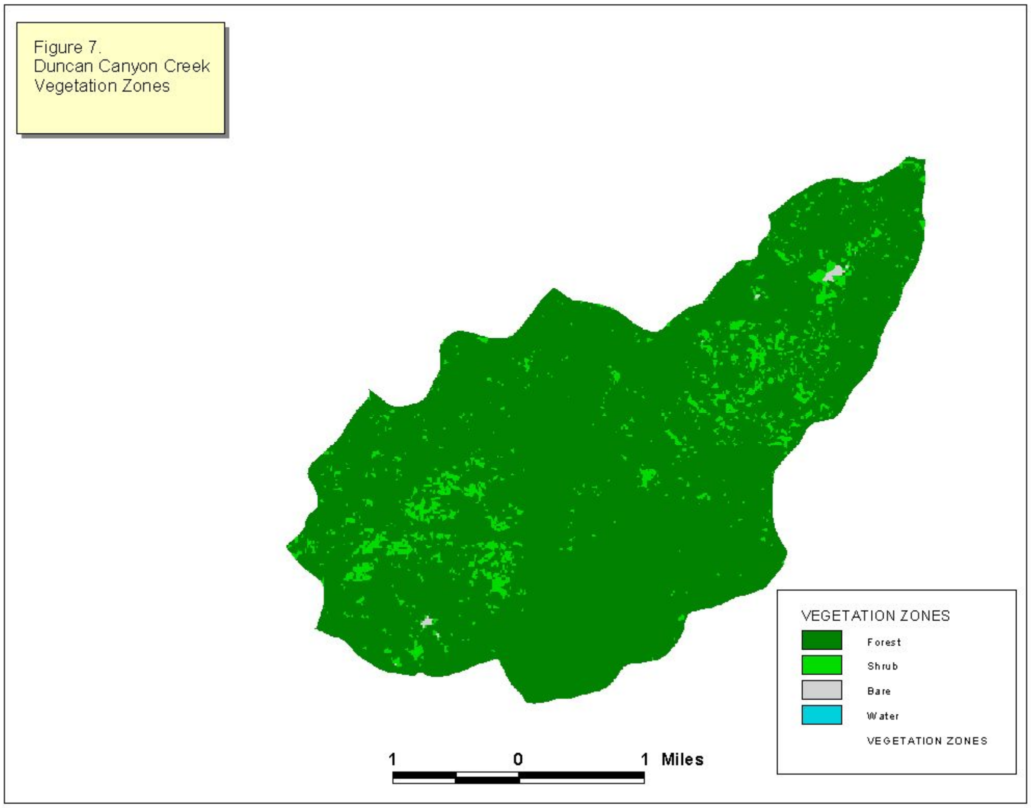


Figure 7.
Duncan Canyon Creek
Vegetation Zones

South Fork Stanislaus River is located in the Central Sierra Nevada region in the Stanislaus River basin. It has a drainage area of 44.8 square miles (116 sq. km) and approximately 50:50 forest cover and bare rock. It has an elevation range of 5500 to 9000 ft.
Bear Creek is located in the South Sierra Nevada region and is a tributary of the Kern River. It has a drainage area of 52.5 square miles (136 sq. km) and has predominately bare rock and grassland with isolated patches of forest. It has an elevation zone range of 5500 to 12000 ft but most of the watershed is above 9000 ft.

### Calibration Procedures

HSPF generated flows were compared to observed daily flows and model parameters were modified to optimize simulation results. The most important model calibration parameters were found to be precipitation elevation zone relationships (Figures 2-4) and specification of the air temperature threshold for discrimination between rain and snow.

Snow cover and spring runoff simulations were emphasized since water available for runoff from the snowpack depends on more model parameters than runoff in the rainfall elevation zones. Snowpack generated runoff is also the most important to resource managers since it occurs when reservoirs, which were drawn down for winter flood control, can be re-filled. In addition, late spring and early summer runoff in the Sierra Nevada is almost always controlled by snowmelt, and agriculture interests without storage facilities and river recreational interests are dependent on this runoff.

## CLIMATE ALTERNATIVES

A separate HSPF database was prepared for each of the climate alternatives. Hourly air temperature and dewpoint temperature files were adjusted by adding 1, 2, 3 and 4 deg C. to the base values. Solar radiation was adjusted for the changes in temperature and cloudiness associated with precipitation changes. A relationship developed between mean annual precipitation and solar radiation, observed at Soda Springs and Reno, was used to adjust values for climatic alternatives. A 25% increase in precipitation and associated cloudiness corresponded to a 10% decrease in solar radiation, and a 25% decrease in precipitation corresponded to a 10% increase in winter and spring solar radiation. Evapotranspiration was adjusted using Penman (1948), which accounted for temperature and solar radiation changes in the climatic alternatives. Average wind speed was adjusted to account for increases or decreases in the number of storm days, corresponding to increases or decreases in precipitation. Average wind speeds for precipitation days were approximately twice those observed in non-precipitation days. 45 HSPF simulation runs were made: Five temperature alternatives (0, 1, 2, 3, 4 deg C), three precipitation alternatives (0, +25%, -25%) and three regions (north, central, south).

## RESULTS

### Calibration

Figures 8 and 9 show examples of watershed calibration. The fit between observed and simulated annual runoff is well within the accuracy of streamflow measurements and the likelihood that the index precipitation station adequately represented the watershed. Daily flows for Bear Creek (Figure 9) show that the HSPF models are not well calibrated to peak flow events, since there was no flow routing simulated. The omission of flow routing has no influence on watershed yield.

**Figure 8.**

**Stanislaus River 44.8 sq. mi.**

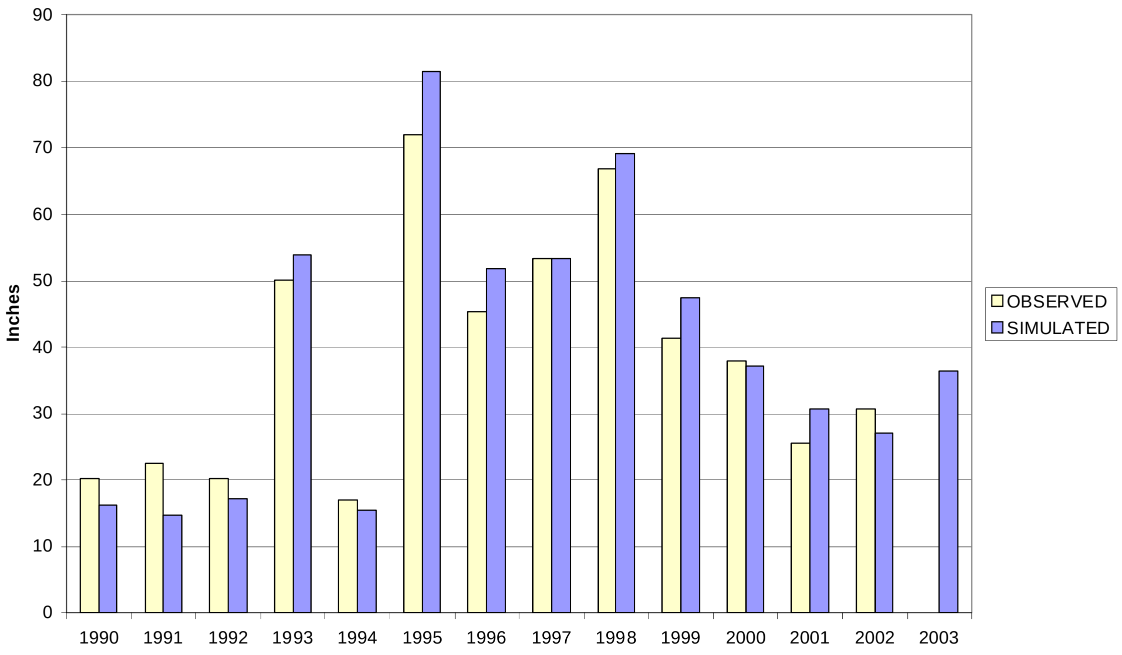
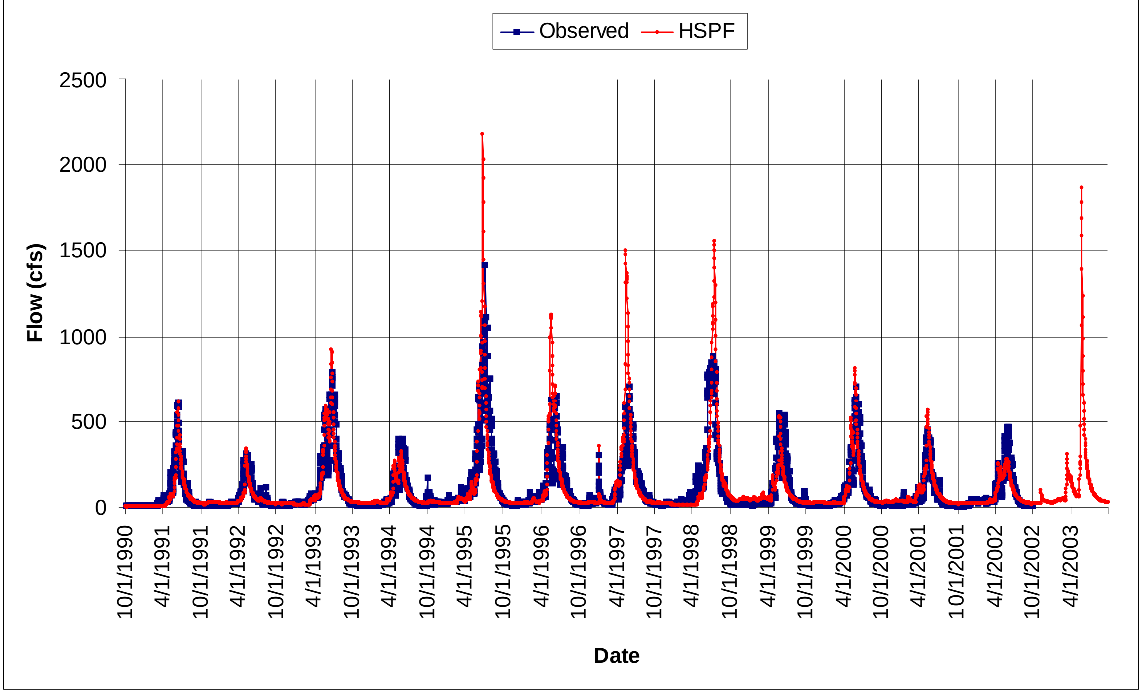


**Figure 9.**

**Bear Creek Daily Flow**



## Climate Alternatives

In order to translate the HSPF model results for 55 years of simulation into a workable tool for resource managers, model run output was processed for representative wet, normal and dry years. These representative years were selected from the American River annual flow frequency distribution for 1948 through 2002. Additional selection criteria were that that they occurred in the last 14 years, when much better climatologic data existed, and that they had typical distributions of winter and spring snowmelt runoff. Year 1992 was selected as a dry year at approximately the annual runoff exceedance 10th percentile. Year 2000 was selected as an average year at the 50th percentile. Year 1998 was selected as a wet year at the 90th percentile.

The calibrated HSPF models were used to generate runoff files for the 189 land types in the three Sierra Nevada regions, for 15 climate alternatives. Monthly output, for the three representative years, 1992, 1998 and 2000, were input into a database, which is accessed by the watershed yield processor.

## Discussion

In general, the influence of climatic change on watershed yield was similar to that found in other studies. Warmer winter temperatures raised the average snowline and consequently shifted runoff from spring to winter. With lower spring snowpack water content, spring runoff ended earlier and summer base flows decreased. Even without a change in precipitation, increased temperature caused increased evapotranspiration losses and reduced annual watershed yield. Relative watershed yield increased with greater efficiency with increased precipitation in wet years. With decreased precipitation, the greatest relative reductions in yield occurred in dry years.

Figures 10-12 show examples of the relationships between climatic change alternatives and watershed runoff. Figure 10 shows April 1st snow water content in the north region for a wet water year. Figure 11 shows relationships between climatic change alternative for the south region for an average year for spring runoff.

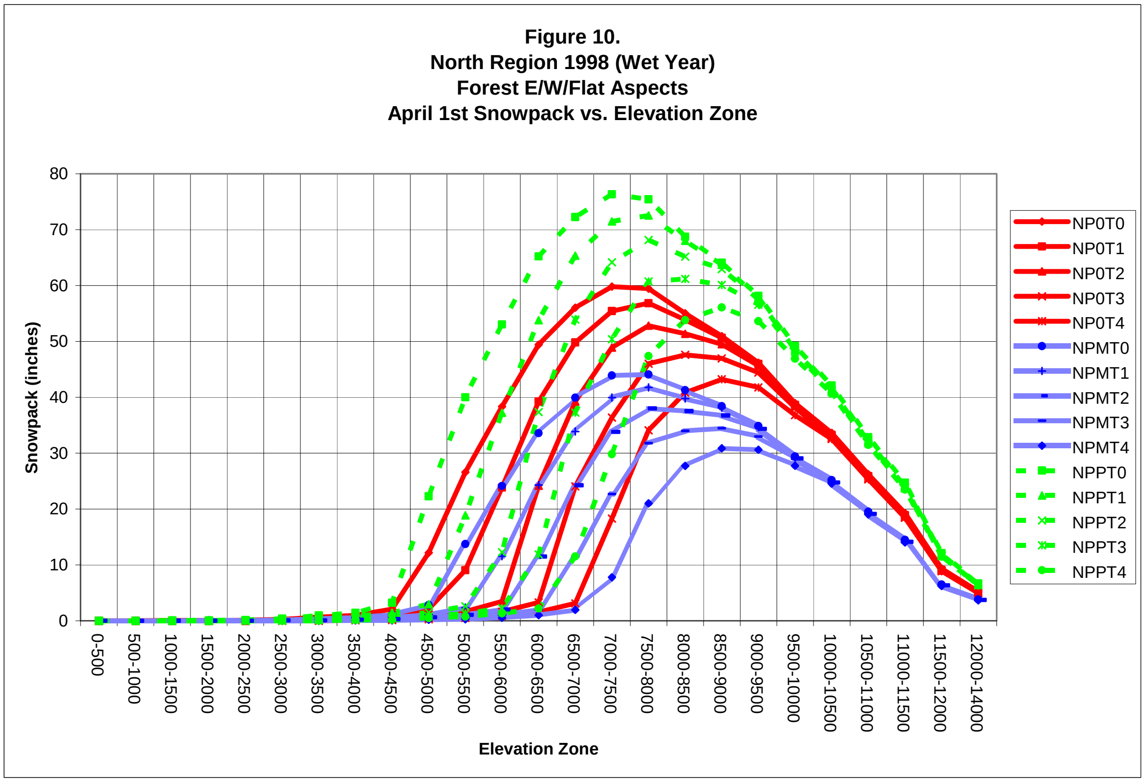


**Figure 10.**
**North Region 1998 (Wet Year)**
**Forest E/W/Flat Aspects**
**April 1st Snowpack vs. Elevation Zone**

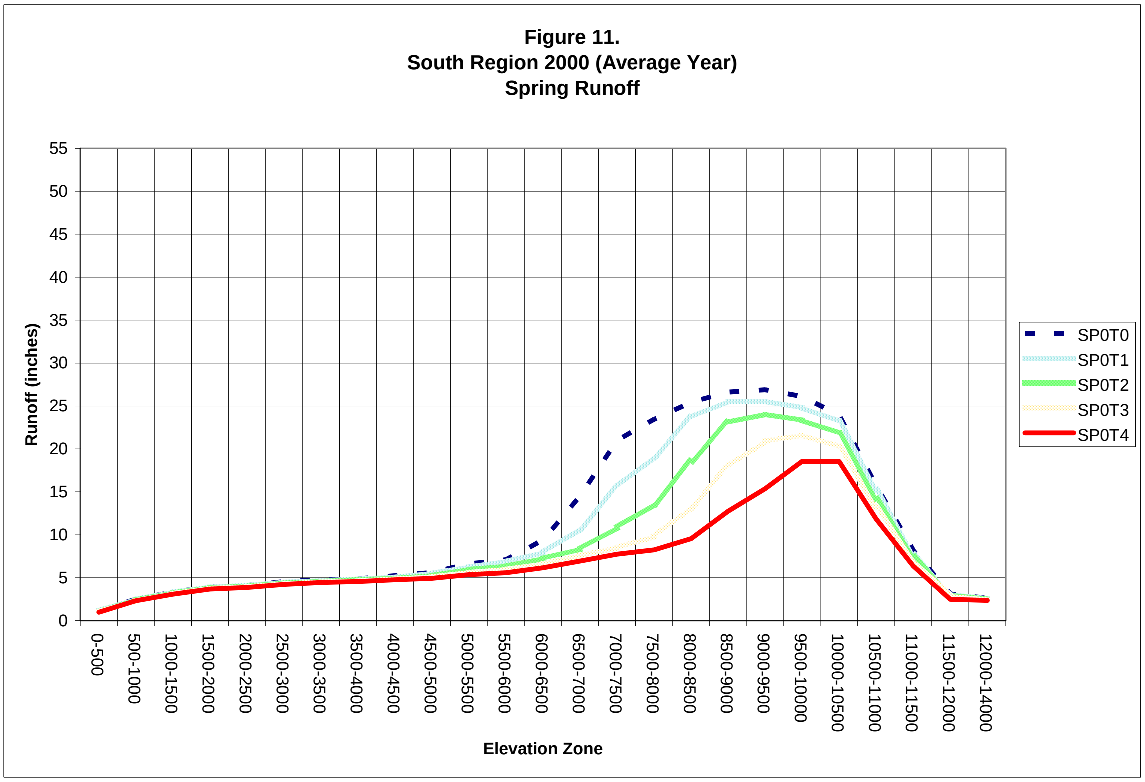


**Figure 11.**
**South Region 2000 (Average Year)**
**Spring Runoff**

Figure 12 is an example graph of average year runoff, for the north region, for no change in precipitation, and for plus 25% and minus 25%. The graph shows variations in runoff for each of the189 land use types, for the three precipitation alternatives.

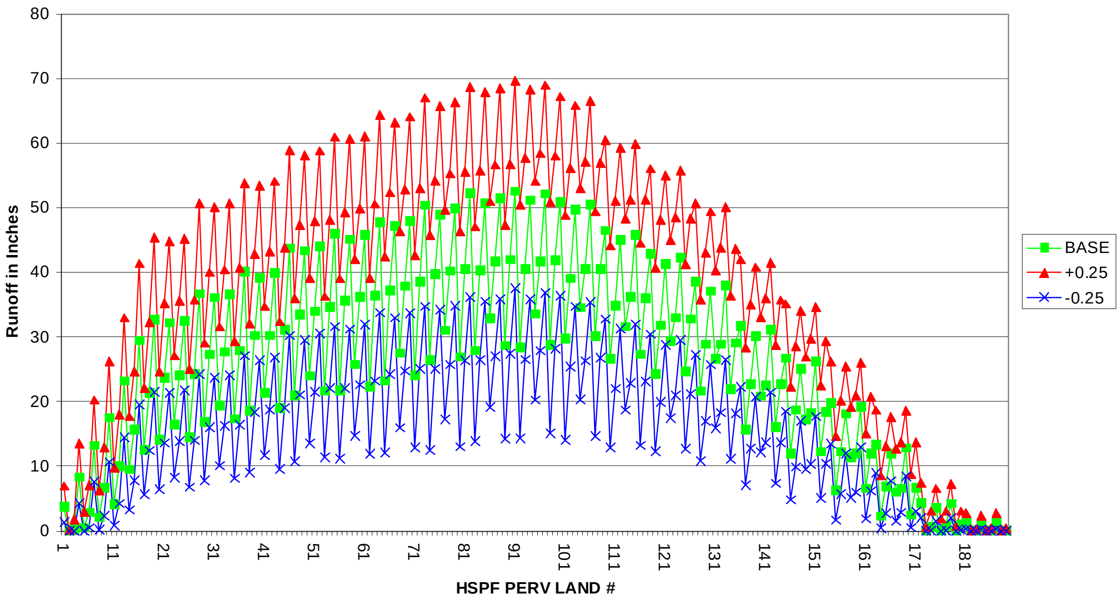


**Figure 12.**

**North Region 2000 (Average Year)**
**Precipitation Alternatives**
**Total Runoff**

## WATERSHED YIELD PROCESSOR (on attached CD)

For each Sierra Nevada region, the HSPF models provided monthly runoff data for all defined 189 land use types. Data for the three representative years were compiled into values for winter runoff (October-March), spring-summer runoff (April-September), annual runoff, and April 1st snowpack water content. This processor runs on the Microsoft Dot Net Framework. The input data form allows the selection of alternative units. The processor accepts precipitation alternatives in 5% increments and increased temperatures in 1.0 degree C. increments. Areas are entered for each of the 189 land use types present in the watershed undergoing evaluation. These values can also be entered with Microsoft Excel spreadsheet files. Examples of these files are provided with the processor. Selection of a climatic alternative provides comparison to the base case.

## REFERENCES

Bird, R.E. and R.L. Hulstrom. 1991."A Simplified Clear Sky Model for Direct and Diffuse Insolation on Horizontal Surfaces". *SERI Technical Report SERI/TR-642-761*. Golden, CO: Solar Energy Research Institute.

Brekke, Levi D., Norman L. Miller, Kathy E. Bashford, Nigel W.T. Quinn, and John A. Dracup. 2004. Climate Change Impacts Uncertainty for Water Resources in the San Joaquin River Basin, California. *Journal of the American Water Resources Association*. 40 (1), February 2004: 149-164.

Buffo, John, Leo J. Fritschen and James L. Murphy. 1972. "Direct Solar Radiation on Various Slopes from 0 to 60 Degrees North Latitude". *Research Paper PNW-142*. Portland, Oregon: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station.

California Data Exchange Center (CDEC). 2004. *Climatological Records for California.* <http://CDEC.Water.CA.Gov>

California Department of Water Resources. 1979. "Evaporation from Water Surfaces in California". *Bulletin 73-79*, Sacramento, CA.

California Department of Water Resources. 1978. "California Sunshine-Solar Radiation Data". *Bulletin 187*.

California Energy Commission. 2003. "Climate Change and California". *Staff Report 100-03-017F*. Sacramento, CA.

Canadian Center for Climate Modeling and Analysis. 2001. *CGCM3*. Ottawa, Canada: Canadian Climate Center. <http://www.cccma.bc.ec.gc.ca>

Dettinger, Michael D., Daniel R. Cayan, Mary K. Meyer and Anne E. Jeton. 2004. Simulated Hydrologic Responses to Climate Variations and Change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900-2099. *Climatic Change 62*: 283-317. The Netherlands: Kluwer Academic Publishers.

Environmental Systems Research Institute, Inc. (ESRI). 2004. *ArcView Spatial Analyst*. Redlands, California.

Intergovernmental Panel on Climatic Change (IPCC). 2001. *Climatic Change 2001: the Scientific Basis*, J.T. Houghton, Y.Ding, M. Nogouer (eds) pp 881. Cambridge University Press.

Jeton, A.E. 1999. Precipitation-Runoff Simulations for the Lake Tahoe Basin, California and Nevada. *WRIR 99-4282*. Denver, Colorado: U.S. Geological Survey.

Penman, H.L. Natural Evaporation from Open Water, Bare Soil, and Grass. 1948. *Proceedings Royal Society of London* A193:120-146. In Jones, Frank E. 1992. *Evaporation of Water.* pp.124-126. Chelsea, MI: Lewis Publishers.

Redmond, Kelly T., David W. Stahle, Matthew D. Therrell, Daniel R. Cayan and Michael D. Dettinger. 2002. 400 years of California Central Valley Precipitation Reconstructed from Blue Oaks. *13th Symposium on Global Change and Climate Variations, 13-17 January 2002*, pp 20-23. Boston, MA: American Meteorological Society.

Schneider, Stephen H. 2004. Can We Estimate the Likelihood of Climatic Changes at 2100? An Editorial Comment. *Climatic Change* 52: 441-451.

Scripps Institute of Oceanography. 2004. Climate Research Division, Experimental Climate Prediction Center. <www.ecpc.ucsd.edu>

Sierra Nevada Science Symposium. 2002. *Special Issue Journal of American Water Resources Association* Vol 35, No. 6.

Snyder, M.A., L.C. Sloan and J.L. Bell. 2004. Modeled Regional Climate Change in the Hydrologic Regions of California: A CO2 Sensitivity Study. *Journal of American Water Resources Association,* in press.

Stewart, Iris T., Daniel R. Cayan and Michael D. Dettinger. 2004. Changes in Snowmelt Timing in Western North America Under a "Business as Usual" Climate Change Scenario. Climatic Change 62: 217-232.

United Kingdom, Hadley Center for Climate Prediction and Research. 2002. *GCM HadCM4.*

University of Utah. 2003. *Cooperative Mesonets in the Western United States*. <www.met.utah.edu/mesowest/>

U.S. Department of Agriculture. National Resources Conservation Service, National Cartography and Geospatial Center. 2003. *State Soil Geographic (STATSGO) Database*. <http://www.ncgs.nrcs.usda.gov/branch/ssb/products/statsgo/>

U.S. Department of Agriculture. Geospatial Data Gateway. 2003. *Topographic Mapping and Aerial Photography*. <http://datagateway.nrcs.usda.gov/>

U.S. Department of the Army. 1957. Corps of Engineers, North Pacific Division. Central Sierra Snow Laboratory. Willamette Basin Snow Laboratory. *Snow Hydrology.* NTIS PB 151660.

U.S. Department of Interior. 2003. Geological Survey. EROS Data Center. *National Land Cover Dataset*. <http://edc2.usgs.gov/natllandcover.asp>

U.S. Department of Commerce, National Climatic Data Center (NCDC). 2003. *Monthly Climatological Data California 1948-2003, Hourly Precipitation Data California 1948-2003, Solar and Meteorological Surface Observation Network 1961-1990 (CD). Hourly Weather Observations 1990-1995 (CD), Integrated Surface Hourly Observations 2000, 2001, 2002 (CD). Cooperative Summary of the Day-TD3200 1948-2002 (CD).* National Climatic Data Center. Asheville, NC.

U.S. Department of Interior. Geological Survey. 2003. *Water Resources Data for California*. http://www.waterdata.usgs.gov/ca/nwis.

U. S. Department of Interior. 1991. Geological Survey. National Park Service. Western Ecological Research Center. *Sierra Nevada Global Change Research Program.*

U.S. Environmental Protection Agency. 2003. Programs Suite (including HSPF). *BASINS 3.0*. <www.epa.gov/waterscience/basins/basinsv3.htm>

U.S. Environmental Protection Agency. 2001. Exposure Assessment Models Web Site *HSP11Y2K.EXE*. <http://www.epa.gov/ceampubl/swater/hspf/>.

U.S. Government. National Science Foundation. National Center for Atmospheric Research. 2003. *CCSM /Parallel Climate Model/Avant Garde.* <www.cgd.ucar.edu/naco/gcm/sm.htm>

U.S. Government. 2003. NOAA, Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL). *Community Climate Systems Model CCSM*. <http://climate.gsfc.nasa.gov/>.

U.S. Government. Global Change Research Program. 2002. *National Assessment of the Potential Consequences of Climate Variability and Change. California Regional Climate Impacts Assessment. The Potential Consequences of Climate Variability and Change for California.* Santa Barbara: University of California. <www.usgcrp.gov>.

U.S. Government, Climate Change Science Program and the Subcommittee on Global Change Research. 2004. *Strategic Plan for the U.S. Climate Change Science Program.* <http://www.climatescience.gov/library/stratplan2004>.