Oregon Statewide Long-Term Water Demand Forecast

Appendix C: Current and Projected Future Irrigation Water Requirements for Oregon

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Current and Projected Future Irrigation Water Requirements for Oregon Technical Report

Introduction

Evapotranspiration (ET) is the second largest component of the hydrologic system and river basin water balances, following precipitation, and is the primary determinant of irrigation water requirements for agricultural crops. The quantification of historical ET and consumptive use for specific crops and regions is required for design of irrigation systems, for basin water balance estimates, for estimating streamflow depletion stemming from irrigation activities, for irrigation water management, for water use reporting, and for review and litigation of water rights in Oregon as well as in other western states. It is important that states develop and apply scientifically sound approaches for estimating irrigation water requirements and actual crop ET under well-watered as well as water limited conditions, that includes information on field-to-field variation. These estimates are necessary to support long-term water resources planning and management, hydrologic studies, and reporting needs as well as obligations in water governance and interstate agreements. The methods summarized in this report for estimating historical ET and the net irrigation water requirement (NIWR) under well-watered conditions are consistent with and accepted by local, state, and federal agencies, as well as by courts and other outside entities. Future projections of crop ET and NIWR are needed for assessing future water demands, and the approaches used for making such estimates should be consistent in methodology with historical estimates for evaluating relative change.

This report summarizes general methodologies for estimating historical and future projections of crop ET and NIWR for station locations within the Klamath and Columbia River basins in the State of Oregon using a consistent approach recently published by the U.S. Bureau of Reclamation as part of the West Wide Climate Risk Assessment (WWCRA) (Huntington, et al., 2015). This report also summarizes a database of historical and future projections of crop ET and irrigation water requirements for WWCRA stations within Oregon, which is included in the 2015 Oregon Statewide Long-Term Water Demand Forecast as Appendix G.

Methods

The methods summarized here are considered to be state-of-the-art and are consistent with and have been accepted by state and federal agencies as well as by several courts and other outside entities. The proposed methodology includes the use of the American Society of Civil Engineers (ASCE) standardized Penman-Monteith method (ASCE-EWRI, 2005) with growing-degree based crop coefficient curves, dual crop coefficient approach that provides separate estimates of transpiration and evaporation, and bias-correction of future and gridded weather time series projections using quality-checked ground-based weather data from agricultural areas. This methodology is supported and recommended by the upcoming revision of the ASCE Manual 70 “Evapotranspiration and Irrigation Water Requirements” (Jensen and Allen, 2015, in press). Coauthors of this technical report have published recent estimates of historical ET for the neighboring states of Nevada and Idaho that are now used in state agency water rights management, hearings and decision-making as well as for irrigation design and hydrologic modeling (Huntington and Allen, 2010; Allen and Robison, 2007).

Definitions

- Evapotranspiration (ET): the combined sum of evaporation from soil plus transpiration from vegetation, plus a minor component that includes any direct evaporation from vegetation surfaces following rain, dew or overhead irrigation.

- -Potential Crop Evapotranspiration (ETc): the volume or depth of water that is removed from available supplies through a combination of evaporation and transpiration from vegetation under full-water supply, where water supply includes both precipitation and irrigation. Potential Evapotranspiration is often interchanged with the term Potential Consumptive Use.

- -Actual Evapotranspiration (ETact): the volume or depth of water that is removed from available supplies through a combination of evaporation and transpiration from vegetation. Actual Evapotranspiration is often interchanged with the term Actual Consumptive Use.

- -Reference Evapotranspiration (ETref): ET from a defined, standardized reference crop that is actively growing, not limited by soil moisture, and is at full cover and standardized height. Standardized reference crops in the US are 0.5 m tall, full-cover alfalfa and 0.12 m tall clipped, cool-season grass and have been defined by ASCE (2005).

- - Effective Precipitation (Peff): in the context of irrigation water requirements, is the portion of precipitation, expressed as a volume, depth or fraction, that is effective in reducing the net irrigation water requirement. As described later, this means that Peff is primarily the portion of precipitation that reduces the transpiration (T) requirement of a crop, rather than the evaporation (E) portion.

- - Net Irrigation Water Requirement (NIWR) is the volume or depth of water required, in addition to precipitation, to grow a well-watered crop under optimal conditions having a full water supply; NIWR is calculated as ETc – Peff.

General Approach

In the WWCRA approach, crop specific historical and future ETc is computed on a daily basis using a two-step process where daily reference ET computed from a combination of bias corrected gridded weather data and agricultural weather station data is multiplied by transient crop coefficient values (Kc). Transient crop coefficients are estimated using the dual-Kc approach developed in FAO-56 (Allen et al., 1998; Allen et al., 2005a) and following procedures recommended in the upcoming ASCE Manual 70 revision (Jensen and Allen, 2015, in press). NIWR is estimated by differencing ETc and effective precipitation, Peff. ETref, Kc, ETc and Peff data are computed using the ET Demands model, which will be briefly summarized below, and is more thoroughly described for WWCRA applications in Huntington et al. (2015). The ET Demands model was developed in collaboration with U.S. Bureau of Reclamation from code that originated in the ET-Idaho model of Allen and Robison (2007) and further evolved in the ET-Nevada model of Huntington and Allen (2010). The U.S. Bureau of Reclamation's WWCRA study employed the ET Demands model for historical and future time periods for to seven major river basins in the western US, including the Columbia River basin and the Klamath River basin, which covers a significant portion of northern, eastern and south central Oregon. Station that are specific to Oregon and analyzed as part this study are shown in Figure 1, and metadata are listed in Attachment 1.

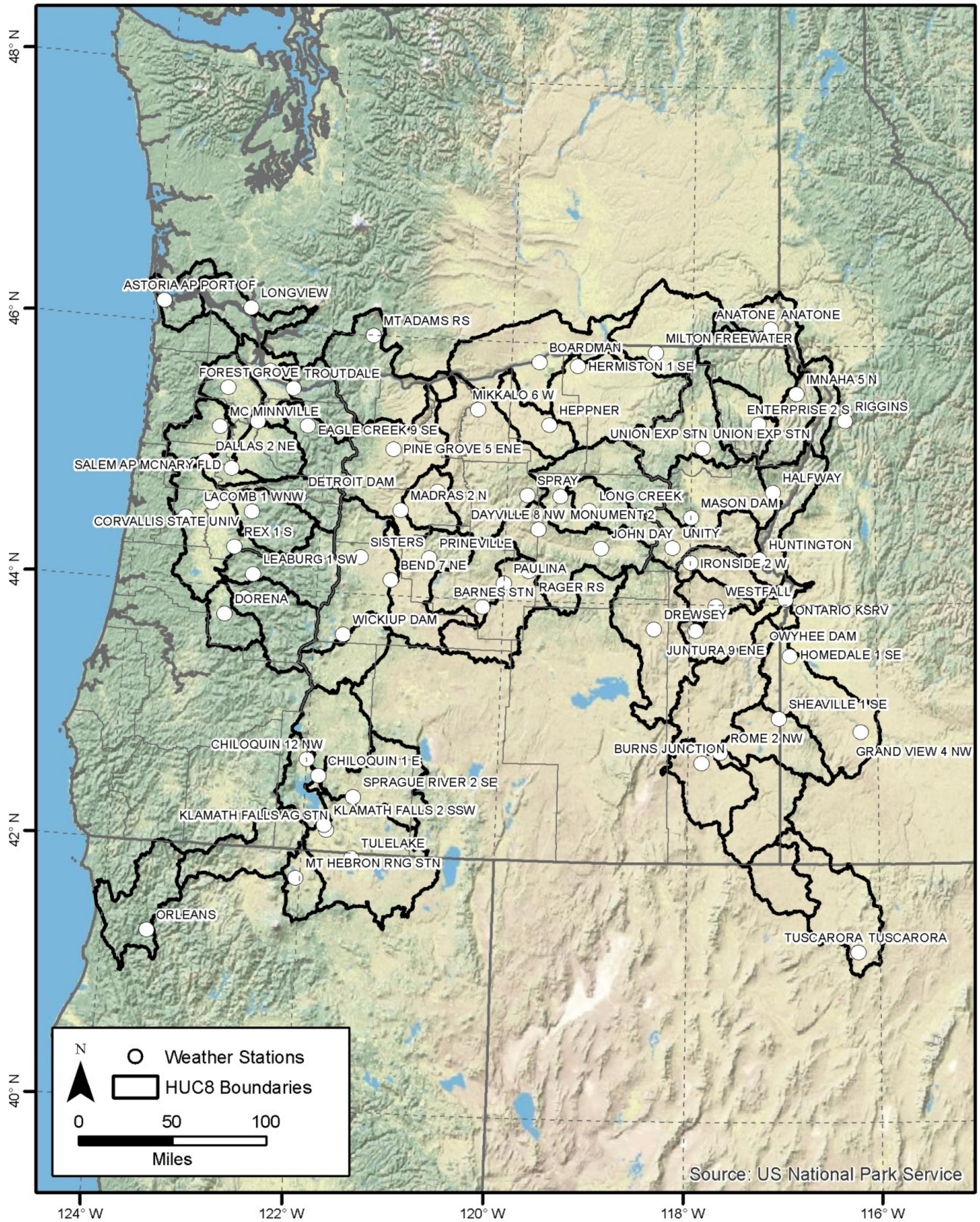
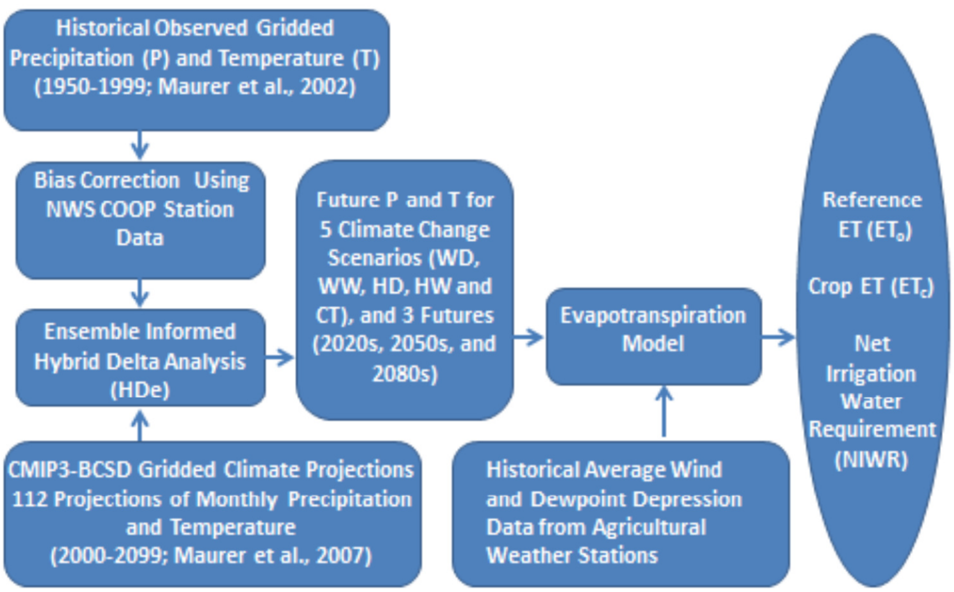


Figure 1. HUC 8 and NWS COOP Weather Stations Studied in the West Wide Climate Risk Assessment (WWRA) Historical and Future Irrigation Demands Study of the U.S. Bureau of Reclamation (Huntington et al. 2015) that are Specific to the Oregon WRD Future Demands Assessment

Historical and Climate Change Scenarios

Historical 1950-1999 climate data from the WWCRA analysis are based on gridded observations from Maurer (2002) downscaled to local National Weather Service COOP climate observations. Historical and future climate projections are ultimately used to force the ET Demands model for estimating ETc and NIWR (Figure 2). Climate scenarios for agricultural demands are derived using an ensemble informed hybrid delta (HDe) method (Hamlet et al., 2013; Reclamation, 2011) where the historical baseline climate observations from Maurer et al. (2002) are perturbed based on future projections of temperature and precipitation. The future climate scenarios were developed based on CMIP3bias corrected and statistically downscaled (BCSD) general circulation model GCM projections, as these projections are considered equally likely potential climate futures at this time. Reclamation, in collaboration with other partners, developed archives of downscaled climate projections from the CMIP3 (Maurer et al. 2007) and CMIP5 (Maurer et al. 2013) climate projections. Downscaled climate projections were developed using the statistical downscaling approach referred to as the Bias Correction and Spatial Disaggregation (BCSD) method (Wood et al. 2002). This technique was used to generate downscaled translations of 112 CMIP3 projections, which are available online at the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections"[1] archive (BCSD climate projections, referring to the methodology described above). The BCSD climate projections ensemble used in WWCRA were produced collectively by 16 different CMIP3 models simulating 3 different emissions paths (B1, A1B and A2).



Note: Figure modified from Huntington et al. (2015).

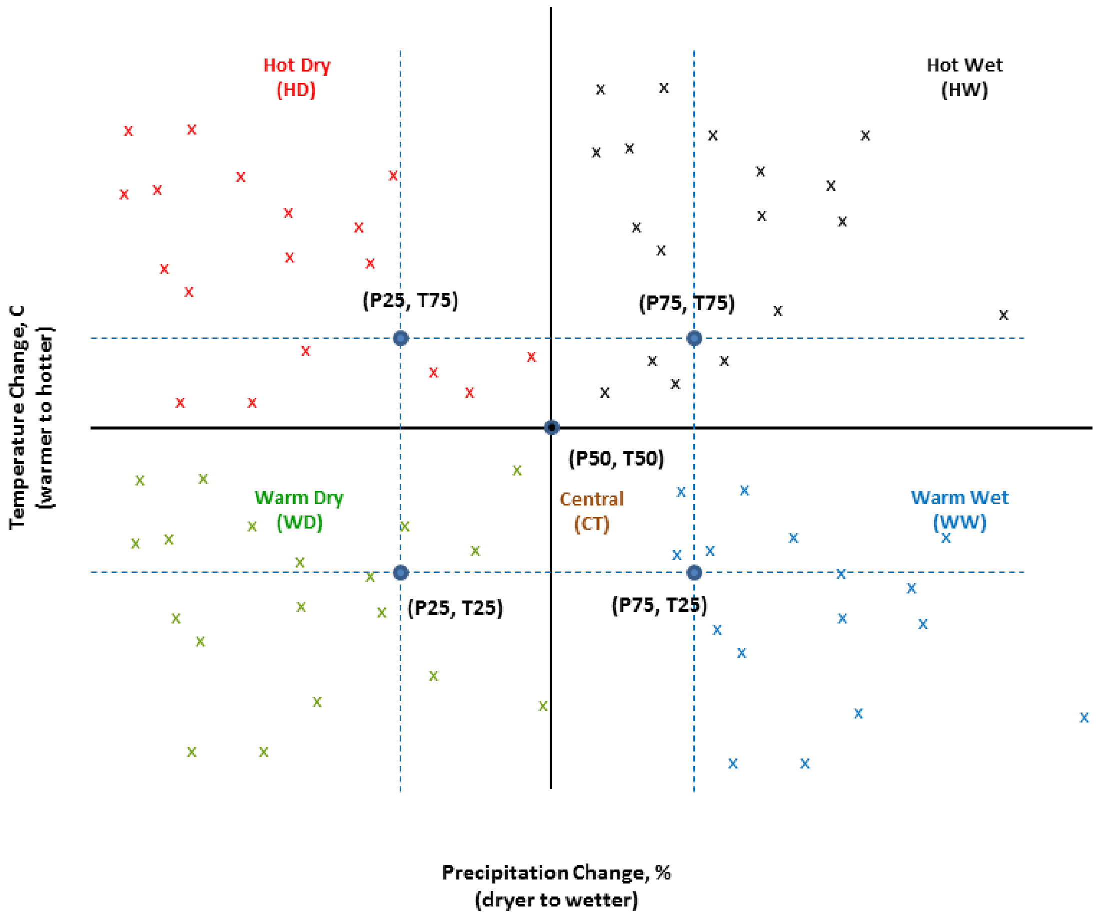
Figure 2. Flow Chart of the General WWCRA Process for Estimating Historical and Future Crop ET and Net Irrigation Water Requirements

[1] Available from http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html. Accessed January 2014.

Processing a large number of downscaled climate projections through a detailed and complex impacts model such as the ET Demands model is data intensive, computationally prohibitive, and complex to interpret and effectively communicate results to stakeholders. The WWCRA approach aimed to keeping this task manageable by defining five climate change scenarios using the HDe method for describing a range of potential future climates, which are used as input into the ET Demands model. The HDe method requires identifying a historical baseline period of climate and a future period of climate to estimate changes in precipitation and temperature between the historical base period and a future period. The baseline period used in the WWCRA study was 1950–1999. Three future periods were defined as (1) 2010–2039; (2) 2040–2069; and (3) 2070–2099. In the WWCRA study, these three future periods were labeled as the 2020s, 2050s, and 2080s, respectively. The basis for the 5 quadrant HDe scenarios of precipitation and temperature used in WWCRA is a suite of monthly statistically downscaled CMIP3 GCM simulations (Reclamation, 2014). Figure 3 illustrates the quadrant HDe approach, where five WWCRA climate change scenarios are selected based on the follow:

- Warm Dry (WD) – climate change scenario is informed by projections that show precipitation change less than P50 and temperature change less than T50
- Warm Wet (WW) – climate change scenario is informed by projections that show precipitation change greater than or equal to P50 and temperature change less than T50
- Hot Dry (HD) – climate change scenario is informed by projections that show precipitation change less than P50 and temperature change greater than or equal to T50
- Hot Wet (HW) – climate change scenario is informed by projections that show precipitation change greater than or equal to P50 and temperature change greater than equal to T50
- Central Tendency (CT) – climate change scenario is informed by projections defined by the boundaries - (P75, T75); (P25, T75); (P25, T25); and (P75, T25).

Percentile changes are represented by suffixes 25, 50, and 75 after P (precipitation) and T (temperature) respectively. Percentile changes are changes with respect to the baseline period (Figure 3). Change factors developed from the HDe approach shown in Figure 3 were used to adjust bias corrected historical baseline time series in the WWCRA approach.



Note: Figure modified from Reclamation (2014). The WWCRA description of the HDe quadrant figure and approach is described as following: point (P50, T50) is used as the center point of the change in precipitation axis and change in temperature axis. The resulting quadrants are then used to assign projections. Change in precipitation values along the precipitation axis ranges from dryer to wetter, and temperature change along the temperature axis ranges from warmer to hotter. Each group of projections within a quadrant is used to inform a specific climate change scenario, and a total of four climate change scenarios are defined this way. The fifth climate change scenario is defined by projections that fall within the box defined by the points (P75, T75); (P25, T75); (P25, T25); and (P75, T25), where the 25th and 75th percentile changes are represented by suffixes 25 and 75 after P (precipitation) and T (temperature) respectively.

Figure 3. Future Projection Membership Diagram to Define Five Climate Change Scenarios for WWCRA Irrigation Demands Based on the Population of Projected Future Climates

Because the historical baseline Maurer et al. (2002) climate data used in WWCRA is at the spatial scale of 1/8° latitude by 1/8° longitude (approximately 12 km^2), better representation of valley floor and agricultural climate were addressed by bias correcting the Maurer et al. (2002) climate data of maximum and minimum temperature, and precipitation to observed National Weather Service (NWS) COOP station climate variable values in the same 1/8° grid cell and over a common time period prior to HDe scenario development. The creation and use of NWS COOP station based bias-corrected historical data produces more accurate and representative historical and projected ET_c and NIWR time series that are a) congruent with real measurements of data, historically, b) reproduce actual time series and correlations among weather parameters, and c) retain congruency between historical and future projected time series regarding bias. These data characteristics are essential for planning studies related to water resources management, state water rights management and water operations and management. For further information on the development of WWCRA climate scenarios see Reclamation (2014) and Huntington et al. (2015). NWS COOP weather stations (i.e., Met Nodes) were carefully chosen in the WWCRA study to represent major irrigation areas within larger Hydrologic Unit Code 8 (HUC8) areas where possible.

ET Demands Model

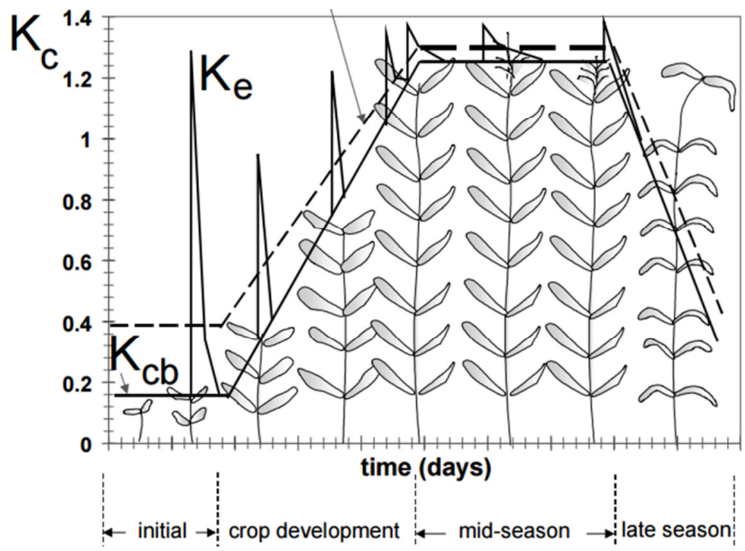
The state-of-the-art approach for operational computation of ET_c and NIWR is the crop coefficient – reference ET approach, where the reference ET, ET_{ref}, representing climatic demand for water, and based on physical relationships, is multiplied by a crop coefficient representing ET from a vegetated surface under stress free and well-watered conditions. There are many methods available for estimating ET_{ref}. While many are simple temperature-based techniques, others are more data intensive, physically based models such as the Penman-Monteith (PM) method. In this report, the PM method is used for estimating historical and future projections of ET_{ref}, ET_c, and NIWR. Estimates of ET_{ref} vary widely among the methods, and until the last decade, there was considerable debate as to the more correct and appropriate method. The professional and scientific communities now generally recognize the ASCE-EWRI (2005) standardized PM method (and its basis, the Food and Agriculture Organization's FAO-56 PM method) as the most appropriate ET_{ref} method. A past impediment to applying the PM method has been the limited numbers of weather stations that collect solar radiation, relative humidity, air temperature and wind speed data. In addition, past General Circulation Model (GCM) projections of climate change only summarized temperature and precipitation. The absence of solar radiation, dew point temperature, and wind speed needed for the physically based ET_{ref} PM model in long-term forecasts has, in the past, led to the use of simpler temperature-based methods for assessing climate change impacts, even though investigators were generally aware that using more physically based methods resulted in more accurate and representative estimates of future ET_{ref}, ET_c and NIWR, and that the physically based methods contained the appropriate sensitivity to changes in all climate variables. More recently, we have developed capabilities to merge gridded weather data available from historical land data assimilation systems with GCM-based projections of maximum and minimum temperature, solar radiation, humidity, windspeed, and precipitation to support application of the ASCE-PM ET_{ref} method with both historical and future projections, thus creating the means to produce more robust and climatically sensitive data sets of ET_c and NIWR over large areas that are consistent with current state and federal ET data sets and that are more readily accepted by the scientific and policy-making communities.

The ET Demands Model estimates potential crop ET, ET_c, following the standardized FAO-56 and ASCE procedures (Allen et al., 1998; ASCE-EWRI, 2005) as

$$ET_c = (K_s K_{cb} + K_e) ET_{ref}$$

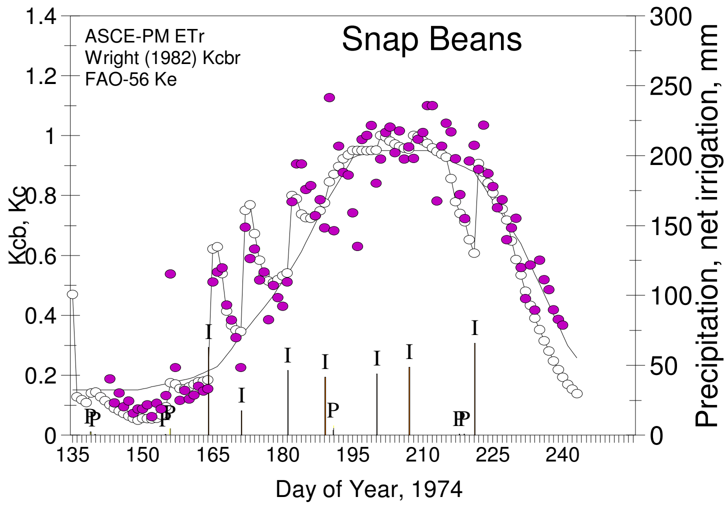
where ET_{ref} is the reference ET, K_{cb} is the basal crop coefficient, and K_e is the soil water evaporation coefficient. K_{cb} and K_e are dimensionless and range from 0 to 1.4 when applied with the clipped grass reference ET that has traditionally been employed in Oregon (Cuenca et al., 1992). The short grass reference crop version of the PM equation (ET_o) was also used in the WWCRA report to be consistent with previous Reclamation work. The K_{cb} curve expresses impacts of time-based development of vegetation on ET that vary from year to year depending on the start, duration, and termination of the growing season, all of which are dependent on temperature conditions during spring, summer, and fall. The stress coefficient, K_s, ranges from 0 to 1, where a value of 1 represents conditions of no water stress, as is the case for fully-irrigated crops during the irrigation season. A daily soil water balance for the simulated effective root zone is required to calculate K_s. In the case of NIWR, K_s is constrained to 1.0 during the growing season by simulating irrigation events following methods outlined in Allen et al. (1998) and Allen et al. (2005a). A soil water balance of the upper soil layer is used to estimate K_e (Allen et al., 2005a). An example of a 'dual' K_c curve incorporating both transpiration and evaporation is illustrated in Figure 4. The advantage of using a dual crop coefficient over a 'mean' or single crop coefficient approach is that it allows for separate accounting of transpiration, via a basal K_c (K_{cb}), and evaporation, via an evaporation coefficient (K_e), to better quantify evaporation from variable precipitation, simulated irrigation events, and during freezing months of winter for dormant covers of mulch and grass as well as for bare soil, thus providing the ability to produce growing season ET_c and year-round ET_c estimates. Winter time ET_c estimation allows for accurate accounting of winter time soil moisture losses and gains, leading to more accurate estimation of NIWR under historical and future climate conditions. ET Demands model applications in the ET-Idaho, ET-Nevada, and WWCRA studies are some of the few study applications that simulate non-growing season ET from dormant agricultural vegetation and soil surfaces.

The dual K_c approach using field measurements is illustrated in Figure 5, where daily K_c data at Kimberly, Idaho are shown, including data measured by lysimeter. The agreement between measured and simulated data is much improved by the use of the dual approach where increases in K_c stemming from wetting events are captured. Many K_c curves in the literature were derived from research weighing lysimeter measurements of actual ET from stress-free crops and calculated ET_{ref} at the lysimeter sites, mainly from Davis, CA, and Kimberly, ID (Doorenbos and Pruitt, 1977; Wright, 1981, 1982). The heritage of many K_{cb} values used in WWCRA are traceable to the Kimberly lysimeter (Wright 1982) and the U.S. Bureau of Reclamation's AgriMet program.



Note: Figure from http://www.kimberly.uidaho.edu/water/fao56/fao56.pdf

Figure 4. Illustration of a Typical Dual Kc Linearized FAO-56 Style Crop Coefficient Curve Showing Labels Typically Used for Kcb During Initial (ini), Development (dev), Midseason (mid) and End of Season (end) Growth Stages



Note: The basal crop curve (K_{cb}) (thin line with no symbols) was derived from K_{cb} values based on Wright, 1982). The 'spikes' in K_c above the K_{cb} curve represent positive values for the evaporation coefficient, K_e, associated with wetting events. Figure from Allen et al., (2008).

Key: —— Basal Kcb —○— Ks Kcb + Ke ● Kc from Lys. P = precipitation event I = irrigation

Figure 5. Measured (red symbols) and Estimated (thin line with open symbols) Daily Crop Coefficients for a Snap Bean Crop at Kimberly, Idaho

Air and soil temperature regulate nearly all plant functions, therefore vegetation phenology is closely related to thermal heat units rather than calendar dates. For this reason, the cumulative growing degree-days (CGDD) concept has gained wide spread use and is used as a primary method in WWCRA ET Demands applications for constructing K_c curves. The starts, durations, and terminations of growing seasons are estimated specific to each year using 30-day moving average temperature (T_{30}) and CGDD prior to the start date, and with minimum air temperature used to define killing frosts. Given the uncertainties in measured ET_c, which is commonly reported to be ~10-20%, ET_c estimated with the ET Demands model is believed to be fairly robust, given accurate estimation of growing season lengths and crop development patterns (crop dependent planting and greenup, cutting cycles, harvests, etc). In the WWCRA approach, calibration of crop dependent planting, greenup, harvests, and termination dates was achieved for major irrigated areas using documented records and typical ranges of dates reported by the U.S. Department of Agriculture (USDA-NASS, 2010). For basins located in Oregon, calibration of these parameters in the WWCRA process were focused using growing season information from major irrigated areas of Klamath Falls (Klamath Basin) and Hermiston (Columbia Basin). Further details of the ET Demands Model and daily water balance proposed can be found in Allen et al. (2005a), Allen and Robison (2007), Allen and Wright (2009), Huntington and Allen (2010), and for specific WWCRA applications see Huntington et al., (2015).

Many basal K_{cb} curves are developed in the ET Demands model as a function of cumulative temperature (i.e., CGDD). For future periods, K_{cb} curves for annual crops (i.e. spring grain, corn, etc.) are developed using both baseline temperatures and future projected temperatures. For perennial crops (i.e. alfalfa and grass hay) K_{cb} curves are only developed using future projected temperatures. Changes in future farming practice of annual crops, such as potential earlier planting, development, and harvest, is highly uncertain under warming climatic conditions. Any potential changes will likely be dependent on future crop cultivars, water availability, and economics. For these reasons, "baseline" or "static phenology" K_{cb} curves were simulated for future periods, where historical baseline temperatures were used for simulating planting, crop development and harvest dates using the GDD approach previously described. In effect, all scenarios and time periods have identical base period start, harvest, termination dates, and therefore seasonal K_{cb} curve shapes for each annual crop, and only exhibit differences in daily ET_c magnitudes due to daily ET_o and precipitation differences. A detailed discussion on this historical baseline temperature or 'static phenology' approach is described in Huntington et al. (2015). Annual crop results summarized in this report for Oregon for are based on the baseline or "static phenology" K_{cb} curves only.

Application of the ET Demands model for historical baseline and projected climate in the WWCRA process was accomplished using data managers[2] developed with Visual Basic for Applications (VBA) in Excel. ET_o was computed at each NWS COOP station location, while all subsequent computations were computed for each ET Cell and crop type specified. Crop types and acreages within each HUC8 and assigned ET Cell were based on the USDA Crop Land Data Layer for the Columbia River basin, and local Reclamation area office crop mix information for Reclamation project lands in the Klamath River basin (USDA-NASS, 2010a). ET Cells incorporate spatial information associated with NWS COOP station HUC8 assignments, such as soil type and crop type and acreages. Ultimately, ET_o is estimated at the NWS COOP station locations, and crop and soil information within agricultural areas of each HUC8 are paired with respective ET_o estimates to compute ET_c and NIWRestimates for each ET Cell. ET Cells serve as the primary unique identifier within the database, and retain attributes of NWS COOP station information, respective HUC8 area pairing, and soil and crop information.

Results and Discussion

Historical baseline and projected irrigation water demand estimates were estimated in the WWCRA process using the ET Demands model, as discussed in the methods section. ET Demands results of historical baseline and future projections of temperature, precipitation, reference ET, ET_c, and NIWR are summarized by HUC8 and ET Cell ID and are crop area weighted averages in the WWCRA report. ET_c and NIWR is summarized per ET Cell and per crop within the WRD database developed in this work. Illustrations of WWCRA crop area weighted average depths of ET_c and NIWR for historical baseline and future periods, and WRD database crop specific baseline and future period changes are discussed and illustrated below.

Results of projected climate and irrigation demands include mean annual precipitation, temperature, reference evapotranspiration (ET_o), crop evapotranspiration (ET_c), and net irrigation water requirement (NIWR) depths. WWCRA results contain projected changes in precipitation, temperature, ET_o, ET_c, and NIWR for 5 climate scenarios and 3 different time periods for areas within Oregon. Appendix A Figures A1 through A10 in this report illustrate WWCRA stations, baseline climate, and future NIWR for 5 climate scenarios and 3 future time periods for Columbia and Klamath basins. Figures A9 and A10 illustrate baseline and projected temporal distribution of mean daily ETc for the NWS/COOP Klamath Falls Ag. Station (station OR4511) for future time periods. Figure A9 illustrating simulated mean daily ETc of alfalfa for different scenarios and 2020 and 2080 time periods, shows slight but noticeable shifts in the growing-season length and alfalfa cutting cycles relative to baseline conditions. By the 2080 time period significant shifts in growing-season length, crop development, and cutting cycles are noticeable relative to baseline conditions, with scenarios S3 and S4 exhibiting the most extreme changes. Figure A10 illustrates simulated mean daily ETc of pasture grass at station OR4511 for different scenarios and time periods. Similar changes in greenup timing and increases in growing-season length and ETc are projected when compared to alfalfa, with S3 and S4 having the most extreme seasonal changes.

Projected changes for Oregon HUC8 areas and ET Cells covered in the WWCRA report are presented as values, difference from historical baseline averages values for temperature, and percent change from baseline average values for all other variables. Tabular results of WWCRA HUC8 areas that cover

[2] West Wide Climate Risk Assessment – Data and Model Managers Manual, Bureau of Reclamation, Technical Services Center, December 2013.

Oregon are summarized in Appendix F of this report and have been subset from the full WWCRA appendix found at http://www.usbr.gov/WaterSMART/wcra/docs/irrigationdemand/Appendices.pdf.

Oregon specific WWCRA historical baseline and projected estimates for each ET Cell and crop type have been compiled into two databases (stats.csv and stats_by_crop.csv) and provided as part of this this technical report focused on WWCRA applications within Oregon. Figures 6 and 7 illustrates baseline and future projections of alfalfa NIWR per ET Cell / NWS COOP station for Oregon. While Figures 6 and 7 only illustrate results for alfalfa due to figure limitations, results from other crops can be evaluated using the two databases summarized by this report. The spatial distribution of projected NIWR percent change for the 2050 period and S3 (Hot and Dry; HD) scenario is shown in Figure 7. The NIWR incorporates growing-season and non-growing-season soil moisture gains and losses from precipitation, bare soil evaporation, and ET. Therefore, spatial variations in the distribution of NIWR percent change for different time periods and scenarios are a function of respective ET_c and precipitation distributions. For example, the cause of relatively high percent increases in the NIWR by 2050 for the S3 scenario is due to a combination of increased growing season length, reduction of precipitation, and relatively small initial baseline NIWR as illustrated in Figure 6. These large increases are most prevalent in the Cascades and south eastern portion of the study area.

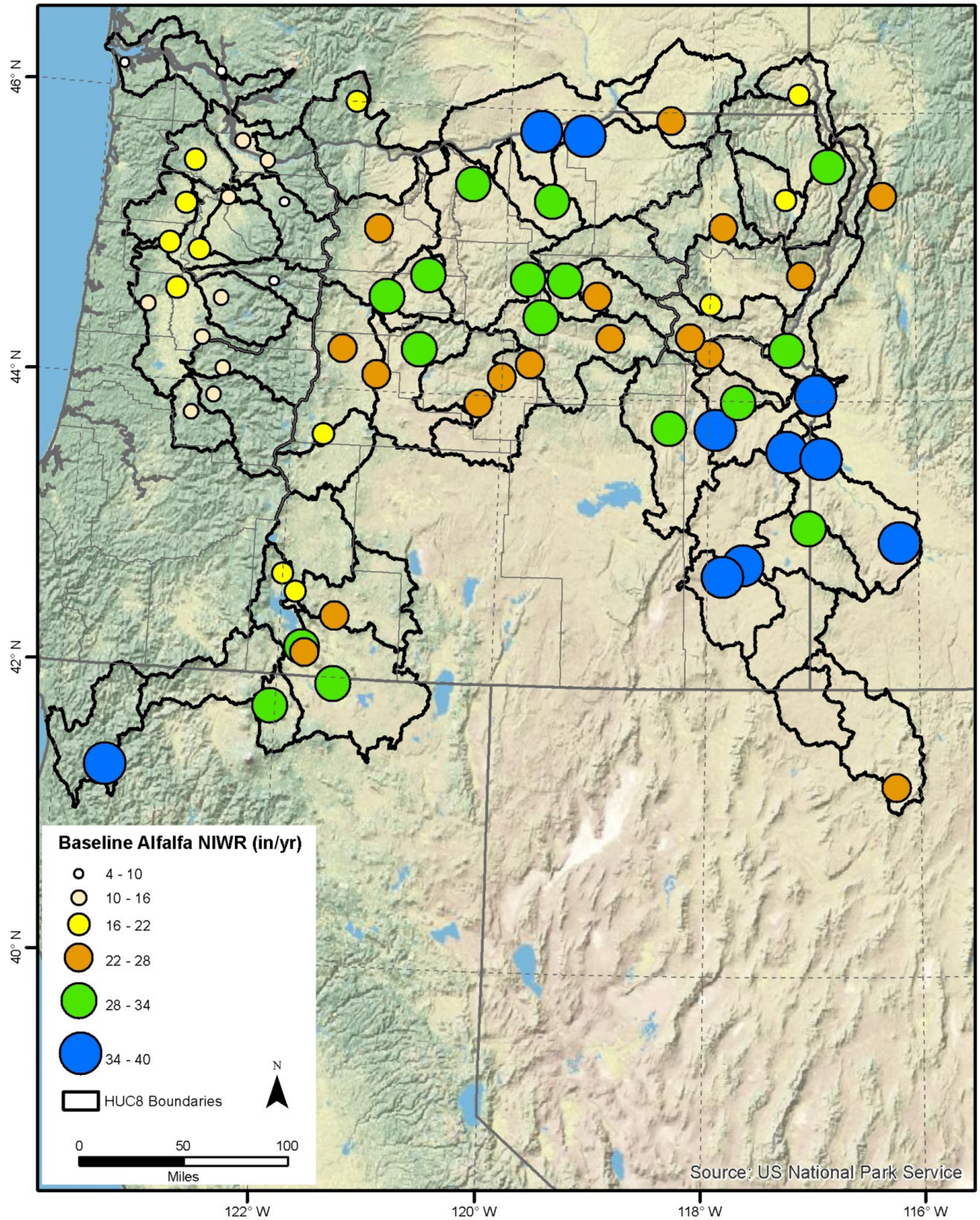


Figure 6. Baseline 1950 – 1999 Net Irrigation Water Requirement (NIWR) for Alfalfa for WWCRA ET Cell/NWS COOP Stations Summarized in the Oregon DWR Irrigation Demands Database Described in this Report

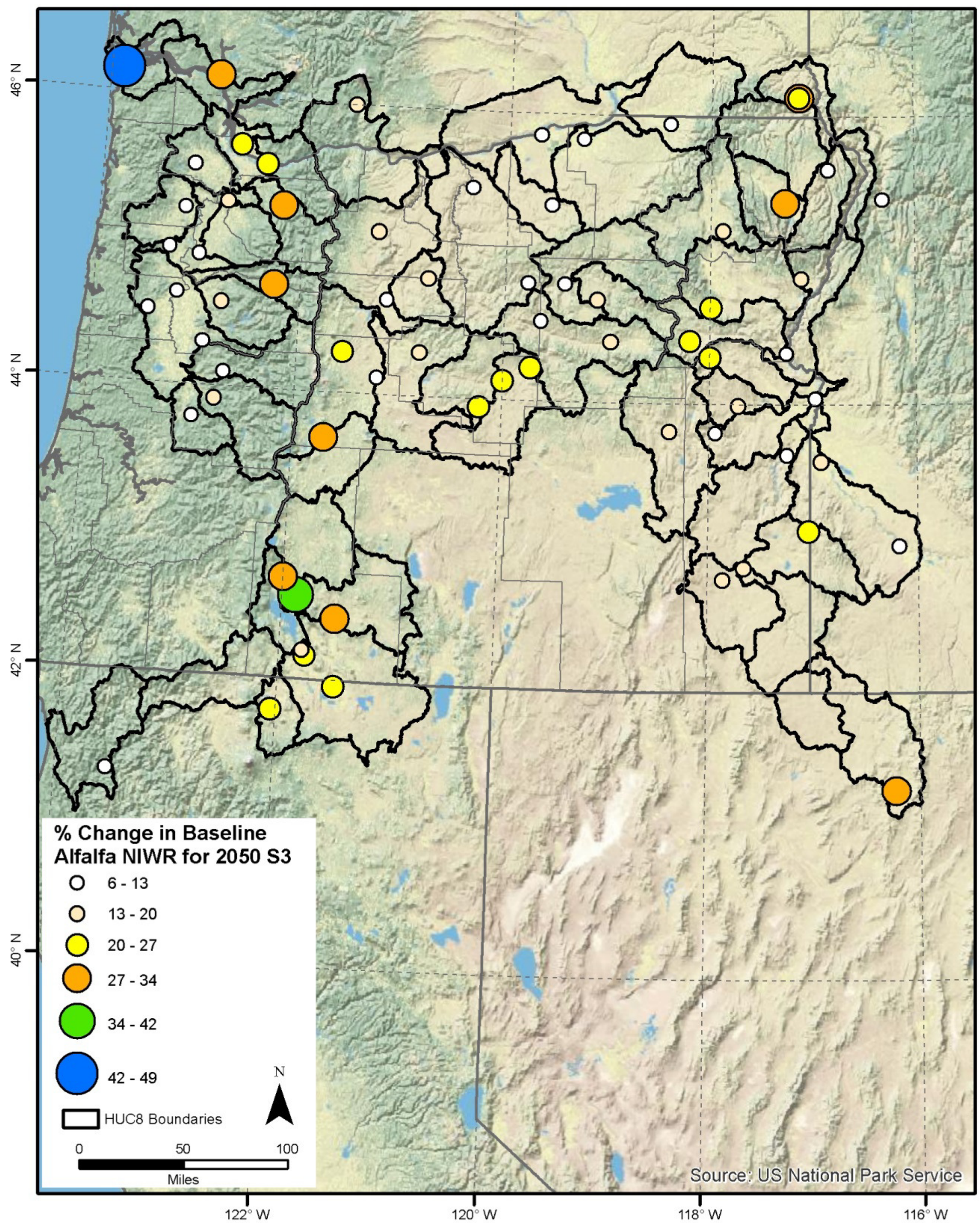


Figure 7. Percent Change in the Net Irrigation Water Requirement (NIWR) for Alfalfa for the 2050 Time Period and S3 Climate Scenario (Hot – Dry) for WWCRA ET Cell/NWS COOP Stations Summarized in the Oregon DWR Irrigation Demands Database Described in this Report

Limitations

Future irrigation demand estimates summarized in this report, and derived from the WWCRA study are meant to provide a starting point for ongoing and future impact assessments and other water planning efforts. The estimates of crop ET and irrigation water requirements do not account for changes in cropping patterns or other socio-economic considerations that require stakeholder input. Therefore, it is important that care be taken when comparing the irrigation demand estimates from this study to those from previous studies that do consider such cropping and socio-economic change considerations. This study does however provide much needed baseline and relative change information that is crop and area specific for major irrigated areas of Oregon. This information could be potentially used to support irrigation system design and management, water balance models, litigation, and state water resource planners.

Forecasts of change in future farming practices for annual crops, such as potential earlier plantings, more rapid development and harvest, are somewhat uncertain under warming climatic conditions. These potential changes will be highly dependent on future crop cultivars, water availability, and economics. In spite of these uncertainties, the best approach to assess impacts of climate change on irrigation water requirements suggests the use of thermally based K_{cb} curves, where planting and harvest dates for annual crops are temperature dependent, where the phenologies are simulated using the T_{30} and the CGDD approach. Baseline or 'static phenology' K_{cb} curves were simulated for future periods, where historical baseline temperatures were used for simulating planting, crop development, and harvest dates using the GDD approach. As a result, shifts in planting, development, and harvest dates only occur during simulations of future time periods for perennial crops, while annual crops have similar growing season characteristics as the base period.

It is important to note the assumption of adequate irrigation water supplies to fulfill crop water needs when estimating ET_c and NIWR, especially with regard to growing season length impacts on total crop water consumption. As climate warms, and it is assumed there are no constraints on crop cycles due to water scarcity, then peak ET_c rates will increase. However, plant phenologies may shift and growing seasons could shorten, or expand, or stay static depending on crop type.

As stated in the WWCRA report, probably the largest uncertainty in the procedures used to calculate future ET_c and NIWR may come from the absence of incorporation of potential impacts of elevated carbon dioxide (CO_2) levels on crop ET. The impact of increased CO_2 on reduced crop transpiration and increased water use efficiency and yield is a much debated topic, and several studies have described how elevated CO_2 concentrations may reduce stomatal aperture, transpiration, and crop production processes (Rosenberg 1981; Kimball and Idso 1983; Manabe and Wetherald 1987; Kruijt et al. 2008; Islam et al. 2012). However, the wide ranges of potential impacts of CO_2 on ET, and suggestions for both increasing and decreasing trends of ET, prevented the inclusion of CO_2 impacts on ET in WWCRA study.

Database Description and Metadata

The following metadata tables lists the database layout, and headers associated with the raw datafiles provided to OWRD, which included 1) a geodatabase of the station locations and respective data of state, county, HUC8, (as shown in appendix 1), 2) stats.csv (Table 2), 3) stats_by_crop.csv files (Table 3). Other database files delivered to OWRD included the crop list (crop_list.csv), and future scenarios (scenario_table.csv) as described in the methods section.

Table 1. Database Layout Created by OWRD Based on .csv Files Provided in this Report

dmd_lkp_climate_scenario

- climate_scenario_id
- climate_scenario_nbr
- scenario_code
- description

dmd_lkp_county_reference

- STATION_ID
- ET_CELL_ID
- HUC8_STR
- COUNTY

dmd_lkp_crop

- crop_nbr
- crop_name

dmd_lkp_station

- ID
- OBJECTID
- ET_CELL_ID
- STATION_ID
- LATITUDE
- LONGITUDE
- ELEVATION
- HUC8_STR
- HUC8_INT
- STATION_NAME
- COUNTY
- STATE

dmd_summary_climate

- static_summary_ID
- et_cell_id
- station_id
- period
- climate_scenario_nbr
- temperature
- precip_mm
- ETO
- temperature_delta
- precip_delta
- eto_delta
- precip_percent_change
- eto_percent_change

dmd_summary_crop

- crop_summary_id
- et_cell_id
- station_id
- period
- climate_scenario_nbr
- crop_nbr
- ET
- net_irrigation_water_requirement
- days_in_growing_season
- et_delta
- niwr_delta
- growing_season_delta
- et_percent_change
- niwr_percent_change
- growing_season_percent_change

Project	: Demand Model		
File Name	: demand_model.DM1		
SubModel	: Main Model		
Author	: Ken Smith		
Company	: Oregon Water Resources		
Version	: 1.0	Modified:	6/19/2015
Copyright (c)	2015 Oregon Water Resources		

Table 2. Stats.csv Header Descriptions

Stats Data	Description
ET_CELL_ID	Unique ID
STATION_ID	NWS COOP/METNODE Station ID
PERIOD	Time period
SCENARIO	Climate Scenario
TEMPERATURE	Mean Annual Air Temperature (C)
PRECIP	Mean Annual Precipitation (mm/yr)
ETO	Mean Annual ASCE Grass Reference Evapotranspiration (ET_o) (mm/yr)
TEMPERATURE_DELTA	Change in Mean Annual Air Temperature (C)
PRECIP_DELTA	Change in Mean Annual Precipitation (mm/yr)
ETO_DELTA	Change in Mean Annual ASCE Grass Reference Evapotranspiration (mm/yr)
PRECIP_PCT_CHANGE	% Change in Mean Annual Precipitation
ETO_PCT_CHANGE	% Change in Mean Annual ASCE Grass Reference Evapotranspiration

Table 3. Stats_by_crop.csv Header Descriptions

Stats by Crop Data	Description
ET_CELL_ID	Unique ID
STATION_ID	NWS COOP/METNODE Station ID
PERIOD	Time period
SCENARIO	Climate Scenario
CROP_NUMBER	Crop Number
ET	Mean Annual Crop Evapotranspiration (ET_c) (mm/yr)
NIWR	Mean Annual Net Irrigation Water Requirement (NIWR) (mm/yr)
GROWING_SEASON	Mean Annual Growing Season Length (days)
ET_DELTA	Change in Mean Annual Crop Evapotranspiration (mm/yr)
NIWR_DELTA	Change in Mean Annual Net Irrigation Water Requirement (mm/yr)
GS_DELTA	Change in Mean Annual Growing Season Length (days)
ET_PCT_CHANGE	% Change in Mean Annual Crop Evapotranspiration
NIWR_PCT_CHANGE	% Change in Annual Net Irrigation Water Requirement
GS_PCT_CHANGE	% Change in Mean Annual Growing Season Length

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Attachment 1. List of WWCRA ET Cells and Corresponding NWS COOP Stations Specific for Oregon Applications

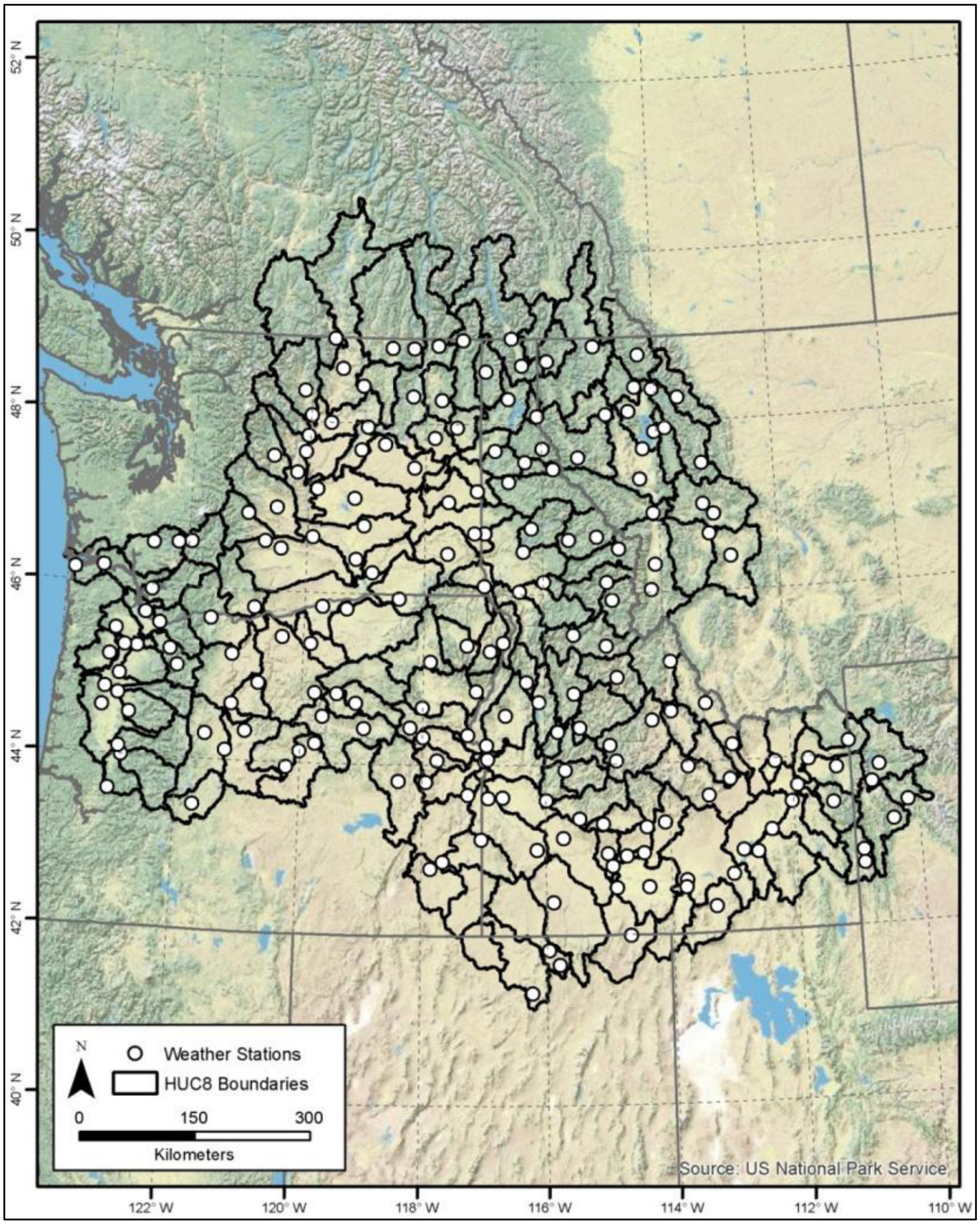
ET Cell ID	Station ID	Latitude	Longitude	Elevation (ft)	HUC8 Number	Station Name	County	State
CB17050103A	ID3760	43.018	-116.177	2400	17050103	GRAND VIEW 4 NW	Owyhee	ID
CB17050103B	ID4318	43.606	-116.921	2230	17050103	HOMEDALE 1 SE	Owyhee	ID
CB17050105A	NV8346	41.314	-116.223	6170	17050105	TUSCARORA	Elko	NV
CB17050106A	NV8346	41.314	-116.223	6170	17050106	TUSCARORA	Elko	NV
CB17050107A	OR7310	42.859	-117.657	3405	17050107	ROME 2 NW	Malheur	OR
CB17050108A	OR7736	43.121	-117.039	4620	17050108	SHEAVILLE 1 SE	Malheur	OR
CB17050109A	OR1174	42.777	-117.853	3930	17050109	BURNS JUNCTION	Malheur	OR
CB17050110A	OR6405	43.650	-117.247	2400	17050110	OWYHEE DAM	Malheur	OR
CB17050115A	OR6294	44.044	-116.972	2145	17050115	ONTARIO KSRV	Malheur	OR
CB17050116A	OR2415	43.807	-118.376	3515	17050116	DREWSEY	Harney	OR
CB17050117A	OR4357	43.800	-117.933	2830	17050117	JUNTURA 9 ENE	Malheur	OR
CB17050118A	OR9176	43.990	-117.718	3040	17050118	WESTFALL	Malheur	OR
CB17050119A	OR4175	44.325	-117.996	3915	17050119	IRONSIDE 2 W	Malheur	OR
CB17050201B	OR3604	44.874	-117.109	2665	17050201	HALFWAY	Baker	OR
CB17050202A	OR4098	44.356	-117.255	2110	17050202	HUNTINGTON	Baker	OR
CB17050202B	OR8780	44.437	-118.189	4031	17050202	UNITY	Baker	OR
CB17050203A	OR8746	45.208	-117.876	2765	17050203	UNION EXP STN	Union	OR
CB17050203B	OR5258	44.672	-117.994	3900	17050203	MASON DAM	Baker	OR
CB17060101A	ID7706	45.424	-116.315	1800	17060101	RIGGINS	Idaho	ID
CB17060102A	OR4151	45.633	-116.850	1762	17060102	IMNAHA 5 N	Wallowa	OR
CB17060103A	WA0184	46.133	-117.133	3573	17060103	ANATONE	Asotin	WA
CB17060104B	OR8746	45.208	-117.876	2765	17060104	UNION EXP STN	Union	OR
CB17060105A	OR2675	45.400	-117.267	3880	17060105	ENTERPRISE 2 S	Wallowa	OR
CB17060106A	WA0184	46.133	-117.133	3573	17060106	ANATONE	Asotin	WA
CB17070101A	OR0858	45.847	-119.693	280	17070101	BOARDMAN	Morrow	OR

Attachment 1. List of WWCRA ET Cells and Corresponding NWS COOP Stations Specific for Oregon Applications (contd.)

ET Cell ID	Station ID	Latitude	Longitude	Elevation (ft)	HUC8 Number	Station Name	County	State
CB17070102B	OR5593	45.943	-118.409	970	17070102	MILTON FREEWATER	Umatilla	OR
CB17070103A	OR3847	45.829	-119.264	640	17070103	HERMISTON 1 SE	Umatilla	OR
CB17070104A	OR3827	45.365	-119.564	1885	17070104	HEPPNER	Morrow	OR
CB17070105A	WA5659	46.000	-121.540	1950	17070105	MT ADAMS RS	Klickitat	WA
CB17070201A	OR2173	44.556	-119.645	2260	17070201	DAYVILLE 8 NW	Grant	OR
CB17070201B	OR4291	44.423	-118.959	3063	17070201	JOHN DAY	Grant	OR
CB17070202A	OR5711	44.819	-119.420	1995	17070202	MONUMENT 2	Grant	OR
CB17070203A	OR5020	44.714	-119.102	3740	17070203	LONG CREEK	Grant	OR
CB17070204A	OR5545	45.467	-120.350	1550	17070204	MIKKALO 6 W	Gilliam	OR
CB17070204B	OR8009	44.819	-119.776	1788	17070204	SPRAY	Wheeler	OR
CB17070301A	OR0699	44.118	-121.210	3358	17070301	BEND 7 NE	Deschutes	OR
CB17070301E	OR7857	44.284	-121.549	3180	17070301	SISTERS	Deschutes	OR
CB17070302A	OR9316	43.683	-121.688	4358	17070302	WICKIUP DAM	Deschutes	OR
CB17070303A	OR6500	44.133	-119.997	3684	17070303	PAULINA	Crook	OR
CB17070303B	OR6982	44.233	-119.733	4003	17070303	RAGER RS	Crook	OR
CB17070304A	OR0501	43.946	-120.217	3970	17070304	BARNES STN	Crook	OR
CB17070305B	OR6883	44.302	-120.808	2915	17070305	PRINEVILLE	Crook	OR
CB17070306A	OR5142	44.663	-121.146	2443	17070306	MADRAS 2 N	Jefferson	OR
CB17070306B	OR6655	45.129	-121.256	2059	17070306	PINE GROVE 5 ENE	Wasco	OR
CB17070307A	OR0197	44.820	-120.753	3030	17070307	ANTELOPE 6 SSW	Jefferson	OR
CB17080001C	OR8634	45.553	-122.389	33	17080001	TROUTDALE	Multnomah	OR
CB17080003A	WA4769	46.151	-122.916	12	17080003	LONGVIEW	Cowlitz	WA
CB17080006A	OR0328	46.157	-123.883	9	17080006	ASTORIA AP PORT OF	Clatsop	OR
CB17090001A	OR5050	43.914	-122.760	712	17090001	LOOKOUT POINT DAM	Lane	OR
CB17090002A	OR2374	43.782	-122.963	820	17090002	DORENA	Lane	OR

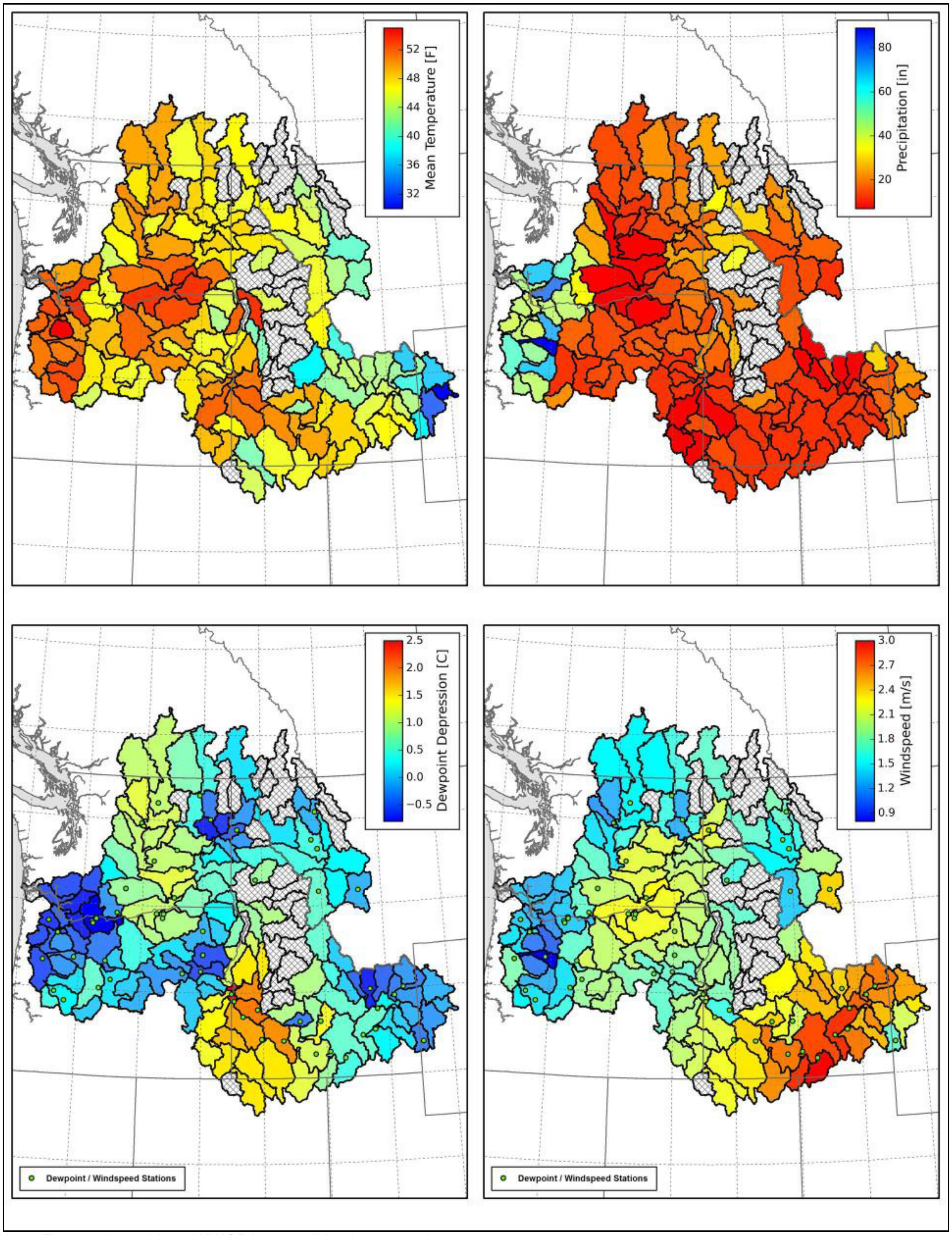
Attachment 1. List of WWCRA ET Cells and Corresponding NWS COOP Stations Specific for Oregon Applications (contd.)

ET Cell ID	Station ID	Latitude	Longitude	Elevation (ft)	HUC8 Number	Station Name	County	State
CB17090003A	OR1877	44.508	-123.458	592	17090003	CORVALLIS WATER BUREAU	Benton	OR
CB17090003C	OR1862	44.634	-123.190	225	17090003	CORVALLIS STATE UNIV	Benton	OR
CB17090004A	OR4811	44.101	-122.689	675	17090004	LEABURG 1 SW	Lane	OR
CB17090005B	OR2292	44.724	-122.255	1220	17090005	DETROIT DAM	Marion	OR
CB17090006B	OR4603	44.583	-122.750	650	17090006	LACOMB 1 WNW	Linn	OR
CB17090007A	OR2112	44.946	-123.291	290	17090007	DALLAS 2 NE	Polk	OR
CB17090007B	OR6151	45.282	-122.752	150	17090007	N WILLAMETTE EXP STN	Clackamas	OR
CB17090007C	OR7500	44.905	-123.001	205	17090007	SALEM AP MCNARY FLD	Marion	OR
CB17090008B	OR5384	45.221	-123.162	155	17090008	MC MINNVILLE	Yamhill	OR
CB17090009A	OR7127	44.303	-122.913	515	17090009	REX 1 S	Linn	OR
CB17090010B	OR2997	45.525	-123.103	180	17090010	FOREST GROVE	Washington	OR
CB17090011A	OR2493	45.274	-122.202	926	17090011	EAGLE CREEK 9 SE	Clackamas	OR
CB17090012A	WA8773	45.678	-122.651	210	17090012	VANCOUVER 4 NNE	Clark	WA
Klamath_1	OR1571	42.583	-121.867	4193	18010201	CHILOQUIN 1 E	Klamath	OR
Klamath_2	OR8007	42.431	-121.489	4483	18010202	SPRAGUE RIVER 2 SE	Klamath	OR
Klamath_3	OR1574	42.704	-121.995	4180	18010203	CHILOQUIN 12 NW	Klamath	OR
Klamath_4	OR4511	42.164	-121.755	4092	18010204	KLAMATH FALLS AG STN	Klamath	OR
Klamath_5	CA9053	41.960	-121.474	4035	18010204	TULELAKE	Siskiyou	CA
Klamath_6	CA5941	41.784	-122.045	4250	18010205	MT HEBRON RNG STN	Siskiyou	CA
Klamath_7	OR4506	42.201	-121.781	4098	18010206	KLAMATH FALLS 2 SSW	Klamath	OR
Klamath_10	CA6508	41.309	-123.532	403	18010209	ORLEANS	Humboldt	CA



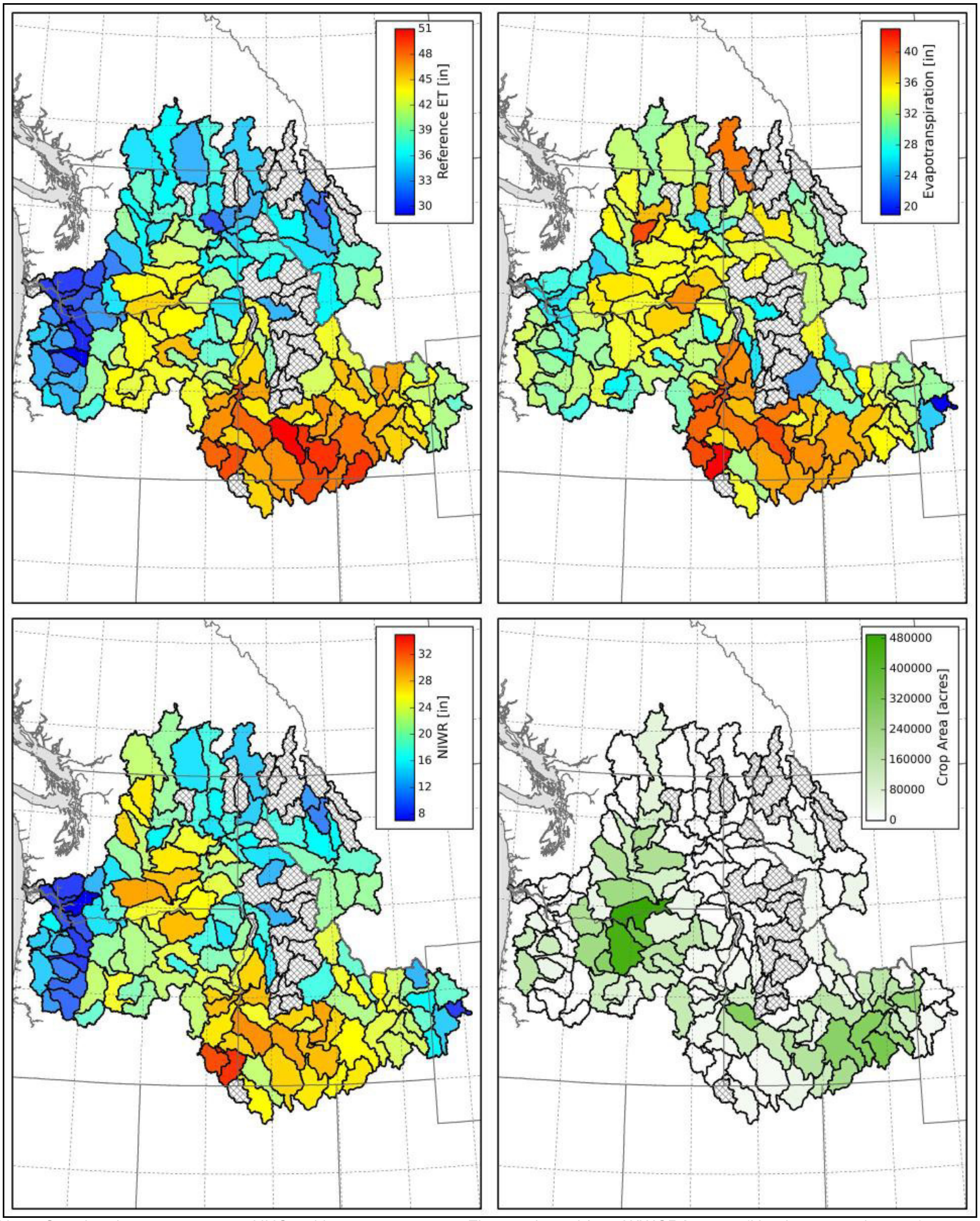
Note: Figure adopted from WWCRA report (Huntington et al., 2015).

Figure A1. Columbia River Basin – COOP Stations Used to Simulate Baseline and Projected Irrigation Demands



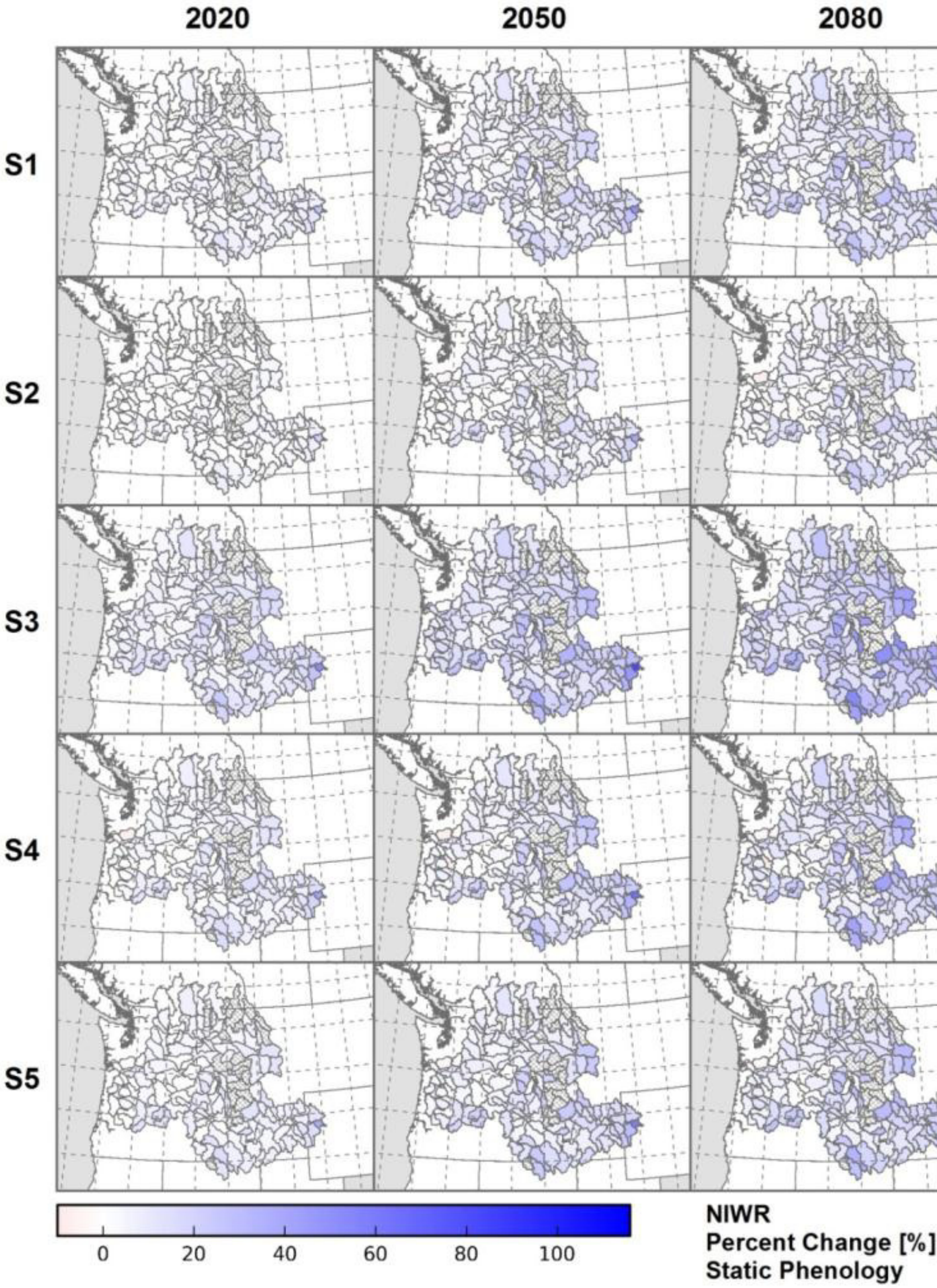
Note: Figure adopted from WWCRA report (Huntington et al., 2015).

Figure A2. Columbia River Basin – Spatial Distribution of Baseline Temperature, Precipitation, Dewpoint Depression, and Windspeed



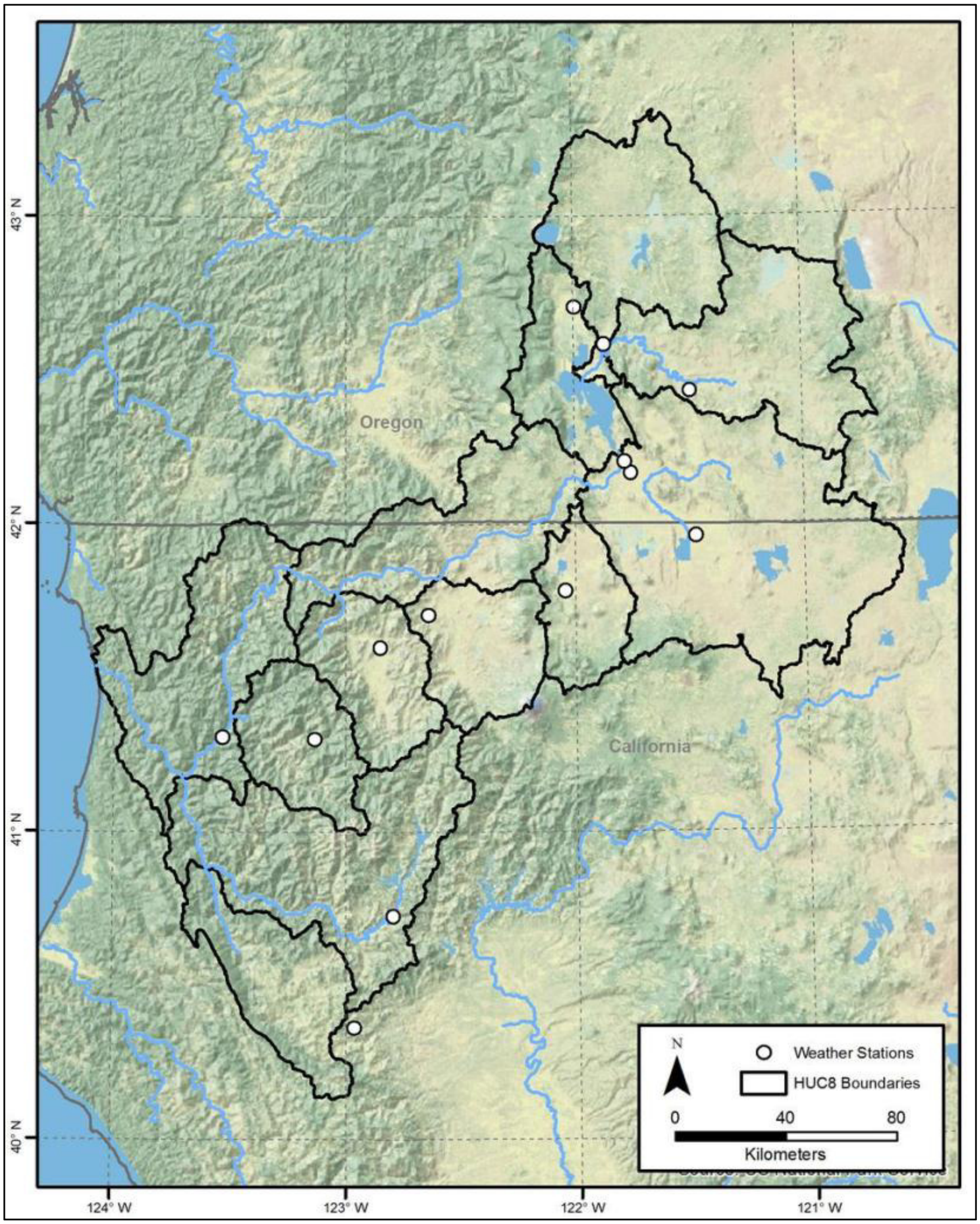
Note: Gray hatch areas represent HUCs with no crop acreage. Figure adopted from WWCRA report (Huntington et al., 2015).

Figure A3. Columbia River Basin – Spatial Distribution of Baseline Reference Evapotranspiration, Crop Evapotranspiration, Net Irrigation Water Requirements (NIWR), and Crop Acreage



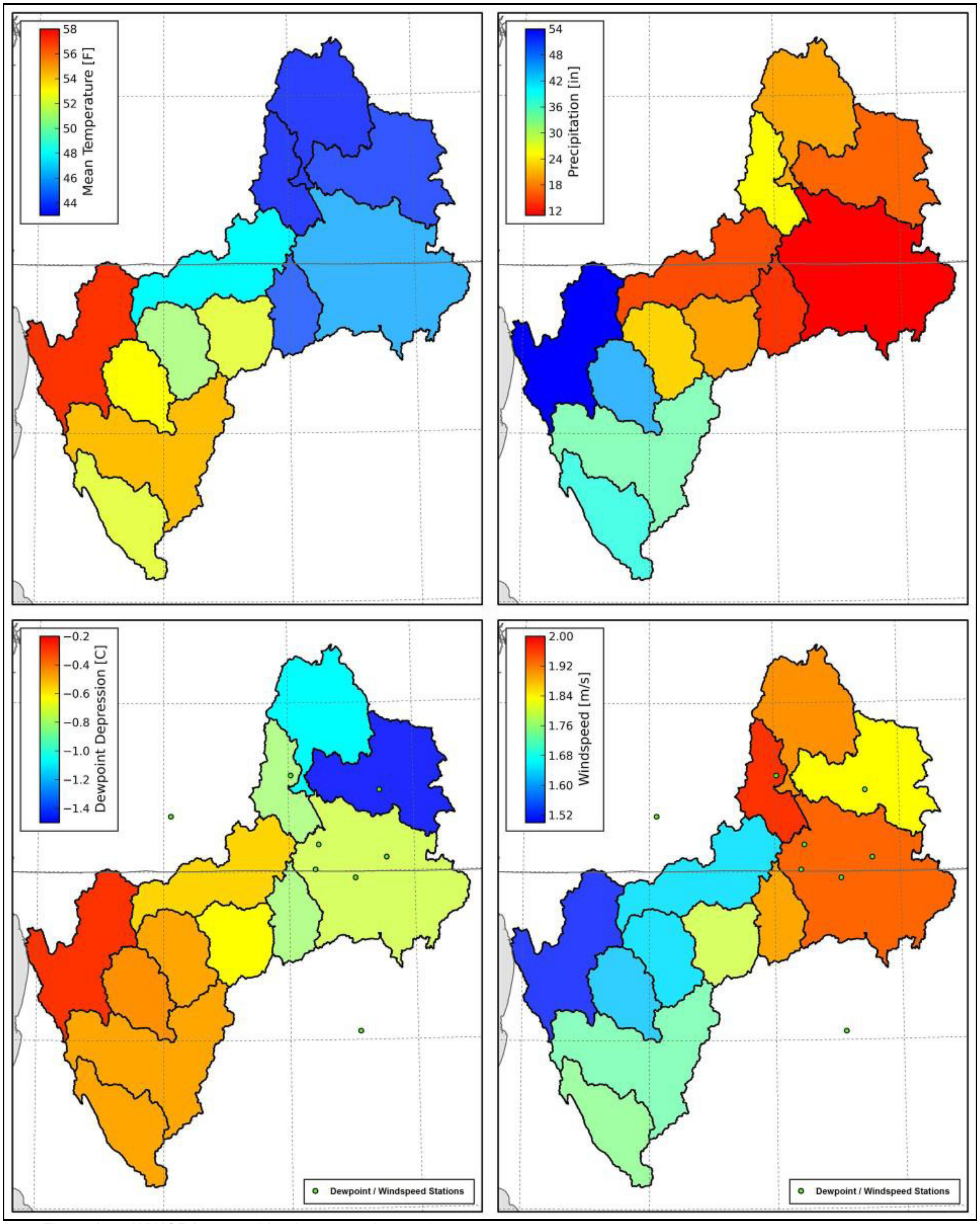
Note: Figure from WWCRA report (Huntington et al., 2015).

Figure A4. Columbia River Basin – Spatial Distribution of Projected Net Irrigation Water Requirements (NIWR) Percent Change for Different Climate Scenarios and Time Periods Assuming Static Phenology for Annual Crops (S1 = WD, S2 = WW, S3 = HD, S4 = HW, S5 = Central)



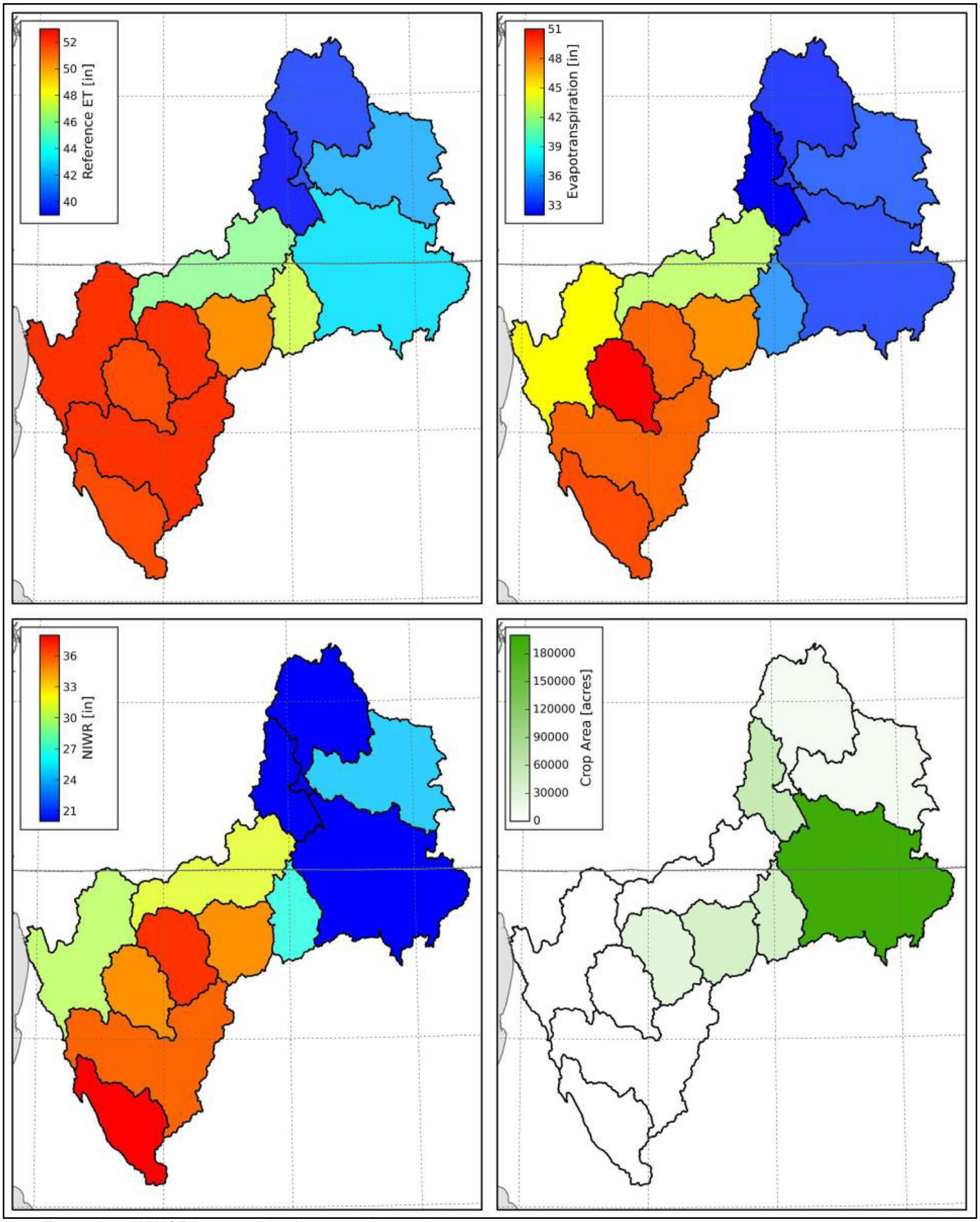
Note: Figure from WWCRA report (Huntington et al., 2015).

Figure A5. Klamath River Basin – COOP Stations used to Simulate Baseline and Projected Irrigation Demands



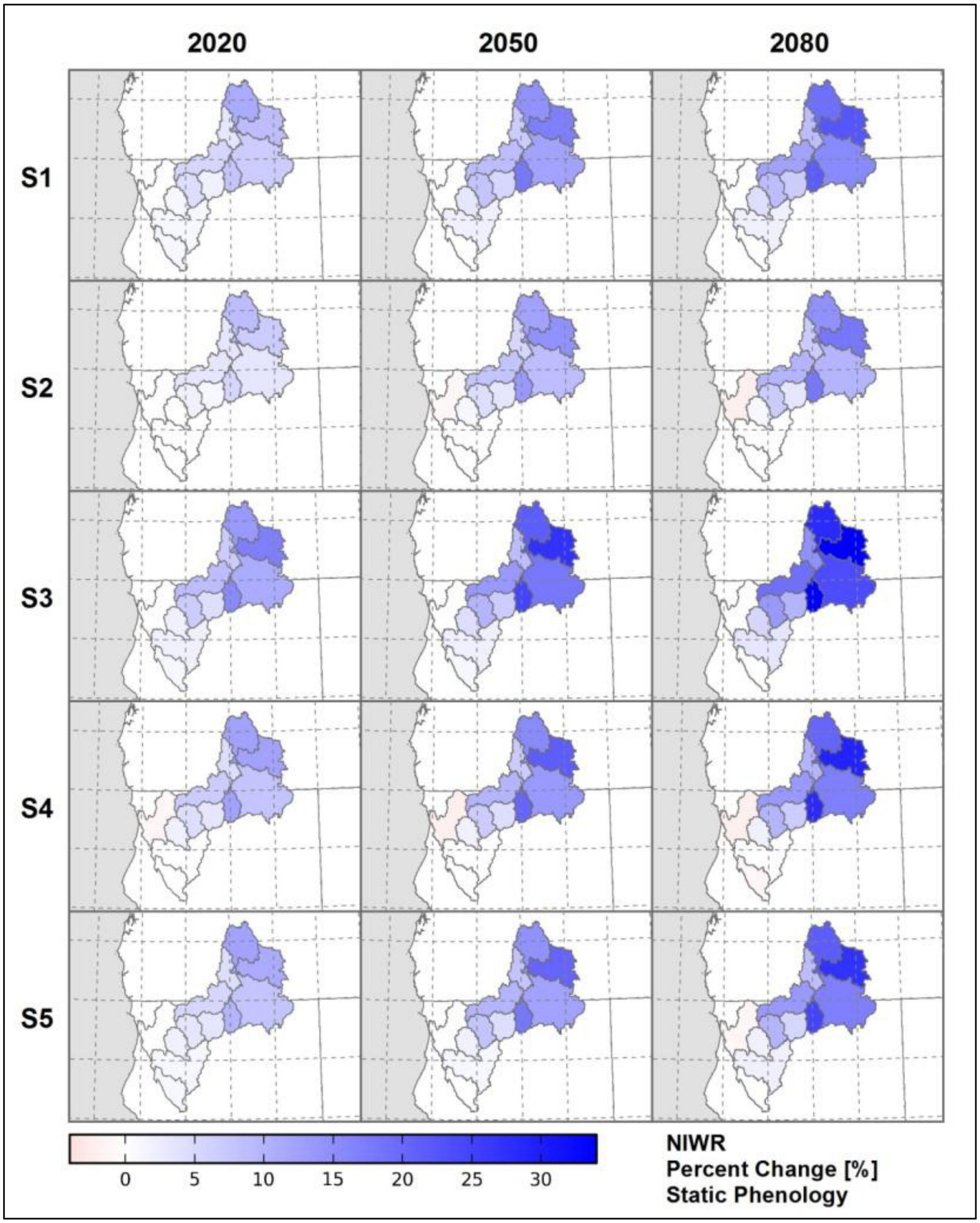
Note: Figure from WWCRA report (Huntington et al., 2015).

Figure A6. Klamath River Basin – Spatial Distribution of Baseline Temperature, Precipitation, Dewpoint Depression, and Windspeed



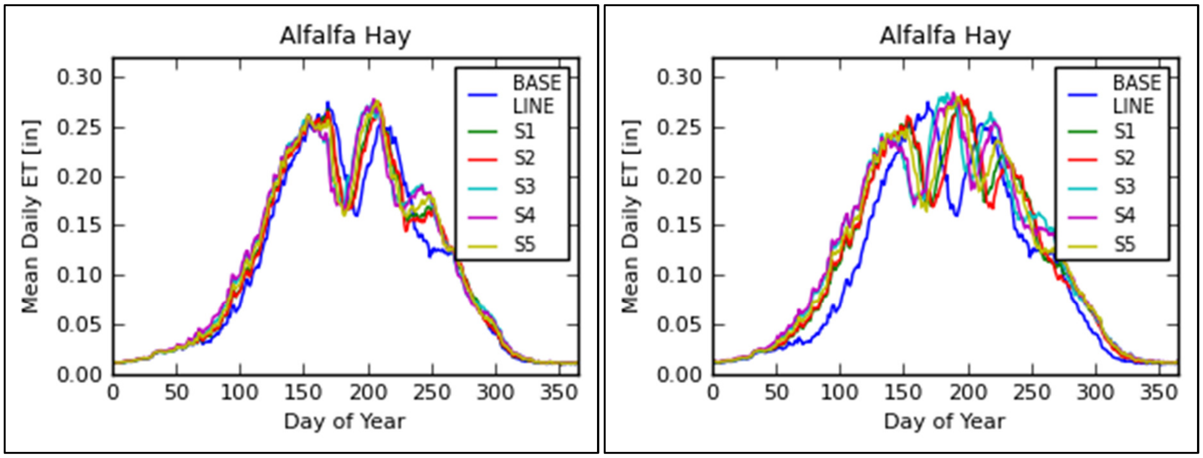
Note: Figure from WWCRA report (Huntington et al., 2015).

Figure 1. Klamath River Basin – Spatial Distribution of Baseline Reference Evapotranspiration, Crop Evapotranspiration, Net Irrigation Water Requirements (NIWR), and Crop Acreage

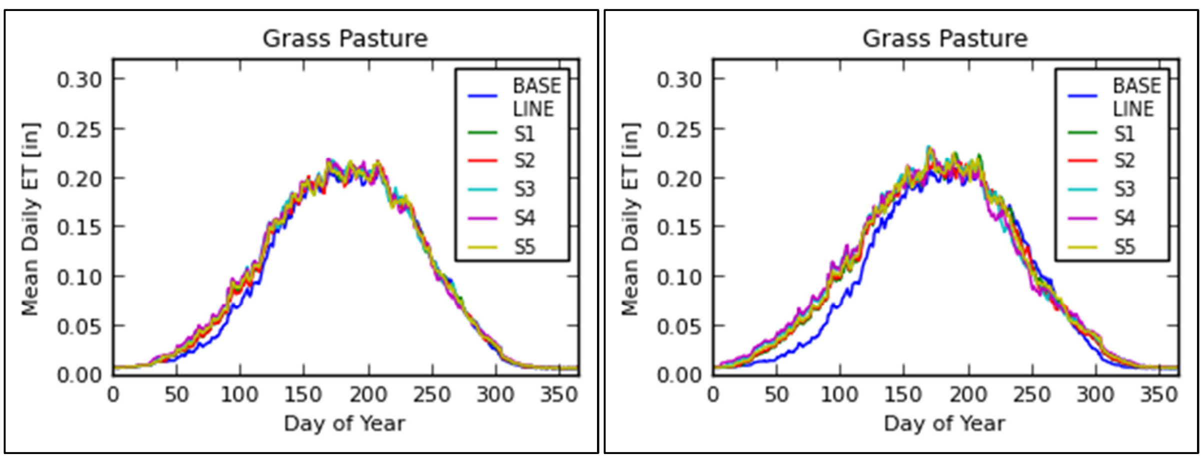


Note: Figure from WWCRA report (Huntington et al., 2015).

Figure A8. Klamath River Basin – Spatial Distribution of Projected Net Irrigation Water Requirements (NIWR) Percent Change for Different Climate Scenarios and Time Periods Assuming Static Phenology for Annual Crops (S1 = WD, S2 = WW, S3 = HD, S4 = HW, S5 = Central)



Note: Baseline and projected mean daily alfalfa evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right). Figure from WWCRA report (Huntington et al., 2015).
Figure 2. Klamath River Basin – COOP Station OR4511 (NWS/COOP Klamath Falls Ag. Station)



Note: Baseline and projected mean daily grass pasture evapotranspiration for all scenarios and for time periods 2020 (left) and 2080 (right). Figure from WWCRA report (Huntington et al., 2015).
Figure A10. Klamath River Basin – COOP Station OR4511 (NWS/COOP Klamath Falls Ag. Station)