Technical Appendix: Development and Application of the QUAL2E-SHADE Temperature Modeling System to the Middle Fork Eel River (Draft)

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1.0 Background

The Middle Fork Eel River (MFE) is located in northwest California. Its basin extends approximately 45 miles from southern Trinity County to northern Mendocino County, with a small portion on the east passing through the northwestern regions of Glenn County. The MFE watershed is composed of four major sub-basins – Round Valley, Wilderness, Eden Valley and Black Butte River, each of which has been identified as providing important habitat for cold-water fish populations such as the salmonid species. One of the major water quality problems for these fish species is the increased water temperatures associated with various land management practices that affect riparian vegetation. The increased temperature resulted in the MFE being listed as impaired on California's Clean Water Act Section 303(d) list and requires the development of a total maximum daily load (TMDL).

To develop the temperature TMDL for the MFE, a method is needed to simulate temperatures in the river and assess how changes in riparian vegetation affect in-stream temperatures. To accomplish this, an integrated modeling system comprising of a GIS-based SHADE model and a receiving water quality model Q2ESHADE (modified version of EPA's QUAL2E model) was developed and applied to the MFE. The modeling system was designed to support previous temperature modeling efforts in the North Coast of California and was adapted and updated for application to the MFE. The major components of the modeling system are summarized in Figure 1.

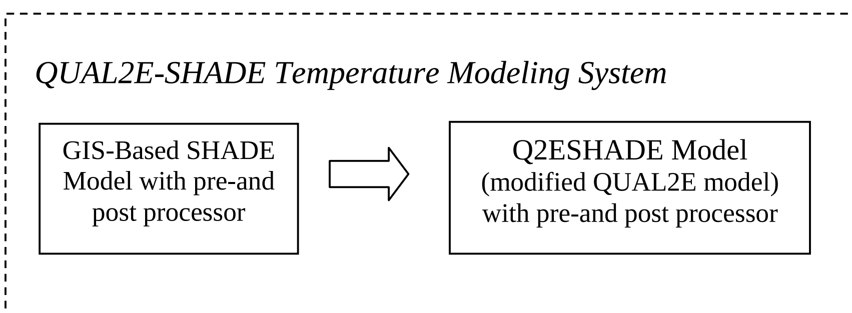

Figure 1. QUAL2E-SHADE Temperature Modeling System

Estimates of hourly shade-attenuated solar radiation at various stream locations based on riparian vegetation characteristics and topographic relief can be simulated using this modeling system. The model output consists of solar radiation "loading" that is then used to predict in-stream temperatures throughout a stream network using the QUAL2E model. The maximum weekly average temperature (MWAT) of the stream can be predicted for various riparian-zone vegetation management strategies.

The modeling system has been modularized such that the user can run the SHADE model alone or run the SHADE model in conjunction with Q2ESHADE. Alone, the SHADE model can provide a screening level view of the influence of shade on in-stream temperatures. The coupled model provides the ability to simulate all or selected reaches within a particular watershed. This allows more flexibility during modeling and supports the elimination of reaches that are not considered important (i.e., no flow during summer). The user defined interval at which model output is generated (stream sampling point system) has been streamlined to automatically generate numbering schemes for both SHADE and Q2ESHADE, along with an upstream to downstream reach ordering system that allows mapping of the stream sampling points to the Q2ESHADE computational elements.

For the MFE, the integrated modeling system was applied to two sub-watersheds– Upper Black Butte and North Fork of the Middle Fork Eel and calibrated using the observed HOBO temp monitoring data. A series of scenarios based on varying riparian vegetation conditions were then simulated to support TMDL development. This document provides a general description of the model structure, data requirements, and assumptions and limitations.

2.0 GIS-Based SHADE Model

The GIS-Based SHADE model is comprised of the underlying SHADE model algorithms and a GIS-based preprocessor for the SHADE model. The following sections discuss the SHADE model algorithms and the preprocessor used to parameterize the model.

2.1 SHADE Model

Chen et al. (1998) incorporated a series of computational procedures identifying the geometric relationships among sun position, stream location, orientation, and riparian shading characteristics into a computer program called SHADE. This model was developed to support the prediction of shade–attenuated solar radiation on a watershed scale.

SHADE computes a time-series of the effective solar radiation absorbed by the stream water after accounting for the effects of riparian vegetation and topography. A detailed description of the SHADE model can be found in the paper *Streams Temperature Simulation of Forested Riparian Areas*: I. Watershed-Scale Model Development (Chen et.al.,1998). The methodology employed in SHADE is summarized below:

1. A watershed's location is determined by latitude and longitude. The latitude is used to compute the solar path (the sun's position over the day defined by two angles: the solar altitude and the solar zenith) and half-day length at a location. The longitude and standard meridian where the time zone of the watershed is centered is used to convert standard time to local time in the watershed.

2. The daily global radiation is disaggregated into hourly direct-beam and diffuse radiation based on the watershed latitude utilizing a number of theoretical considerations and empirical relationships.

3. Using an hourly time step, the topographic and vegetation shading effects on direct-beam radiation are computed from sunrise to sunset by relating the solar path geometry to shade angles provided by the topography and vegetation. Computations are performed at every stream point where topographic and vegetation shading characteristics are available (referred to as a 'stream sampling point'). The final direct-beam radiation with shading effects is calculated as a function of the stream width.

4. Shading effects on diffuse radiation are assumed to be controlled by sky openness (the fraction of the sky not blocked by riparian vegetation or topography) which is regarded as constant over time and estimated at each sampling point from topographic and vegetation shade angles.

5. Direct-beam and diffuse radiation are further reduced by the albedo (reflectivity) of the moving water surface. The albedo of direct-beam radiation is assumed to be a function of the solar zenith angle, while a constant value is assumed for diffuse radiation albedo.

6. Direct-beam and diffuse radiation is summed to obtain the effective solar radiation absorbed by the stream water at each stream sampling point. The solar radiation factor (effective radiation for heating divided by the incoming radiation) is also computed at each stream sampling point.

The input requirements and output for the SHADE model are given below in Table 1 and Table 2 respectively.

Table 1. Inputs for the SHADE model

Input	Parameter Description
Watershed location	• Watershed latitude • Watershed longitude • Standard meridian of the time zone in which the watershed is located
Global solar radiation	Time series of daily global solar radiation at watershed location (Langleys) for duration of simulation
Stream coordinates	Universal Transverse Mercator (UTM) coordinates of all stream sampling points (where topographic and vegetation shading characteristics will be defined)
Stream width	Wetted stream width for each reach

Topographic shading characteristics	Topographic shade angles (degrees) measured from the stream surface to up to the topographic features that obstruct the sunbeam. (Input in 12 standard azimuth directions at each stream sampling point)
Vegetation shading characteristics	Includes five vegetation characteristics that are input at a stream sampling point: • Distance from edge of stream to riparian buffer (m) • Average absolute height of vegetation canopy (m) • Average height of vegetation canopy with respect to the stream surface (m) • Average canopy density (%)

Table 2. SHADE outputs

Output	Description
Adjusted global solar radiation	Time series of hourly (and daily) global solar radiation (Langleys) reaching the stream surface available for elevating the stream temperature at every stream sampling point
Solar radiation factor	Ratio (dimensionless) of effective radiation for stream heating divided by the incoming radiation on the top of the channel valley

2.2 SHADE GIS Preprocessor

Predicting temperatures on a basin scale using the SHADE model requires significant spatially variable data. A GIS framework allows a means for storing large data sets and efficiently parameterizing models, like SHADE, especially when there is little field-measured data.

A preprocessor was developed using a GIS platform to generate the three input files required by the SHADE model. It uses elevation data (DEM), site-specific vegetation data or landuse data (USGS Multi-resolution Land Characterization - MRLC), stream data (EPA Reach File 3 – RF3), time zone, and watershed boundary information. By itself, this system can be used to evaluate relative shade-influencing scenarios for management, such as variations in vegetation due to logging, fire, etc. All the data and their sources are discussed in subsequent sections of this document.

To generate the SHADE model files, the preprocessor creates user-specified stream sampling points (SSP) and buffer widths for each stream sampling point. These values depend on the spatial variability and level of detail required and can be varied based on user specified values. The SSP for the Upper Black Butte and the North Fork of the Middle Fork Eel were specified as 200 and 500 meters, respectively. Buffer widths for both the watersheds were specified as 300 meters.

For each of the SSPs, the preprocessor computes/extracts the latitude/longitude, and along their corresponding buffer width characterizes the vegetation and topography information. The SSP configuration for the Upper Black Butte and North Fork of the Middle Fork is shown in Figure 2 and Figure 3. The preprocessor generates the required input files for the SHADE model for each reach in the watershed. The SHADE model can then be run to generate an attenuated hourly global solar radiation time series at each SSP, which feeds into the Q2ESHADE model. Figure 4 shows the GIS-based procedure to generate the input to the SHADE model.

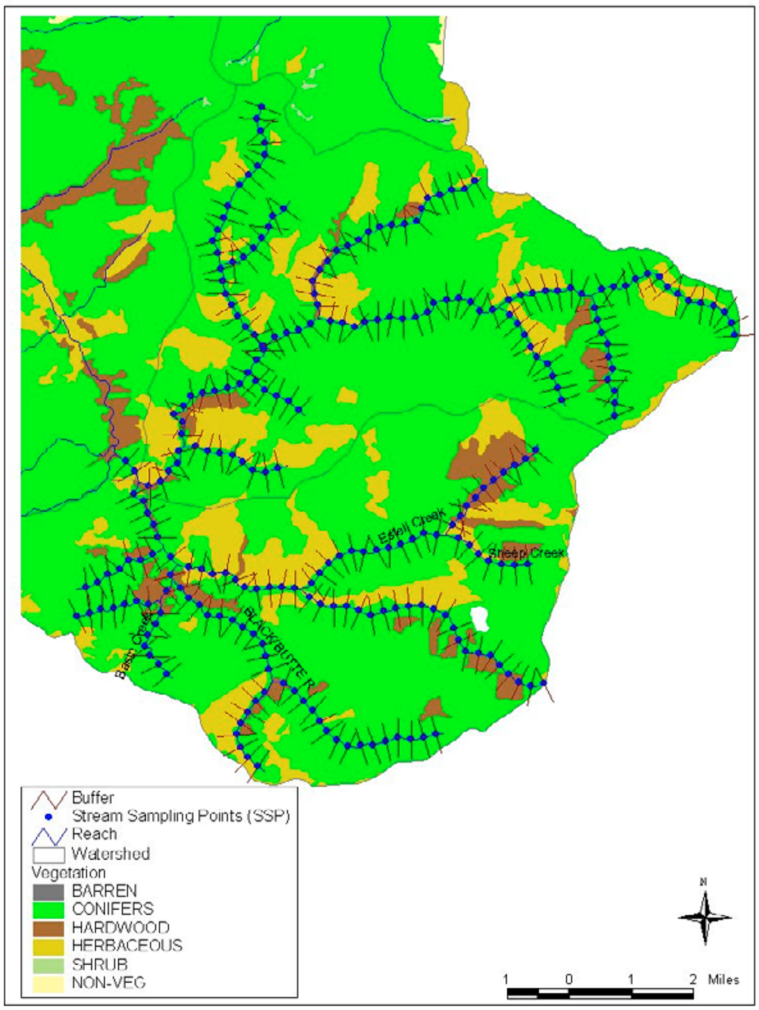

Figure 2. Stream Sampling Point Representation for Upper Black Butte

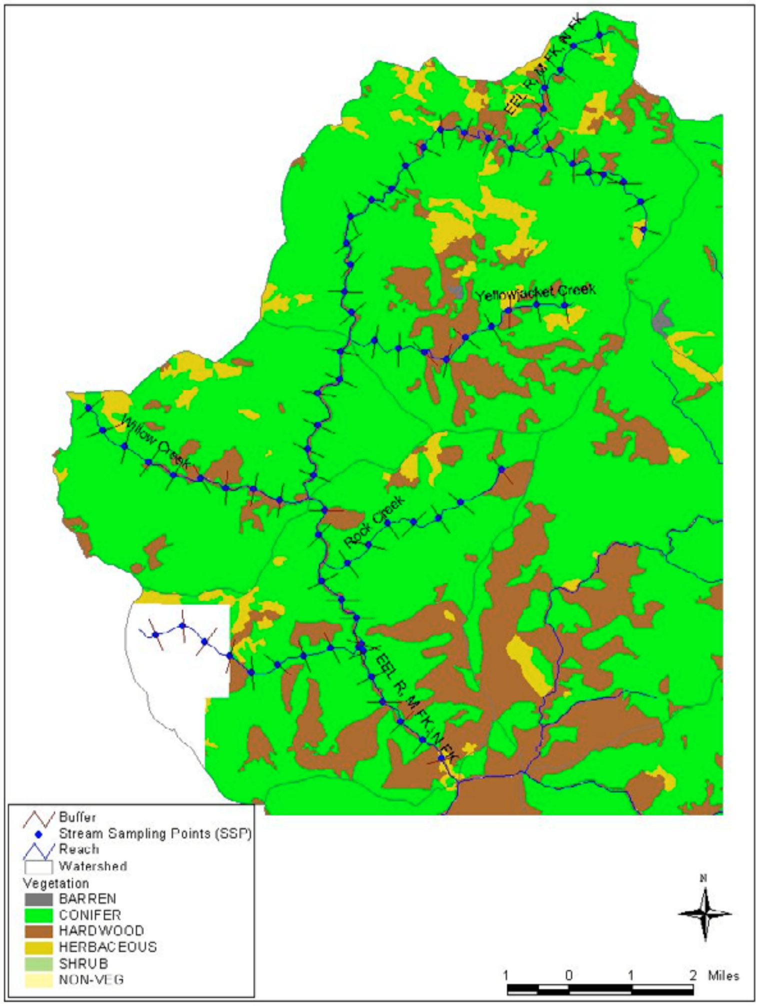

Figure 3. Stream Sampling Point Representation for North Fork of the Middle Fork Eel River

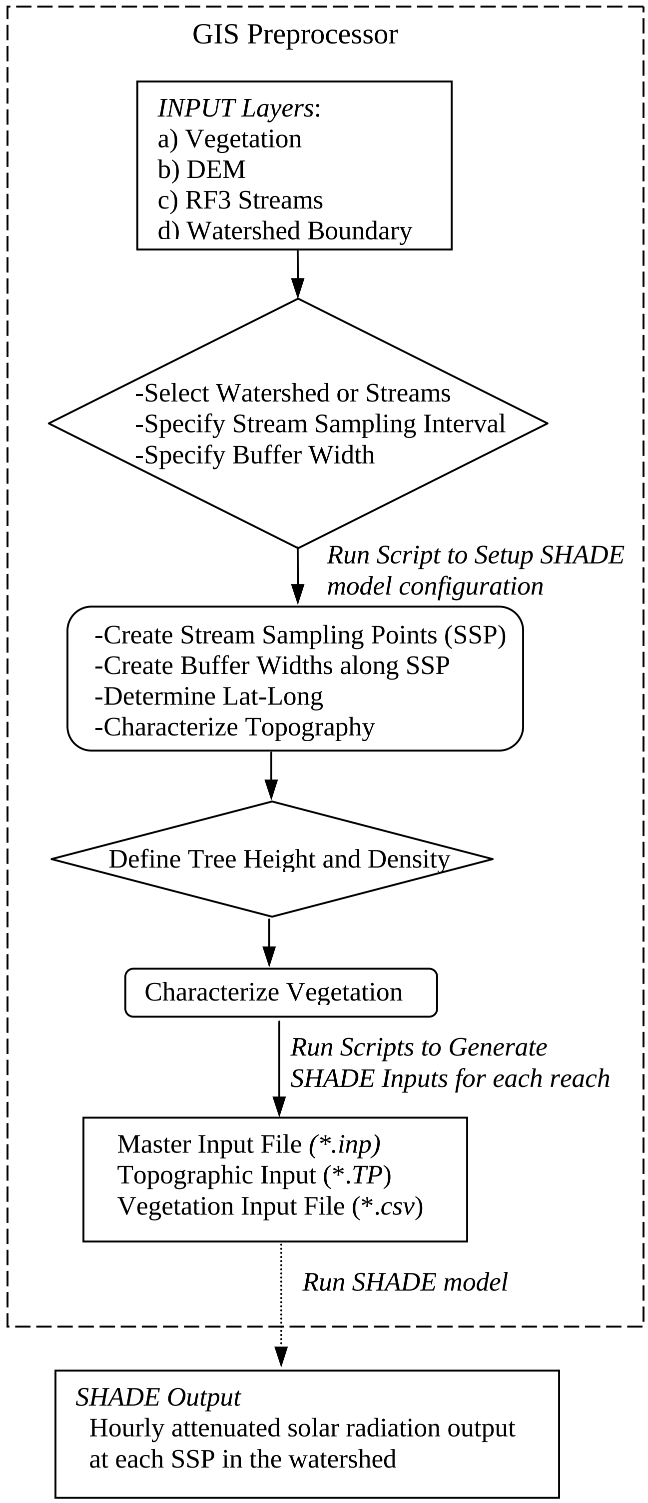

Figure 4. SHADE GIS Preprocessor Functionality

3.0 Q2ESHADE Model

A customized version of U. S. EPA's QUAL2E (Brown, et al., 1987) in-stream model was developed (Q2ESHADE) that uses all of the underlying algorithms of QUAL2E and is linked with preprocessed SHADE model simulation results. The QUAL2E model and the customized Q2ESHADE model and its preprocessing features are discussed below:

3.1 QUAL2E Model

The QUAL2E model is capable of predicting in-stream temperature at different segments throughout a stream network. This steady-state model is applicable to dendritic streams that are well mixed and assumes a constant stream flow at the headwaters. These capabilities enable it to be used as a planning tool to simulate user-defined conditions in the stream such as the critical period/low-flow conditions. QUAL2E is a one-dimensional model (i.e., main transport mechanisms are significant only in the major direction of flow). Because temperatures are typically highest during low-flow conditions, the model is suitable for critical condition temperature modeling.

In QUAL2E, the stream is conceptualized as a series of computational elements (completely mixed batch reactors) that have the same hydrogeometric properties within a reach. Flow is routed through them via the mechanisms of transport and dispersion, and mass balance is performed for the constituent of concern (temperature in this case). By keeping the computational element spacing the same as the constant spacing of the stream sampling points in the SHADE model, a direct linkage can be made.

Although the in-stream model algorithms are used to represent a single flow condition, the model can be operated quasi-dynamically to simulate temperature fluctuations. Based on available hourly local climatological data, the model can update the source/sink term for the heat balance over time. Therefore, the diurnal response of the steady-state hydraulic system to changing temperature conditions can be simulated.

Enhancements were made to the QUAL2E source code to facilitate the linkage between the output from the SHADE model and QUAL2E. The modified version of QUAL2E was called Q2ESHADE. The enhancements provide interpretation of hourly solar radiation time series data from the SHADE GIS model output, as well as heat balance calculations. A preprocessor was developed to reformat the SHADE hourly solar radiation time-series data into a format that can be read by Q2ESHADE. Thus the hourly shade attenuated solar radiation output at each SSP can be routed through a stream network to dynamically simulate temperature within each stream.

For constant headwater inflows, the model can currently simulate temperature dynamically for a period of 31 days (744 hours). This limitation was stipulated because the model stores hourly solar radiation in memory for each computational element, and the array size grows very large as the length of period modeled increases. One month was determined to be reasonable because the model is not dynamic with respect to flow.

This time period appropriately represents the critical period with regard to temperature (constant low flow condition). Figure 5 presents functionality in the Q2ESHADE modeling system.

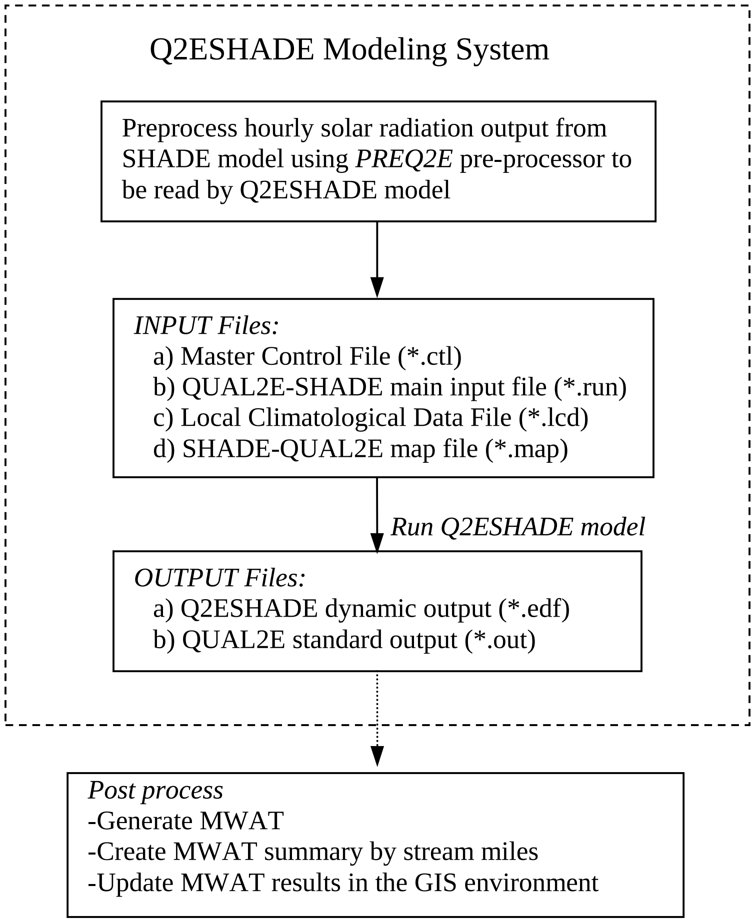

Figure 5. Q2ESHADE Model Functionality

3.2 QUAL2E-SHADE Model Output

Diurnal simulation produces an enormous amount of data that needs to be processed for analysis. To analyze the time series data at each SSP along the reach network, a series of postprocessors were developed to facilitate/automate the analysis of output data from the GIS-based SHADE and Q2ESHADE model. These post-processors helped quantify and summarize the time series data for TMDL analysis.

SHADE Model:

Output from the SHADE model post-processor includes:
i) A statistical summary of the maximum, minimum and average amount of shade attenuated solar radiation for the simulation period (one month) at each SSP. These

values are used to estimate the amount of effective shade (i.e. the amount of reduction (%) in solar radiation after being attenuated by the topography and vegetation of the region).

ii) An average heat load value for the entire watershed (Langley/day).

Q2ESHADE Model:

The Q2ESHADE model post-processor generates the following statistics:

i) The maximum mean weekly average stream temperature (MWAT). The MWAT is computed for the entire month of simulation. It is calculated as the maximum of the seven-day average for the one-month simulation period.
ii) The stream mileage that falls into specified stream temperature categories, including – Good (<15^{o}C), Fair (15^{o}C – 16.99^{o}C), Marginal (17^{o}C – 18.99^{o}C), Stressful (19^{o}C – 23.99^{o}C), and Lethal Conditions (>=24^{o}C).

Output from the SHADE and Q2ESHADE models are updated in the GIS environment for each SSP. This allows spatial analysis and map preparation.

4.0 Data Sources/Requirements for the Middle Fork Eel River Watershed

This section describes the different data sources/requirements for implementation of the MFE QUAL2E – SHADE modeling system

4.1 SHADE Model Data

The data used in the simulation of the SHADE model are presented below:

4.1.1 Vegetation Data

Vegetation data from the USDA Forest Service (2002) were used to determine necessary vegetation parameters. This data set was chosen because it was more recent than the California Vegetation & California Wildlife Habitat Relationships theme (CALVEG & WHR). The extent of the vegetation data provided by the USDA Forest Service was for the Black Butte and Wilderness sub-basins of the MFE watershed. Key data fields within the coverage include detailed tree species information, a size class for the dominant tree layer, total canopy closure (percent), and seral stage information. Minor preprocessing of the vegetation data was performed to incorporate it into the SHADE-QUAL2E system. This included aggregating the detailed vegetation species into more general cover types and assigning canopy closure class codes. Aggregation of species was done by classifying the tree species into i) barren, ii) conifer, iii) hardwood, iv) herbaceous, v) shrub, and vi) non-vegetated cover types.

The USDA Forest Service vegetation layer was used to derive the tree height and density data layers, which are necessary inputs to the SHADE model. The size field attribute in the USDA Forest Service coverage was used to compute the height

The tree heights were derived using the asymptotic height-diameter regression equations (Garman et al., 1995) available for 24 tree species in Oregon. For each of the different tree species existing in the watershed, based on the vegetation coverage, the tree heights were determined using the DBH (diameter –at-breast height) and local site-specific information about tree height and DBH values. The DBH classification for each size class was provided by the USDA Forest Service (Table 3).

The various tree species were then simplified into two distinct categories – Conifers and Hardwoods, using the dominant tree species and local site-specific information, resulting in two generalized DBH versus Tree Height relationships for coniferous and hardwood trees. A constant minimum height of 0.5-meter was assigned to herbaceous plants and 1-meter to other deciduous species. The general form of the asymptotic height-diameter equation (Garman et al., 1995) is given below in equation 1:

$$Height(m) = 1.37 + (b_0[1 - \exp(b_1 \cdot DBH)]^{b_2}) \quad \text{(Garman et al, 1995)} \qquad (1)$$

where, DBH = diameter-at-breast height (cm), b_0, b_1, and b_2 are regression coefficients depending on the type of tree species and site class — b_0 = asymptote or maximum height; b_1 = steepness parameter; and b_2 = curvature parameter

Table 3. Tree Size Classes

Size Class	DBH Range (inches)
0	0-1
1	1-4.9
2	5-11.9
3	12-23.9
4	24-39.9
5	>=40

The vegetation data was then summarized to identify the dominant coniferous and hardwood tree species in the MFE watershed. Based on the vegetation data it was found that the most dominant conifer and hardwood tree species were Douglas Fir and Oregon White Oak respectively. Height-Diameter Regression Coefficients for various site classes for Douglas Fir and White Oak in southern Oregon (Garman et al., 1995) were then selected. These coefficients were then used to compute a rating curve of tree heights from various DBH using equation 1 (Figure 6 and 7).

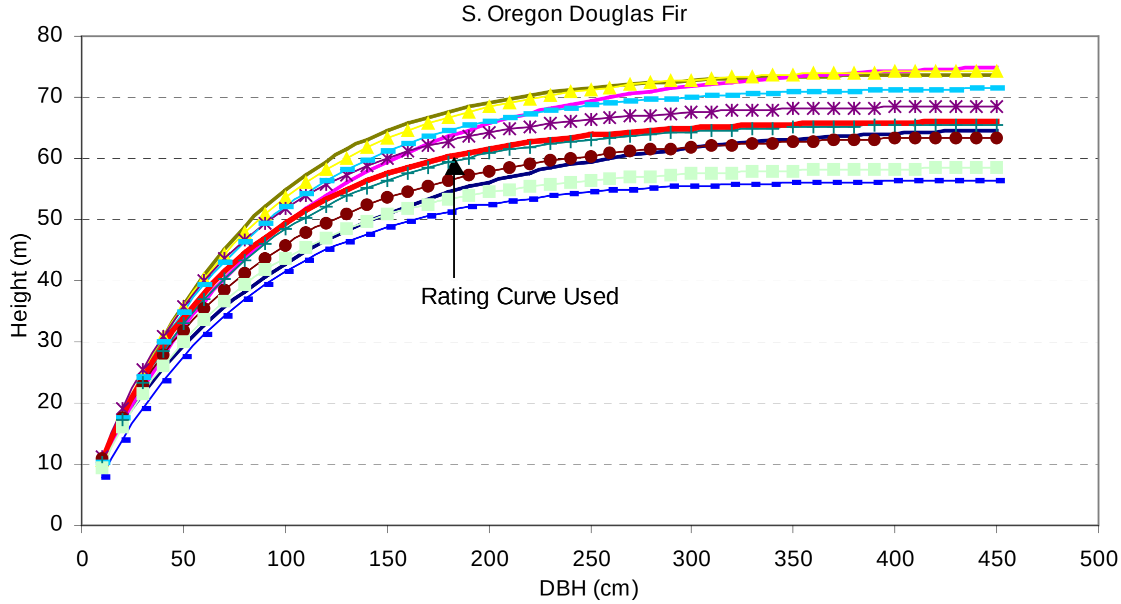

Figure 6. Tree Height–Diameter for various site classes for Douglas Fir in S. Oregon/Klamath Mountains

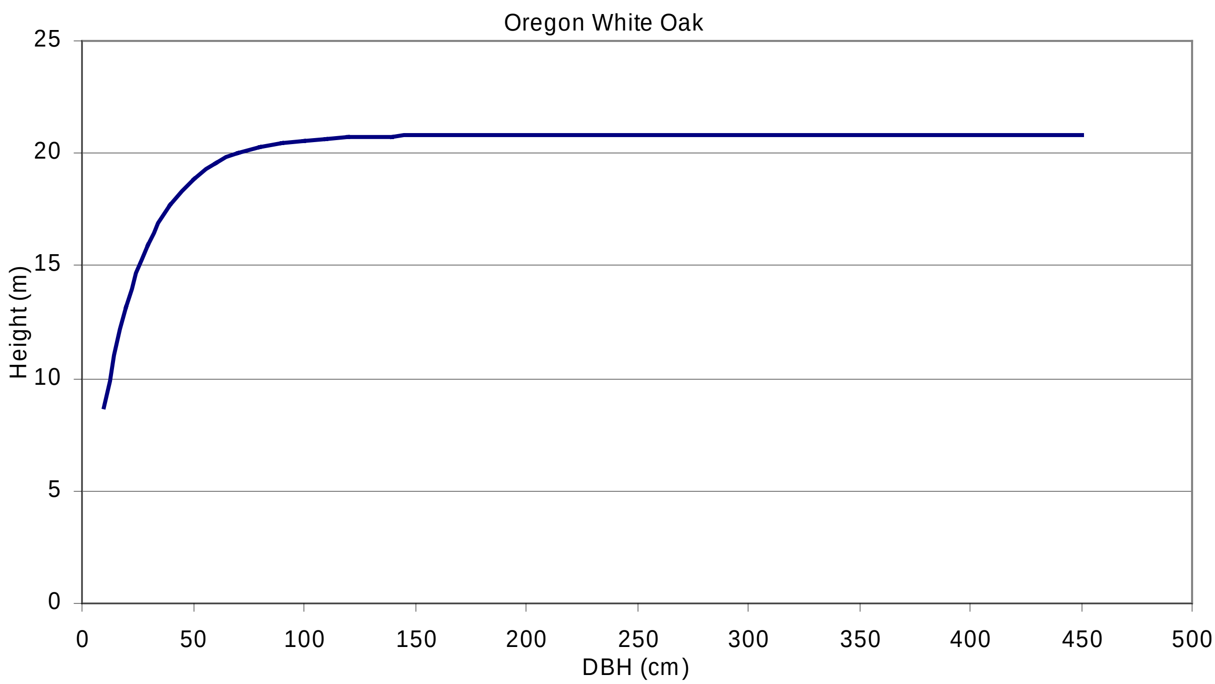

Figure 7. Tree Height–Diameter for all site classes for White Oak in S. Oregon/Klamath Mountains

The computed tree heights showed a wide variability for the Douglas Fir, and in general the maximum tree heights were found to be on the higher end compared to what has been identified in the study site. This is likely due to a combination of environmental factors including rainfall differences between Oregon and the Eel watershed. The average rating curve identified in Figure 6 was selected for the Douglas Fir species. This curve resulted in a maximum tree height of 49 m for a DBH of 101.6 cm (40”), which is consistent with trees found in the Middle Fork Eel watershed. It also had a site class of 3, which is the most dominant size class found in the available vegetation coverage. For hardwood trees, the coefficients for Oregon White Oak were used directly to compute the tree heights, which resulted in a maximum height of 21 m for a DBH of 101.6 cm (40”). The coefficients used in the modeling study for Conifers and Hardwoods are shown below in the Table 4. The heights derived from using these coefficients were then used consistently for all TMDL scenarios involving variable DBH conditions.

Table 4. Height-Diameter Coefficients used

Vegetation Type	b_0	b_1	b_2
Conifers	64.4681400	-0.0122890	0.9131890
Hardwood	19.4262100	-0.0451160	0.9588970

Another parameter required for SHADE model computations was density. The available canopy closure (%) attribute information in the vegetation coverage was simplified by assigning a Closure Class code based on Canopy Closure ranges (%) (Table 5). The tree density was then determined in the modeling system by assigning the appropriate average density based on the Closure Class Code.

Table 5. Canopy Closure Classes

Closure Class	Canopy Closure (%)
0	0-9
1	10-19
2	20-29
3	30-39
4	40-49
5	50-59
6	60-69
7	70-79
8	80-89
9	90-100

The vegetation theme was also used to determine the two-character vegetation cover code required for the vegetation shade input file (*.csv). This code is generated programmatically based on the cover type in the vegetation theme.

4.1.2 Digital Elevation Model (DEM)

Elevations were determined from the 30-meter DEM data distributed by USGS/EROS, 2003. This was used in determining the topographically controlled solar radiation at each stream sampling point.

4.1.3 Stream Network

The RF3 (EPA reach file version 3) stream network was used to represent the Eel River and its tributaries. It provides detailed stream connectivity information and supports development of stream routing for modeling purposes.

4.1.4 Watershed Information

The California Watersheds (CALWATER 2.2) from the California Department of Forestry and Fire Protection, along with overall Middle Fork Eel watershed boundaries provided by EPA, were used for the watershed boundaries.

4.1.5 Time Zone

The USGS (2002) time zone GIS layer was used. The standard time zone in which the watershed is located was determined using the time zone data layer. The center point of the selected watershed was determined and the standard time zone meridian, i.e., the longitude, was determined in decimal degrees.

4.1.6 Solar Radiation Data

The SHADE model requires daily global solar radiation. Hourly Solar radiation data for the year 2002 at the Alders Springs weather station (approximately 10 miles east of the Upper Black Butte watershed was downloaded from the California Department of Water Resources web site (CDEC, 2003). A daily time-series containing the cloud attenuated solar radiation for the modeling period was generated, as per SHADE model requirements.

4.2 Q2ESHADE Model Data

The data used in the simulation of the Q2ESHADE in-stream model are presented below:

4.2.1 Channel Geometry

The RF3 stream network identified in section 4.1 provides connectivity information, but does not include wetted stream width information required by the model. Stream width information for each reach is necessary to calculate the surface area for individual reaches and account for the total solar radiation received at the stream surface. Where available, the observed low-flow widths from the CA Department of Fish and Game

Reports (CADFG, 2002) were used. Table 6 shows the available CADFG survey locations within the watershed modeled. Where not available, widths were estimated based on California Digital Ortho (Quarter) or USGS maps from the California Spatial Information Library, best professional judgment, and linear interpolation.

Table 6 CADFG Survey Locations

Stream Name	Stream length surveyed from mouth (ft)	Sample Dates
Spanish Creek	18664	9/9/02 - 9/23/02
Spanish Creek – Trib. #4	337	9/22/02
Spanish Creek – Trib. #6	453	9/22/02

4.2.2 Channel Hydraulics

Since QUAL2E is a steady-state model, it requires a constant stream flow and temperature at the headwaters. The flow and initial temperature for the headwater reaches in the QUAL2E model were populated using summer base-flow values reported in the CADFG reports. To account for losing streams at some locations negative outflows were applied in the QUAL2E model as incremental flows. The incremental flows were less than 0.2 cfs and were distributed along the entire reach, hence had a negligible effect on the energy budget.

In order to describe the hydraulic characteristics of the system, the functional representation option within QUAL2E was used. This involves calculating the velocity and depth for the system using power equations. The power equations are of the form $v = aQ^b$ and $d = cQ^d$;

where, v = velocity
d= depth
Q=flow
a and c are the coefficients, and b and d are the exponents

Based on the base-flow and depth measurements provided in the CADFG Reports, one set of coefficients *a, c* and exponents *b, d* were derived, that were assumed to be representative of the entire system. The rating curve derived using these coefficients and exponents was such that the range of summer base flow conditions reported in the CADFG Reports would be covered. Values of depth and velocities from the QUAL2E model were verified with those observed in the CADFG reports.

4.2.3 Climatological Data

The Q2ESHADE model requires time-series climatological data including atmospheric pressure, dry bulb temperature, wet bulb temperature, wind speed, and cloud cover data for simulating dynamic the diurnal variation in the temperature. The CDEC station at Alders Spring did not have all the require weather parameters, e.g., wet bulb temperature data to prepare a weather file for the Q2ESHADE model. A complete data set with hourly time-series data by month were available for the Ukiah, CA station. This station is located 32 miles south east of the Middle Fork Eel watershed. Climatological data was downloaded from the National Oceanic and Atmospheric Administration (NOAA) and the National Climatic Data Center (NCDC) Unedited Local Climatological Data (ULCD) system for the year 2002.

The Q2ESHADE model allows for the clear-sky solar radiation to be adjusted by the observed cloud cover. However, since the solar radiation used in the SHADE model was cloud cover attenuated and not clear sky, this switch was turned off. It should be noted that the Ukiah weather station does not measure solar radiation, hence was not used in the SHADE model simulation.

5.0 Model Setup and Calibration

Once the required data sets were collected the SHADE and Q2ESHADE models were setup. The SHADE-GIS system was used to generate the input files for the SHADE model simulation, based on the specified SSP interval and buffer width. Height-Diameter coefficients presented in Table 4 were used to compute the tree heights for the existing/baseline condition. The resulting shade attenuated solar radiation time-series were then routed through the in-stream Q2ESHADE model to simulate the MWATs in the streams.

The hourly HOBO Temp Data (USEPA, 2002) monitored (approximately from 5/2002 to 10/2002) at various locations in the MFE watershed were used for calibration. Two stations were available in the Upper Black Butte watershed and one station was available in the North Fork of the Middle Fork Eel watershed. MWATs were calculated for the HOBO Temp Data for the period of simulation (7/15/2002 to 8/15/2002) and were compared to the MWATs predicted by the model. Table 7 shows the various stations used for calibration along with their MWATs, and Figure 8 shows the locations of the HOBO Temp stations used for calibration. The overall percent error between the model and predicted values was approximately 2 %.

Table 8. HOBO Temp Station Locations

Hobo Temp Station	Location	Observed Temperature MWAT (deg C)	Predicted Temperature MWAT (deg C)
338105	Black Butte (upper)	18.77	19.00
338102	Spanish Creek	18.71	18.34
18243	North Fork of Middle Fork Eel	19.61	19.00

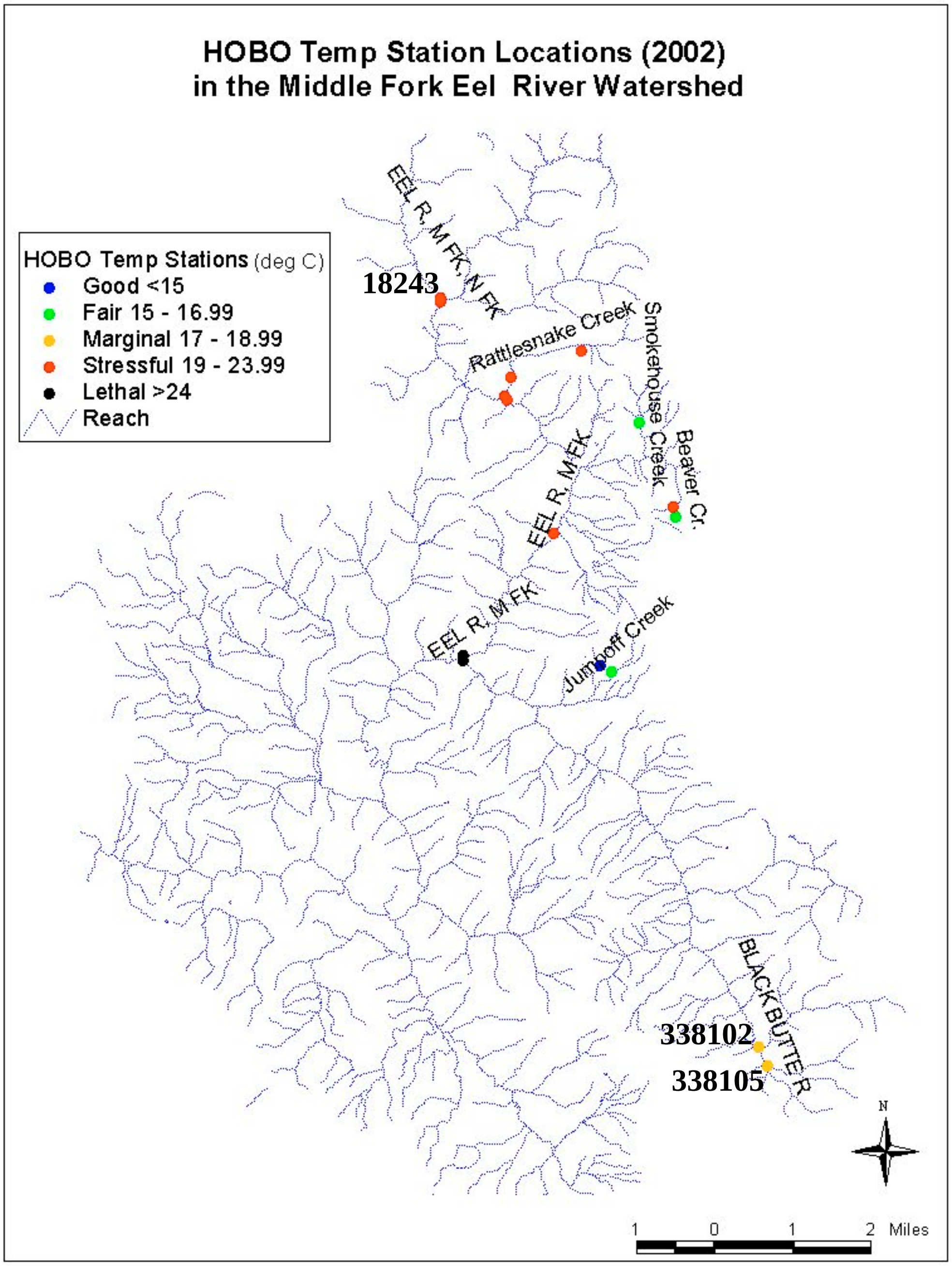

Figure 7. Locations of Monitoring Stations – HOBO Temp Data

6.0 Scenarios

The SHADE-GIS model allows the user to simulate scenarios based on the regression equation (equation 1), a constant height or a percent change in the tree height based on a particular reference vegetation height theme. Various scenarios based on varying DBH/tree height conditions were simulated for TMDL development. It was assumed that tree density remains the same as the baseline conditions for all the scenarios. The different scenarios simulated are presented below:

1. Topographic Shading Only – This scenario involved simulating the shading effects due to topography only. All trees were assigned a zero height and density.
2. Old Growth Condition – A maximum 48" DBH was assigned to Conifer for this simulation. The corresponding tree height for a 48" DBH was computed using equation 1 and the coefficients presented in Table 4 for Conifers. This gave a maximum tree height for Conifers as 53 m. Hardwoods were assigned a maximum height of 21 meters, which was the maximum height based on equation 1 and coefficients for Hardwood from Table 4. Hence for this scenario all the Conifers were assigned a height of 53 meters and all Hardwoods were assigned a height of 21 meters regardless of the seral stage in the entire watershed.
3. Forest Service Practice Rules – 18" DBH and 24" DBH conditions for Conifers. With no harvesting being allowed below a DBH of 18". For this scenario similar to the Old Growth condition scenario using equation 1 and coefficients from Table 4 for Conifers the maximum height was computed for Conifers. This gave a maximum height of 31 meters and 37 meters for the 18" and 24" DBH conditions respectively. Since no information was available on the DBH for the hardwoods, the hardwoods were assigned a maximum height of 21 meters (maximum height) for both the 18" and 24" DBH conditions. Hence for this scenario all the Conifers were assumed to be 31 meters for the 18" DBH condition and 37 meters for the 24" DBH condition, and all hardwoods were assumed to be 21 meters, regardless of the seral stage.

7.0 References:

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