4.2: Methods and Analytic Approach

1) The Climate Change Watershed Yield Calculator;

The primary need in this study was to address issues generic to the hydrologic, channel, and water resource characteristics of the Sierra Nevada at large and not those specific to individual stream reaches nor specific watersheds. This necessity dictated that a watershed modeling framework be developed that included both reasonable calibration to existing watershed response characteristics throughout the Sierra Nevada, and results in conclusions generalizable to the entire Sierra Nevada study area. The Yield Calculator, developed for this study and intended to meet the objectives of this study, is described in detail in Part 2, and addressed here only to explicate some of the details relevant to the following assessment of the hydrologic implications of climate warming at a Sierra Nevada wide scale.

The Yield Calculator was designed to evaluate the yield and runoff implications of a range of possible climate change scenarios. These scenarios include 1) various possible magnitudes of climate warming relative to a present baseline condition, and 2) various possible magnitudes of increases and decreases in annual average precipitation relative to a present baseline condition. This study does not provide predictions of the temperatures and precipitation patterns that may be associated with any future climate warming condition nor does it estimate at what date in the future any particular climate scenario may occur. The Yield Calculator is designed to provide an estimate of the changes in runoff and yield patterns should, if, and whenever some climate change scenario occurs. It is also designed to provide a basis for estimating the runoff and yield patterns along a progression of warming and precipitation changes and to identify any critical climate change magnitudes at which rates of hydrologic consequences changes notably.

- Study Area

This study is intended to address the possible hydrologic implications of climate warming in the Sierra Nevada. This mountain system can be variously defined and delimited based on varying parameters. The specific delineation of the Study Area is significant in that one of the products include a calibrated Yield Calculator and the use of this calculator in areas outside of the calibrated region is not appropriate.

Topographically, the Sierra Nevada does not stand as an isolated mountain range in that on the south it curves toward the southwest and grades into the Transverse Ranges of Southern California, and on the north it grades into the Cascades of Northern California and Oregon holding a consistent north and northwesterly alignment.

Geologically, the Sierra Nevada is usually characterized by a complex of granitic intrusions which melted their way up into a complex of pre-existing faulted and upturned metamorphic rocks derived from the progressive accretion of sea floor units. This geology is not found in the sedimentary Transverse Ranges nor the volcanic Cascades, however this geology is found in the topographically separated (but genetically related) Siskiyou-Klamath Mountains of northwestern California.

Hydrographically, the Sierra Nevada is divided along the crest into large westslope main-trunk watersheds and small eastslope watersheds. The eastslope watersheds are short (on the order of 5-10 mi.), of low stream order, have steep channel gradients, drain mostly glaciated terrain, and are dominated by rain shadow precipitation and dry adiabatic evapo-transpiration influences. The westslope watersheds are long (30-60+ mi.), of high stream order, have variable stream gradients, drain areas of variable geomorphic characteristics, and are dominated by orographic wet adiabatic precipitation and seasonally variable evapo-transpiration influences. While most of the westslope main-trunk watersheds head at the crest of the range, in the northern end of the Sierra Nevada several main-trunk stream systems have headwater areas on the eastside of the Sierra crest which are influenced by rain shadow processes.

These watershed areas east of the Sierra crest have active faulting and topography similar to the Basin and Range province and have bedrock geology that includes both the Sierra Nevada metamorphic/granitic material mix and the Cascade volcanic material. These features result from the presence of active faults and the geologically recent migration of the Basin and Range style fault system westward into the Sierra Nevada microplate with its characteristics Sierra Nevada bedrock geology.

Tectonically, the Sierra Nevada is a microplate which includes both a characteristic suite of bedrock geology units (see above) and tectonic displacement in the form of faulting along the eastern edge, a hinge line along the western edge and the progressive rotation of the more or less rigid block of the range up along the eastside Sierra Nevada Fault system from the hinge line along the westside. This creates the characteristic shape of the range with steep rugged eastslope only a few miles wide, and the long relatively gradual westslope about 80-100 miles wide. The eastside fault system is relatively simple south of Lake Tahoe. In this area the fault systems is a long series of single or multiple thread on-echelon faults which have a strong vertical displacement component and which separate the uplifting Sierra Nevada from the down faulting blocks of the Owens Valley and other valleys. From Lake Tahoe north, the eastside of the Sierra Nevada has a very complex faulting system. The western edge of the Basin and Range block-faulting system, characteristic of the state of Nevada, is progressively extending into the Sierra Nevada microplate by way of the enlarging Mohawk Fault system. This system is creating a complex of block-fault movements that tend toward more isolated smaller mountain bodies and block-fault valleys penetrating into areas of both Sierra Nevada and Cascade geologies. It also includes large headwaters areas of the westward draining North Yuba, Middle Fork Feather, and North Fork Feather Rivers.

For this study we have selected a Study Area that includes that portion of the Sierra Nevada that is both westslope draining, and the characteristic terrain on the Sierra Nevada microplate. The western edge the Study Area is defined by the margin of the Central Valley. The north and south ends of the Study Area are defined hydrographically by the watershed boundaries of the West Branch Feather River and the South Fork of the Kern River respectively. The geological and tectonic Sierra Nevada south of the Kern River watershed is excluded from the study area because of the change in alignment and change in orographic/rainfall conditions. The eastern edge of the Study Area, south of the North Yuba River, is defined hydrographically at the Sierra crest by the headwaters of western draining streams. The eastern edge of the Study Area from the North Yuba River and north, is defined by a series of interrupted ridges along the eastern edge of the Sierra Nevada microplate, and includes watershed areas west of these ridges.

This Study Area excludes, south of the North Yuba River the eastslope draining streams into the Basin and Range river systems, and excludes from the North Yuba River and north the headwater areas of several main-trunk Sierra Nevada watersheds. Both of these areas have significant influences from rain shadow precipitation and dry adiabatic evapotranspiration processes.

- Study Regions

To accomplish the stated objectives of this study within the geographic extent and the hydro-meteorological context of the Study Area, three Study Regions were identified. The major element in the necessity of separating out three Study Regions for analysis within the large Study Area was the hydro-meteorological condition variability along a north to south and latitudinal gradient. This hydro-meteorological variability has three dimensions. First is a progressive elevation shift of major hydro-meteorological processes to higher elevations along a north-south gradient due to latitudinal and insolation factors. Second is a progressively higher crest elevation trend in the Sierra Nevada from north (6000-9000 ft) to south (12,000-14,000 ft) which has a strong influence on the proportions of watersheds that have significant spring snowpack under both baseline and climate warning scenarios. Third is the length of the Study Area (360 mi), its orientation of basically north-south, its latitudinal position (35d30mN to 40dN), and its geographic position parallel to the west coast of North America, all of which causes a north-south variation in the hydro-meteorological implications to regional- and global-scale weather patterns (such as El Nino/La Nina cycles).

An additional factor in the selection of the number and boundaries of the three Study Regions was the number and locations of long-term meteorological records within the Study Area. Three main record sets were located that could be reasonably used to calibrate against long-term streamflow records. These weather stations are 1) Blue Canyon on the American River-Yuba River interfluve, 2) Pinecrest in the Stanislaus River watershed, and 3) Lodgepole in the Kaweah River watershed.

The three Study Regions are;

<u>North-Study Region</u> is from the West Branch Feather River and the North Fork Feather River watersheds south to the South Fork of the American River watershed inclusively.

Central-Study Region is from the Cosumnes River and the North Fork of the Mokelumne River watersheds south to Fresno River and the Merced River watershed inclusively.

South-Study Region is from the San Joaquin River watershed south to Kern River watershed inclusively.

- Wateryear Types

The hydro-meteorological data from the weather station in each Study Region were used in conjunction with nearby long-term streamflow gage data to develop a calibrated precipitation-runoff model. For each Study Regions the data sets used were calibrate the model using 30 years of record (1970-2000) and these models were used to simulate precipitation-runoff relationships for a 55 year period (1948-2003) for the purpose of verifying the model against streamflow records.

To achieve the study objectives and develop a data base that could be used to assess the changes in runoff and yield, and to evaluate the hydrologic implications of climate warming at the scale of the Sierra Nevada Study Area, the Yield Calculator was based on three representative Wateryear Types. The Wateryear Types are represented through the selection of three actual wateryears from the 30 years of record used to develop the calibrated runoff model and were based on relative total wateryear runoff.

The three Wateryear Types are;

Dry-WY is that wateryear in which 90% of the 30 years had greater total annual runoff (1992).

Ave-WY is that wateryear in which 50% of the 30 years had greater total annual runoff (2000).

Wet-WY is that wateryear in which 10% of the 30 years had greater total annual runoff (1998).

- Hydrologic Response Units

The Yield Calculator was developed using EPA’s Hydrologic Simulation Program-Fortran (HSPF) as a watershed modeling approach. This watershed model, like many, is a “distributed attribute parameter” model which can be used to estimate various watershed runoff parameters based on the physical characteristics of specific watersheds and the spatial distribution of those characteristics. Distributed attribute parameter modeling formats are based on the anticipated watershed hydrologic characteristic of various land units, how these land units may respond to precipitation inputs, and how they behave in routing water from the soil surface precipitation to the resulting runoff from these land units. In the HSPF, as in many distributed attribute watershed models, these land units are referred to as hydrologic response units (HRUs).

HRUs; In typical watershed modeling exercises specific HRUs are developed which define a specific suites or configuration of salient physical elements of watershed processes. The separate elements that may contribute to the suite of each HRU include soil types, geologic units, vegetation, slope, aspect, elevation, topographic position, and etc. Depending on the information available and the objectives of the studies, each of the watershed process elements may be characterized by 2 to 6 or more categories based on their influences on watershed processes and routing.

The HSPF model is structurally limited to 160 types of HRUs. This limitation has severe implications to its application in considering the watershed processes of the entire Sierra Nevada Study Area as opposed to the intended application of the HSPF to specific and well defined watersheds. Sculpting the HSPF to accommodate the objectives of this study necessity generalizing HRU characteristics to the point that 160 HRU types could be used to estimate watershed processes in a study area of **about __ sq mi**, over an elevation range of about 14,000 ft, and ranging to about 60 miles wide and 360 miles long.

G-HRUs; In this study the HRUs developed in, and modeled by, the Yield Calculator are considered as generalized HRUs (G-HRUs) because the extent of generalization needed to achieve the objectives of this study make them unsuited for site specific and watershed specific modeling. These 160 G-HRUs were developed by; 1) considering soils and vegetation together by using major vegetation types (forest, brush, and other) to reflect both general vegetation and general soil characteristics based on assumption that greater vegetation development indicates soils with greater infiltration and soil-water storage capacity, etc., 2) modeling elevation increments on 500 ft intervals because elevation distribution may be the most sensitive parameters under climate warming, 3) limiting the elevations modeled to those below 12,500 ft because higher elevations receive very little precipitation inputs, 4) modeling 3 slope aspects because of the expected importance of evapotranspiration and snowmelt processes based on variable insolation, and 5) limiting the aspect modeling to elevations below 3000 ft because of decreasing importance of snowmelt at these lower elevations.

These G-HRUs were used to calibrate the watershed runoff model in each of the study regions and are the basis of all watershed process outputs of this study. However to facilitate and make practical Sierra Nevada-wide assessments of the possible hydrological implications, an additional step of simplification was needed.

EW-HRUs; The next step in simplification was the normalization of all G-HRU factors, except elevation, and then the use of elevation increment and seasonal climatic factors to model the distribution of seasonal runoff along an elevation spectrum. This approach results in runoff and snowpack relationships as if there was an equal distribution of each non-elevation G-HRU factor (Equal Weighted-HRUs [EW-HRU]) within each elevation increment from sea level to 12,500 ft. By modeling runoff and snowpack in terms of water depth per unit area, the simplified approach also normalizes for watershed surface area in each elevation increment: That is, the modeled outputs tacitly express runoff and snowpack relations as if the watersheds are perfectly rectangular and every elevation increment has exactly the same surface area. The modeled outputs based on this simplifying approach are entirely synthetic. For instance this approach incorporates the assumption that the deep soil and heavily forested conditions of the mid-elevation westslope of the Sierra Nevada are distributed evenly from the lowest xeric foothills to the bare bedrock glaciated terrain of the High Sierra. Similarly the approach assumes that the xeric foothill and the glaciated High Sierra HRU factors are distributed evenly along the full elevation spectrum and have the same representation in each elevation increment as do the HRU factors of the deep soil and thick forest conditions of the mid elevations.

The aspects of hydrologic implications of climate change that can be addressed in this study are both facilitated by and limited by both the coarseness and homogenized nature of EW-HRU model outputs and by the need to address issues generic to the hydrologic, channel, and water resource characteristics of the Sierra Nevada at large and not those specific to individual stream reaches nor specific watersheds. Therefore, short of modeling many actual watersheds of the Sierra Nevada, the use of EW-HRUs along an elevation spectrum in the three study regions is the only practical approach toward a general of hydrologic implications at a Sierra Nevada-wide scale for this study. This analytic approach may offer interesting insights into generalized hydrologic responses to climate warming conditions over the elevation range of the Sierra Nevada westslope.

Instead of using an EW-HRU approach the application of the Yield Calculator to an actual watershed will result in different runoff and snowpack relations when elaborated along an elevation spectrum. This is due to both the watershed-specific distribution of actual G-HRU factors and the actual variability of drainage area within each elevation increment. However the Yield Calculator is designed to calculate seasonal yield factors as an integration of all watershed catchment factors contributory to a point on, or a small reach of a stream channel. As a result, as typically used, Yield Calculator estimates will not reveal the distribution of runoff and snowpack relations along a range of elevation increments within the catchment unless each elevation increment is analyzed separately and the results maintained in a desegregated state.

- Limitations and Applications of the Watershed Yield Calculator

The structure of the HSPF modeling and the construction of the Yield Calculator in this study were dictated by the limits of available data, the size limitations of the watershed runoff modeling framework, the size and complexity of the whole of the Study Area, and the necessity to develop Study Area-wide and Study Region-wide generalized results. These limitation meant that the Yield Calculator runoff and yield results, and the descriptions of hydrologic implications, are constrained to limited appropriate applications. The uses of the watershed runoff models, Yield Calculator results, and any interpretations presented in this study must be limited to the analytic and assumption constraints used in this study.

The following is a list of the major study elements that constrain the application of the watershed runoff models, Yield Calculator results, and any interpretations presented.

- The watershed modeling was calibrated for a set of wateryears (1972-2002) in which there is evidence that they have already been effected by climate warming including greater average temperatures, advanced-season snowmelt, advanced-season spring runoff regime, longer baseflow seasons, and increased magnitudes of maximum daily precipitation.

- The individual wateryears selected as representative the three wateryear types (Dry, Average, and Wet) were applied to those wateryear conditions in all three Study Regions. Evidence of precipitation deviations from near annual averages show that El Nino conditions result in increasingly greater increased annual total precipitation southward from near average in the north to much greater than average in the south. Conversely La Nina conditions result in increasingly greater decreased annual total precipitation southward from near average in the north to much less than average in the south. As a result the Study Area-wide applications of any one of these representative wateryears as wateryear types may not reflect the precipitation patterns of the El Nino or La Nina events.

- The seasonal precipitation patterns that occurred during the three representative wateryears were unique to those particular years and may include significant deviations from typical season precipitation distribution under present baseline conditions. The runoff and yield and their seasonal patterns reflected in the watershed models and the Yield Calculator may not represent typical seasonal precipitation patterns under baseline conditions.

- The typical season precipitation distribution under present baseline conditions may not be representative of the seasonal distribution under the conditions of climate warming because of altered regional weather patterns that may include both more intense development of the North American Monsoon System, and more frequent and larger east Pacific hurricanes. Both of these weather system processes would introduce greater summer season precipitation into the Sierra Nevada, increase the degree of cloudiness, and increase humidity. Much of the summer precipitation may be in the form in higher intensity convectional systems, which in turn, will result in further increased maximum daily average precipitation intensities, and could result in increased summer streamflow in small order channels.

- The Yield Calculator uses three WY-Types based on three selected representative wateryears which may contain unusual year-specific precipitation and runoff patterns that are not reflected by the annual total runoff.

- The watershed model is calibrated (relative to present baseline) for five temperature alternatives (0 to +4dC) and three precipitation alternatives (-25%, no change, and +25%), and any other precipitation alternative selected during the application of the Yield Calculator will result in estimates based on direct mathematical interpolation (within the -25% to +25% envelop), not be independent calibration nor simulation steps.

- The HRUs used in the watershed modeling are based on the present land cover conditions and does not address the changes in vegetation that may occur with climate warming (or precipitation changes) nor how those vegetation changes may additionally influence hydrologic implications.
- The HRUs used in the watershed modeling process and in the Yield Calculator are G-HRUs which are highly generalized from the detailed and specificity level of the HRUs typically developed in site-specific watershed modeling that use distributive attribute approaches.

- The HRUs used as the main basis for describing the hydrologic implication of climate warming are based of the very highly generalized and regionalized EW-HRUs and are only applicable as regional-scale generalizations of hydrologic processes.

The watershed modeling and its yield calculator are strictly bi-seasonal (winter and spring). They do not address the summer season base flow period (July through October). In the Yield Calculator, total annual runoff is the direct sum of winter runoff and spring runoff. Yield losses between climate scenarios are based on the difference in total annual runoff.

G-HRU's used in the watershed modeling do not include details of soil characteristics that allow for consideration of deep percolation and groundwater recharge. Also, do not include any geologic characteristics that allow for consideration of groundwater discharge to surface flow at springs and seeps. These factors prohibit the watershed model and the yield calculator from directly addressing summer base flow runoff.

The following is a list of the appropriate and inappropriate application of the watershed runoff models, Yield Calculator results, and any interpretations presented.

- The Yield Calculator cannot develop estimates of instantaneous streamflows at specific sites nor monthly average flows due to the by-seasonal time-step nature of the Yield Calculator.

- The Yield Calculator should not be used to create a larger set of WY-Types by artificially selecting a range of different precipitation scenarios for a single temperature scenario because monthly precipitation patterns will vary, temperatures will vary and the model does not accommodate carry-over storage in watersheds.

- The Yield Calculator should not be used to develop estimates of change runoff or yield for the purposes of resource management planning project planning nor the environmental evaluation of project proposals.

- The Yield Calculator should not be used to develop specific estimates of the potential impacts of climate warming on site specific water resource projects, reservoirs, instream flow requirements, and water supply and power diversions.

- The Yield Calculator cannot be used to estimate the consequences of vegetation management projects on present baseline nor climate warming conditions because the G-HRUs do not attribute vegetation-specific hydrologic parameters.

The yield calculator cannot be used to estimate the timing magnitude of advanced season snowmelt processes, and the timing shift from spring season runoff to winter season runoff at any particular location because the yield calculator is bi-seasonal and not on a daily/weekly/monthly time-step.

The yield calculator cannot be used to directly estimate base flow season lengths, not baseflow season magnitudes, because these factors were not modeled. Baseflow conditions may be indirectly inferred from spring-flow runoff estimates and should be considered as “potential” base flow conditions.

- The Yield Calculator may be used to develop a preliminary risk assessment of existing or proposed site specific water resource projects, reservoirs, instream flow requirements, and water supply and power diversions.

- The Yield Calculator may be used to develop a preliminary risk assessment of existing or proposed site specific near-channel development projects and drainage infrastructures when site specific channel and floodplain features are appropriately considered.

- The regional estimates of hydrologic implications may be used to identify broad scale risks and uncertainties associated with resource management planning, land use planning, water resource management, and environmental/ecologic conflicts and to develop general policies and strategies to address the risks and to identify possible adaptive management directions.