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ACRONYMS

ARS	Agricultural Research Service
BDCF	Biosphere Dose Conversion Factors
BSC	Bechtel SAIC Company, LLC
CNWRA	Center for Nuclear Waste Regulatory Analyses
CRWMS	Civilian Radioactive Waste Management System
DOE	Department of Energy
ERMYN	Environmental Radiation Model for Yucca Mountain Nevada
FEP	Features, events and processes
FAO	Food and Agriculture Organization of the United Nations
NASS	National Agricultural Statistics Service
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
NRC	Nuclear Regulatory Commission
QARD	Quality Assurance Requirements and Description
TSPA	Total System Performance Assessment
TWP	Technical Work Plan
USDA	United States Department of Agriculture
YMP	Yucca Mountain Site Characterization Project

VARIABLES

a_s	Fraction of extraterrestrial radiation reaching the earth on overcast days
$a_s + b_s$	Fraction of extraterrestrial radiation reaching the earth on clear days
a_j	Empirical factor for dust interception fraction (Ra_j) calculations ($m^2 kg^{-1}$)
c_p	Specific heat ($MJ kg^{-1} °C^{-1}$)
Cp_{root}	Radionuclide concentration in plant foodstuffs from plant root uptake
$Cp_{leaf\ i,j}$	Radionuclide concentration in plant foodstuffs from plant leaf uptake
C_{si}	Radionuclide concentration in surface soil density ($Bq m^{-2}$)
$C_{s_{m,i}}$	Activity concentration of radionuclide i in surface soil per unit mass ($Bq m^{-2}$)
CV	Coefficient of Variation
Cw_i	Radionuclide concentration in groundwater used for irrigation ($Bq m^{-2}$)
d	Depth of surface soil (m)
DB_j	Dry biomass ($kg m^{-2}$)
$D_{i,j}$	Deposition rate from irrigation water ($Dw_{i,j}$) or resuspended dust ($Da_{i,j}$) ($Bq m^{-2} year^{-1}$)
DP	Deep percolation (mm)
DW_j	Dry to wet ratio
Dw_{ij}	Deposition of radionuclides onto the surface of plants
$e^{\circ}(T)$	Saturation vapour pressure at temperature (T) (kPa)
e_a	Actual vapor pressure (kPa)
EC	Electrical conductivity ($dS m^{-1}$)
EC_w	Electrical conductivity of the irrigation water ($dS m^{-1}$)
EC_e	Crop salt tolerance under acceptable yield reduction ($dS m^{-1}$)
e_s	Saturation vapor pressure (kPa)
ET	Evapotranspiration ($mm day^{-1}$)
ET_c	Crop evapotranspiration ($mm day^{-1}$)
ET_o	Reference evapotranspiration ($mm day^{-1}$)
$e_s - e_a$	Vapour pressure deficit (kPa)
$exp(x)$	Base of natural logarithm (2.7183) raised to the power (x)
f_{oj}	Fraction of overhead irrigation
$F_{s \rightarrow p\ i,j}$	Soil-to-plant transfer factor
G	Soil heat flux ($MJ m^{-2} day^{-1}$)
Ge	Groundwater contribution to the water requirement (mm)
h	Mean plant height (m) during the mid-season
I	Irrigation intensity ($cm hour^{-1}$)
i	Index of primary radionuclide

VARIABLES continued

IA_j	Irrigation application (mm)
I_n	Seasonal irrigation requirement (mm)
IR	Irrigation rate-annual average (m/year)
IRD_j	Irrigation rate-daily average (mm/day)
Irr	Amount of irrigation water applied to avoid crop stress (mm). Used in soil water balance calculations.
j	Crop type
J_{max}	Day of year that maximum rooting depth is attained
J_{start}	Day of year that rooting depth (Z_{ri}) exceeds minimum rooting depth ($Z_{r\ min}$)
K	Empirical constant for water interception fraction (RW_j) calculations
Kc	Crop coefficient
Kc_i	K_c crop coefficient on day i
Kc_{ini}	Crop coefficient for initial growth stage
Kc_{mid}	Crop coefficient for mid-season growth stage
Kc_{end}	Crop coefficient for late season growth stage
Kc_{prev}	K_c for the previous growth stage
Kdi	Surface soil solid/liquid partition coefficient (m^3 liquid kg^{-1} solid)
K_o	Correction for minimum temperature used to calculate dewpoint temperature under arid conditions ($^{\circ}C$)
LF	Leaching fraction (mm)
LR	Leaching requirement
$Lstage$	Length of crop growth stage (days)
n/N	Relative sunshine duration
OW	Overwatering rate (m/year)
p	Percent of annual sunlight used in Blaney Criddle ET_o equation
p	Crop specific average fraction of total available water that can be depleted from the root zone before moisture stress occurs.
Pe	Effective precipitation (mm)
P_d	Average daily precipitation input used to calculate irrigation application (mm)
Ra	Extraterrestrial radiation ($MJ\ m^{-2}\ day^{-1}$)
r_a	Aerodynamic resistance ($s\ m^{-1}$)
R_{aj}	Dust interception fraction
RAW	Readily available soil water (mm)
RH_{max}	Relative humidity, daily maximum (%)
RH_{min}	Relative humidity, daily minimum (%)

VARIABLES continued

R_j	Interception fraction for irrigation water ($R_{w_{i,j}}$) or air dust ($R_{a_{i,j}}$)
R_n	Net radiation energy ($\text{MJ m}^{-2} \text{ day}^{-1}$)
R_{nl}	Net longwave radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
R_{ns}	Net shortwave radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
R_s	Incoming solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
r_s	Bulk surface or canopy resistance (s m^{-1})
R_{so}	Clear sky radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)
R_{wj}	Water interception fraction
SD	Standard deviation
SE	Standard error
SWB_d	Daily soil water balance (mm)
t	Time (years)
T	Temperature ($^{\circ}\text{C}$)
TAW	Total available water in the root zone (mm)
T_j	Translocation factor
T_d	Tillage Depth (m)
T_{dew}	Dewpoint temperature ($^{\circ}\text{C}$)
TEW	Total evaporable water from the soil surface
T_{gj}	Growing time (days)
T_k	Absolute temperature ($^{\circ}\text{C} + 273.16$)
T_{max}	Temperature, daily maximum ($^{\circ}\text{C}$)
T_{min}	Temperature, daily minimum ($^{\circ}\text{C}$)
T_x	Correction for local climatic conditions used in the Jensen-Haise equation for calculating ET_o
u_2	Wind speed at 2 m height (m s^{-1})
Wb	Stored soil moisture in the root system (mm)
W_f	Temperature related weighting factor used in the FAO corrected Penman equation for calculating ET_o
W_s	Seasonal water requirement (mm)
Y_j	Yield (kg/m^2)
z	Height of wind speed measurement above ground surface (m)
Z_e	Depth of the soil surface layer that is subject to drying through evaporation (m)
Z_r	Rooting depth (m)

VARIABLES (continued)

α	Crop specific constant used in the Priestly Taylor ET equation. Values range from 1.08 to 1.34 depending on the crop and location
α	Albedo of grass reference crop
γ	Psychrometric constant (kPa °C ⁻¹)
λ	Latent heat of vaporization (MJ kg ⁻¹)
λ_e	Surface erosion removal constant (years)
λ_{di}	Radionuclide decay constant (years)
λ_{li}	Radionuclide leaching removal constant (years)
λ_w	Weathering constant (units day ⁻¹)
Δ	Slope of saturation vapor pressure curve (kPa °C ⁻¹)
ρ_s	Surface soil bulk density (kg/m ³)
ρ	Density of air (kg m ⁻³)
σ	Stefan-Boltzmann constant (4.90 x 10 ⁻⁹ MJK ⁻⁴ m ⁻² day ⁻¹)
$\Sigma (L_{prev})$	Sum of previous growth stage lengths used to calculate monthly K _c (days)
θ	Volumetric water content of soil
θ_{FC}	Soil water content at field capacity
θ_{WP}	Soil water content at the wilting point

1. PURPOSE

This analysis is one of nine technical reports that support the Environmental Radiation Model for Yucca Mountain Nevada (ERMYN) biosphere model. It documents input parameters for the biosphere model, and supports the use of the model to develop Biosphere Dose Conversion Factors (BDCF). The biosphere model is one of a series of process models supporting the Total System Performance Assessment (TSPA) for the repository at Yucca Mountain. The ERMYN provides the TSPA with the capability to perform dose assessments. A graphical representation of the documentation hierarchy for the ERMYN is presented in Figure 1-1. This figure shows the interrelationships between the major activities and their products (the analysis and model reports) that were planned in the biosphere Technical Work Plan (TWP, BSC 2003a). It should be noted that some documents identified in Figure 1-1 may be under development and therefore not available at the time this document is issued. The *Biosphere Model Report* (BSC 2003b) describes the ERMYN and its input parameters.

This analysis report, ANL-MGR-MD-000006, *Agricultural and Environmental Input Parameters for the Biosphere Model*, is one of the five reports that develop input parameters for the biosphere model. This report defines and justifies values for twelve parameters required in the biosphere model. These parameters are related to use of contaminated groundwater to grow crops. The parameter values recommended in this report are used in the soil, plant, and carbon-14 submodels of the ERMYN (Table 1-1). The twelve parameters addressed are:

Dry Biomass (kg/m^2), DB_j —Total, above-ground standing dry biomass for each crop type (j = crop type).

Dry to Wet Ratio, DW_j —Ratio of dry to wet biomass of edible plant foodstuffs for each crop type.

Fraction of Overhead Irrigation, $f_{o,j}$ —Probability that a crop type is irrigated with overhead spray or sprinklers.

Growing Time (days/season), $t_{g,j}$ —Length of growing season(s) for each crop type.

Irrigation Rate—Annual Average (m/year), IR —Average amount of groundwater applied per year to irrigated lands, including cropland, gardens, and landscapes.

Irrigation Intensity (cm/hour), I —Rate at which groundwater is applied during sprinkler irrigation.

Irrigation Application (mm), IA_j —Amount of groundwater applied each time a crop type is irrigated during the last 30 days of growth.

Irrigation Rate—Daily (mm/day), IRD_j —Average daily irrigation rate applied over all growing seasons, per crop type.

Overwatering Rate (m/year), OW —Average amount of precipitation or groundwater applied by irrigation that percolates beyond the root zone and leaches salts and radionuclides out of that zone, for all crop types.

Tillage Depth (m), T_d —The depth to which soil is tilled or plowed prior to planting.

Yield (kg/m^2), Y_j —Production, or wet biomass, of edible plant foodstuffs for each crop type.

Rooting Depth (m), Z_r — Mean maximum effective rooting depth for all crops.

This analysis was conducted according to AP-SIII.9Q, *Scientific Analyses*, and the biosphere TWP (BSC 2003a). This report deviates from the TWP by development of the Dry to Wet Ratio parameter and its recommended distribution. This was done because it was determined during development of the biosphere model that the parameter will be required.

The parameters developed in this report support treatment of thirteen features, events, and processes (FEPs) addressed in the biosphere model (Table 1-1). Inclusion and treatment of FEPs in the biosphere model is described in the *Biosphere Model Report* (BSC 2003b, Section 6.2).

This report includes information related to the technical justification to support that the crop water interception fraction is appropriate for all radionuclides considered and does not result in underestimation of dose. Three parameters are used in the ERMYN to calculate the crop water interception fraction: Dry Biomass (Section 6.1), Irrigation Intensity (Section 6.6), and Irrigation Application (Section 6.7). Selection of parameter distributions that are consistent with present knowledge of the agricultural practices and other conditions in the region surrounding the Yucca Mountain site are described in those sections. This issue also is addressed in the *Biosphere Model Report* (BSC 2003b).

Two climate states were considered for all parameters in this analysis, modern interglacial (current) and glacial transition (future), and when applicable, separate distributions were developed for each climate. These climates and their predicted occurrence at Yucca Mountain in the future are described in *Future Climate Analysis* (USGS 2001). The modern interglacial climate includes current conditions (USGS 2001, pp. 66 through 67) and is referred to as current climate in this report. Current conditions are characterized by hot, dry summers, warm winters, and have lower annual precipitation and higher annual temperatures than glacial transition climate states. Weather measurements taken at or near Yucca Mountain, and agricultural practices in southern Nevada and other arid southwestern regions (e.g., Imperial Valley California, Maricopa County Arizona) were used to characterize conditions for the current climate state. The lower bound monsoon climate state predicted to occur after the modern interglacial climate state is also characterized by current conditions (USGS 2001, pp. 66 through 67). Therefore, parameter distributions that are developed for current climate are also applicable to the lower bound monsoon climate. The glacial transition climate is characterized by cool, wet winters, and warm to cool dry summers relative to current conditions (USGS 2001, p. 73), and is referred to as future climate in this report. Recommended analog weather stations for the upper bound (i.e., cooler and wetter) of this climate are Spokane, St. John, and Rosalia, Washington (USGS 2001, p. 66 Table 2, and p. 74). Data from the Spokane weather station and agricultural practices in east central Washington were used in this analysis to characterize conditions for the future climate state.

Upper bound monsoon and lower bound future climates were only considered for Annual Average Irrigation Rate (see Section 6.5). This was done to develop an average value for each

intermediate climate state that could be used to help define sampling limits for Biosphere Dose Conversion Factors (BDCFs) that would include variation within climate states. These climates and their predicted occurrence at Yucca Mountain in the future are described in *Future Climate Analysis* (USGS 2001). The upper bound monsoon climate is characterized by strong summer monsoons. Winter seasons are warmer than the current climate with more winter precipitation (USGS 2001, p. 72). Recommended analog weather stations for the upper bound monsoon climate are Nogales, Arizona and Hobbs, New Mexico. Temperature, precipitation, and wind speed data from the Nogales weather station were used in the analysis. Solar radiation data were not available from either the Nogales or Hobbs weather stations. Therefore, these data were obtained from the Tucson, Arizona weather station, which was the closest station to Nogales that had the required information. Agricultural practices in southern Nevada and other arid southwestern regions (e.g., Imperial Valley California, Maricopa County Arizona) that were used to characterize the conditions (i.e., crop selection and season lengths) for current climate were also used to characterize conditions for the upper bound monsoon climate.

The lower bound future climate is characterized by predominantly winter precipitation. Precipitation for this climate state is higher and temperatures are cooler than for current climate (USGS 2001, pp. 74 – 75). The recommended weather stations for the lower bound future climate are Delta, Utah and Beowawe, Nevada. Temperature, precipitation, and dewpoint temperature from Delta were used in the analysis. Wind speed and solar radiation data were not available from either the Delta or Beowawe weather stations. Therefore, these data were obtained from the Milford, Utah weather station, which was the closest station to Delta that had the required information. Cold limiting temperatures that affect crop growth and season length occur during March through April in the spring and October in the fall for both Delta and Spokane (see Tables 4.1-4 and 4.1-5). Therefore, the agricultural practices (i.e., crop selection and season lengths) in east central Washington that were used in this analysis to characterize conditions for the upper bound future climate state were also used for the lower bound. In this report, the upper bound future climate state is generally referred to as future climate. The lower bound future climate state is always designated as such.

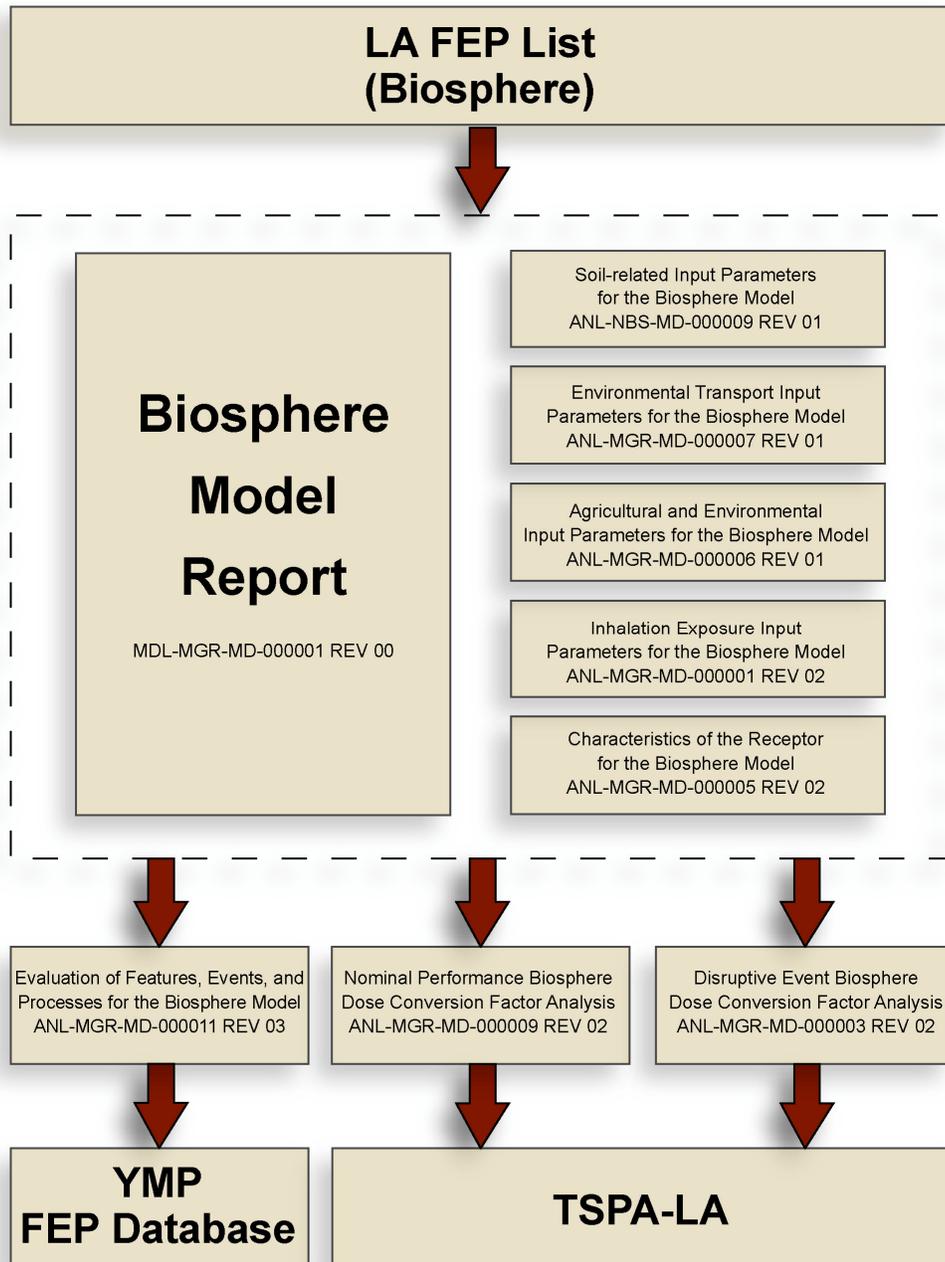
Five of the parameters in this analysis are used in both the biosphere groundwater exposure scenario and the biosphere volcanic ash exposure scenario (BSC 2003b, Section 6.6.3, note that tillage depth and rooting depth are treated as one parameter [surface soil depth] in the biosphere model). For the volcanic ash exposure scenario under normal, variable wind conditions, the initial, predicted thickness of tephra deposit 20 km south of Yucca Mountain, calculated for the *Total System Performance Assessment for the Site Recommendation* (CRWMS M&O 2000a, Section 3.10.5.1), ranged from less than 1×10^{-8} cm to about 10 cm. About 66 percent of predicted depths were less than 0.1 mm, about 80 percent were less than 1 mm, and about 95 percent were less than 1 cm. The use of tillage, irrigation, and fertilizers with agricultural and garden crops would result in rapid mixing of the thin ash layer with little effect on soils or crop characteristics. Therefore, separate distributions for parameters in this analysis are not necessary for the two biosphere exposure scenarios. The location of the receptor considered for the TSPA analysis in support of a license application may differ from that used for the site recommendation (based on requirements in 10 CFR 63.302). Thus, ash thickness at the receptor location may be slightly different than that reported in the *Total System Performance Assessment for the Site Recommendation* (CRMWS M&O 2000a, Section 3.10.5.1).

Table 1-1. Parameters and Related FEPs^a

Parameter	Related FEP	YMP FEP Number	Biosphere Submodel	Location of Summary of Disposition in TSPA ^b
Dry Biomass	Plant uptake	3.3.02.01.0A	Plant	Section 6.1
Dry to Wet Weight Ratio	Plant uptake	3.3.02.01.0A	Plant	Section 6.2
Fraction of Overhead Irrigation	Water management activities	1.4.07.01.0A	Plant	Section 6.3
	Agricultural land use and irrigation	2.4.09.01.0B		
	Plant uptake	3.3.02.01.0A		
Growing Time	Biosphere characteristics	2.3.13.01.0A	Plant	Section 6.4
	Agricultural land use and irrigation	2.4.09.01.0B		
	Climate change, global	1.3.01.00.0A		
	Plant uptake	3.3.02.01.0A		
Irrigation Rate—Annual Average	Biosphere characteristics	2.3.13.01.0A	Soil, Carbon-14	Section 6.5
	Agricultural land use and irrigation	2.4.09.01.0B		
	Climate change, global	1.3.01.00.0A		
	Precipitation	2.3.11.01.0A		
	Radionuclide accumulation in soils	2.3.02.02.0A		
	Urban and industrial land/water use	2.4.10.00.0A		
Irrigation Intensity	Water management activities	1.4.07.01.0A	Plant	Section 6.6
	Biosphere characteristics	2.3.13.01.0A		
	Agricultural land use and irrigation	2.4.09.01.0B		
	Plant uptake	3.3.02.01.0A		
	Soil type	2.3.02.01.0A		
Irrigation Application	Biosphere characteristics	2.3.13.01.0A	Plant	Section 6.7
	Agricultural land use and irrigation	2.4.09.01.0B		
	Climate change, global	1.3.01.00.0A		
	Precipitation	2.3.11.01.0A		
	Plant uptake	3.3.02.01.0A		
Irrigation Rate—Daily	Biosphere characteristics	2.3.13.01.0A	Plant, Carbon-14	Section 6.8
	Agricultural land use and irrigation	2.4.09.01.0B		
	Climate change, global	1.3.01.00.0A		
	Plant uptake	3.3.02.01.0A		
	Precipitation	2.3.11.01.0A		
Overwatering Rate	Biosphere characteristics	2.3.13.01.0A	Soil	Section 6.9
	Agricultural land use and irrigation	2.4.09.01.0B		
	Climate change, global	1.3.01.00.0A		
	Precipitation	2.3.11.01.0A		
	Radionuclide accumulation in soils	2.3.02.02.0A		

Table 1-1. Parameters and Related FEPs Continued^a

Parameter	Related FEP	YMP FEP Number	Biosphere Submodel	Location of Summary of Disposition in TSPA ^b
Tillage Depth (surface soil depth)	Radionuclide accumulation in soils	2.3.02.02.0A	Soil, Air, Carbon-14, External Exposure	Section 6.10
	Soil type	2.3.02.01.0A		
	Soil and sediment transport in the biosphere	2.3.02.03.0A		
	Surface runoff and flooding	2.3.11.02.0A		
	Atmospheric transport of contaminants	3.2.10.00.0A		
	Plant uptake	3.3.02.01.0A		
	External exposure	3.3.04.03.0A		
Yield	Plant uptake	3.3.02.01.0A	Plant	Section 6.11
Rooting Depth (surface soil depth)	Radionuclide accumulation in soils	2.3.02.02.0A	Soil, Air, Carbon-14, External Exposure	Section 6.12
	Soil type	2.3.02.01.0A		
	Soil and sediment transport in the biosphere	2.3.02.03.0A		
	Surface runoff and flooding	2.3.11.02.0A		
	Atmospheric transport of contaminants	3.2.10.00.0A		
	Plant uptake	3.3.02.01.0A		
	External exposure	3.3.04.03.0A		
Notes: ^a FEPs (features, events, and processes) are listed in DTN MO0303SEPFEPS2.000. ^b The effects of the related FEPs are included in the Total System Performance System through the BDCFs. See BSC (2003b, Section 6.2) for a complete description of the inclusion and treatment of FEPs in the biosphere model. The treatment of each parameter is described in the listed sections of this report and summarized in Section 7.				



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Figure 1-1. Documentation Hierarchy for the Environmental Radiation Model for Yucca Mountain Nevada

2. QUALITY ASSURANCE

Development of this report involves analysis of data to support performance assessment, as described in the TWP (BSC 2003a), and thus is a quality affecting activity in accordance with AP-2.27Q. Approved quality assurance procedures identified in the TWP (BSC 2003a, Section 4) have been used to conduct and document the activities described in this report. Electronic data used in this analysis were controlled in accordance with the methods specified in the TWP (BSC 2003a, Section 8).

This analysis did not require classification of the quality level of natural barriers or other items in accordance with AP-2.22Q, *Classification Criteria and Maintenance of the Monitored Geologic Repository Q List*, or other applicable implementing procedures.

3. USE OF SOFTWARE

The only software used to analyze data was the commercial off-the-shelf product Microsoft® Excel 97 SR-2. Standard functions of that software were used to calculate means and standard deviations (SD) for distribution development in Section 6, to develop graphs used in sensitivity analyses (Figures 6.1-1 and 6.6-1), and to manipulate data for calculation of irrigation parameters (Appendices C through E). Uses of those functions, including formulas, algorithms, inputs, and outputs are described in the tables, figures, or associated text.

4. INPUTS

The technical product inputs for each parameter are described with justification below and summarized in Table 4.1-1. See the Document Input Reference System for the status of all inputs and references.

All references cited in this document and listed in Section 8, other than those identified as inputs in this section, were included to support or corroborate the methods and conclusion of the analyses.

4.1 DATA AND TECHNICAL INFORMATION

4.1.1 Water Content of Foods

Information on water content of foodstuffs from the *Nutrient Database for Standard Reference Release 14*, prepared by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS, [USDA 2002a]) was used to calculate Dry Biomass and Dry to Wet Ratios of vegetables, fruits, and grains, as described in Sections 6.1.2 and 6.2.2, respectively. The inputs from this source are technically defensible and appropriate for this analysis for the following reasons:

- As the principal in-house research component of USDA, ARS provides the scientific expertise needed to support the work of most of the Department's action and regulatory agencies and other Federal agencies, such as the Food and Drug Administration, the U.S. Environmental Protection Agency, some components within the U.S. Department of Defense,

and the U.S. Department of the Interior. For example, the Food and Nutrition Service, which administers the nutrition assistance programs of the USDA, uses data from the ARS' Continuing Survey of Food Intakes by Individuals and Diet and Health Knowledge Survey to update the thrifty food plan that, in turn, is used to monitor the effectiveness of food assistance programs by measuring the dietary status of low-income Americans, analyze the nutrient content of foods commonly eaten by low-income individuals, and develop improved methods to assess the absorption and bioavailability of key nutrients in the diets of important population subgroups.

- The ARS information is documented and substantiated in electronic databases and publications and is considered factual and suitable for quality-affecting work.

The information in USDA (2002a) is appropriate for this analysis because it comes from a comprehensive dataset that summarizes percent water content of most representative crops, and these values can be used directly to calculate dry to wet ratios. According to the USDA, this dataset is the major source of food composition data in the United States and provides the foundation for most food composition databases in the public and private sectors (USDA 2002a, p. 2). The data were compiled from numerous sources and the water content of most representative crops was derived from 10 to more than 200 "data points" or sources of information. The percent water contents used in parameter development are presented in Table 6.2-1. An additional external source was required for Dry to Wet Ratios of cattle forage because the *Nutrient Database for Standard Reference Release 14* (USDA 2002a) does not include animal forage.

4.1.2 Dry to Wet Ratios for Cattle Forage

Values of dry to wet ratios for alfalfa (0.227), corn silage (0.238), and oat hay (0.182) were selected from NUREG/CR-3332, *Radiological Assessment, A Textbook on Environmental Dose Analysis*, (Till and Meyer 1983, Table 5.16, with oat hay = grass forage). The dry to wet ratios from this source were used to develop the distribution for dry to wet ratios for cattle forage as described in Section 6.2.2. The original source of this data is an out-of-print USDA handbook on food and forage composition compiled by the ARS (see Section 4.1.1 for source justification). This source is appropriate for this analysis because it is similar to information from USDA (2002a), and it has been used in other radiological assessments for dose analysis (e.g., IAEA 1994, Table 5; Kennedy and Strenge 1992, Table 6.17; Napier et al. 1988, Table 4.25). This additional source is necessary because the primary source for dry to wet ratios (USDA 2002a) does not include values for cattle forage. Use of these dry to wet ratios, and discussions of uncertainty associated with their use, is further described in Section 6.2.2.

4.1.3 Harvest Indices

Aboveground dry biomass for grains, other vegetables, and fruits cannot be determined directly from yield and dry to wet ratios because not all of the aboveground plant parts are considered edible. The non-edible parts are not included in yield and dry to wet ratio measurements. Therefore, harvest indices were used with yield and dry to wet ratios to calculate total above ground dry biomass for these crop types. Harvest indices are a measure of the ratio of seed, fruit, or tuber dry biomass to total aboveground dry biomass. Dividing the product of yield and dry to

wet ratio by the harvest index gives the total above ground dry biomass (i.e., biomass of fruits, leaves, and stems) for a representative crop.

Harvest index values for grains, other vegetables, and fruits reported in Neitsch et al. (2002, Table A-8, pp. 381 through 384) were used in Section 6.1.2 to calculate total aboveground dry biomass. The methods for determining harvest indices in this source resulted in values that were appropriate for calculation of dry biomass from USDA measurements of commercial crop yield. The document contains a comprehensive list of harvest indices for the representative crops within each crop type. It is a joint publication between the USDA Agricultural Research Service (see source justification in Section 4.1.1) and the Texas Agricultural Experimental Station. The Texas Agricultural Experimental Station is the research extension of the land-grant system in agriculture. It is committed to basic and applied research in the areas of agriculture, life sciences, and natural resources. The agency is a leader in agricultural research nationwide and is therefore an appropriate source for this analysis. The selected harvest indices are reported in Table 6.1-1.

Harvest indices tend to be conservative unless crops are grown under extreme stress conditions, and have changed little in recent years (Prince et al. 2001, pp. 1196 through 1197). Most published measurements of harvest indices for grains reviewed by Prince et al. (2001, p. 1197) varied by no more than ± 0.06 from the values selected for this analysis. Additionally, the distribution of dry biomass is more sensitive to variation in yield than variation in harvest indices (see Section 6.1.2). Therefore, changes in the accuracy of harvest indices has little influence on the bounds for the distributions of dry biomass for crop types. Therefore, the selected harvest indices are appropriate for this analysis. Use of these harvest indices, and discussions of uncertainty associated with their use, is further described in Section 6.1.2.

4.1.4 Growing Season

The following sources were used to determine the start of the growing season (i.e., planting time for annuals, initiation of growth and start of irrigation for perennials) and season length for representative crops. This information on season length was used in Section 6.4 to determine Growing Time distributions. Planting period and season length were also used in the development of growth stages (initial, development, mid-season, and late-season), which define the period of time that a crop coefficient (K_c) is used in the calculation of crop evapotranspiration (ET_c , see Appendix D). Mean monthly ET_c is used to calculate the four irrigation parameters (Sections 6.5, 6.7, 6.8, and 6.9). Growing season length is also used to identify total number of growing days per month and the thirty-day period prior to harvest for each crop. This information is required for calculation of Annual Average Irrigation Rate (Section 6.5 and Appendix E), Irrigation Application (Section 6.7), Daily Average Irrigation Rate (Section 6.8 and Appendix E), and Overwatering Rate (Section 6.9 and Appendix E).

4.1.4.1 Growing Season–Current Climate

Garden Crops and Turf – Information on agricultural and horticultural practices compiled by state Cooperative Extension Services was used to establish planting periods, harvest periods, and growing seasons for garden crops and turf for current climate conditions. Information from

Cooperative Extension Services is technically defensible and appropriate for this analysis for the following reasons:

- Cooperative Extension Services are partnerships between state land-grant colleges and the U.S. Department of Agriculture Cooperative State Research, Education, and Extension Service. They serve as the outreach branches of state universities and the Department of Agriculture. The mission of the Cooperative Extension Services is to develop and disseminate information on agriculture, horticulture, health, environment, economics, and other topics of importance developed by the USDA and universities.
- Cooperative Extension Services are one of the most comprehensive sources of agricultural and horticultural information. No other organization summarizes and presents a wide range of site-specific information on how to grow crops and garden plants. For many garden crops, Cooperative Extension Services are the only source of site-specific information.
- Information distributed by Cooperative Extension Services is widely used by farmers, gardeners, and homeowners. For example, in southern Nevada, pamphlets and publications are available from Nevada Cooperative Extension offices, over the internet, and from other outlets such as gardening supply stores.
- Personnel working for Cooperative Extension Services are recognized experts in agriculture, gardening, and horticulture.

The planting dates of garden crops under current climatic conditions at Yucca Mountain were obtained from *Beginning Gardening in the Desert* (Mills et al. no date). This document was published by the Southern Nye County Cooperative Extension. The document includes ranges of suggested planting dates for garden crops in southern Nye County, which includes Amargosa Valley. This source is appropriate because it contains information for a large selection of crops and is specific to the current climatic conditions in southern Nye County. These, and all other data described in this subsection, are presented in Table D-1.

Growing season lengths of garden crops for the current climate are derived from the *Arizona Master Gardener Manual* (Call 1999), published by the University of Arizona Cooperative Extension. Crop-specific information on pages 71 through 125 of Chapter 10 was used if available; otherwise, data from Table 10.10 was used. This source is appropriate because it contains a comprehensive list of season lengths for garden crops grown under arid to semi-arid conditions. There is no similar, comprehensive source of season lengths for garden crops in southern Nevada. This source does not include information on growing season lengths for apples, strawberries, or grapes.

Duration of home irrigation (which is only used to calculate annual average irrigation rate in Section 6.5) is from *Maintaining Hybrid Bermudagrass for Urban Mojave Desert Landscapes* (Morris and Johnson 1991, pp. 3 and 4), published by the University of Nevada Cooperative Extension. This site-specific pamphlet recommends irrigating bermudagrass year-round in southern Nevada.

Feed Corn and Corn Silage - Growing seasons for feed corn and corn silage are from *Nevada Agricultural Statistics 2000–2001* (USDA 2002b, pp. 16 and 17), a state office of the USDA National Agricultural Statistics Service (NASS). Use of data from this source is technically defensible and appropriate for this analysis for the following reasons:

- The NASS is the statistical agency for the USDA. The mission of the NASS is to serve the United States, agriculture, and its rural communities by providing meaningful, accurate, and objective statistical information and services. They are responsible for conducting surveys of agricultural production and practices and reporting the results of those surveys.
- The NASS is the only organization in the U.S. that compiles nationwide information on commercial crop production and agricultural trends. Therefore, they are the most consistent and comprehensive, and for many topics the only source of this information.
- USDA quality-assurance processes developed specifically for the types of surveys conducted by NASS are followed to control the accuracy of released information. Information provided by this organization therefore is suitable for quality-affecting work related to characterization of agricultural production and practices.

According to this source, corn is planted during May and June, silage is harvested in August through October, and grain corn is harvested in October and November. Because this source describes growing seasons for all of Nevada, much of which has later and longer planting times than southern Nevada, the first months listed for planting and harvest were chosen for this analysis.

Apples and Strawberries - Planting date and growing season lengths for several crops, planting periods, and climatic regions are reported in *Crop Evapotranspiration* (Allen et al. 1998, Table 11, p.107), a publication by the Food and Agriculture Organization of the United Nations (FAO). The growing season information for fruit orchard trees and berries from this source was used in Appendix D to establish planting dates and season lengths for apples and strawberries, respectively. The information is presented in Table D-1. This source was required because the information for apples and strawberries was not included in the primary information sources for growing season lengths used in this analysis (i.e., state Cooperative Extension Services and NASS). Information from this source is technically defensible and appropriate for use in this analysis for the following reasons:

- The FAO is one of the largest specialized agencies in the United Nations system and the lead agency for agriculture and rural development. Included in its many functions are collection, analysis, interpretation, and dissemination of information relating to nutrition, food, agriculture, forestry, and fisheries. The Organization serves as a clearing-house, providing farmers, scientists, government planners, traders and non-governmental organizations with the information they need to make rational decisions on planning, investment, marketing, research, and training.
- A series of *Irrigation and Drainage Papers* were written by experts in the various related fields of study and published by the FAO. *Crop Evapotranspiration* (Allen et al. 1998, FAO Irrigation and Drainage Paper 56) describes comprehensive guidelines for determining crop

water requirements. Planting dates and growing season lengths for several crops and several climatic zones are found in Table 11, pp. 104 to 108. Information on orchard fruit trees and berries for climatic zones that are very similar to that of Nye County are included. This information is appropriate because the growing season information includes the appropriate climate zones, and the growing season information is reasonable for an arid climate.

Use of this growing season information and discussions of uncertainty associated with its use, is further described in Appendix D and Section 6.4.

Grapes, Grains, and Cattle Forage – Usual planting and harvesting dates for grapes, barley, winter wheat, and oat hay, and cutting schedules for alfalfa in Amargosa Valley are provided in LeStrange 1997a and 1997b (DTN: MO0210SPAGRO06.029). The growing season information from this source is presented in Table D-1. These data were used in Appendix D to establish growing season lengths for grapes, barley, winter wheat, oat hay, and alfalfa. This source was required because it provides site specific data from the Amargosa Valley farming community.

Bloom and harvest dates for grapes were provided by the founder of the Pahrump Valley Vineyards in Amargosa Valley (LeStrange 1997a). Grapes for several wine varieties have been successfully produced at this vineyard since 1990. Therefore, this data source is appropriate because it is the only site specific data available for Amargosa Valley, and the information is based on several years of successful grape production.

Usual planting dates, harvest dates, and cut schedules for barley, winter wheat, oat hay, and alfalfa were provided by a local Amargosa Valley resident with 40 years of farming experience in Amargosa Valley (LeStrange 1997b). This data source is appropriate because it is the only site specific data available for Amargosa Valley, and the information is based on 40 years of farming experience.

4.1.4.2 Growing Season–Future Climate

Planting season of most garden crops for future climate conditions were obtained from *Vegetable Gardening* (Washington State University Cooperative Extension 2002, p. 2). This document was published by Washington State University Cooperative Extension in Spokane County (see source justification in Section 4.1.4.1). It lists ranges of suggested planting dates for garden crops in eastern Washington. This source is appropriate because it contains information for a large selection of garden crops and is specific to eastern Washington. These, and all other data described in this subsection, are presented in Table D-2.

Growing season length of most garden crops for future climatic conditions are from *Home Gardens* (Antonelli et al. 1998, Table 2), a guide to gardening in Washington published by Washington State University Cooperative Extension. This source was selected because it contains a comprehensive list of season lengths for most garden crops grown in Washington.

Planting dates for apples, grapes, and strawberries are derived from the midpoint of the “Usual Planting Dates” in the *1999 Annual Bulletin: Usual Planting & Harvesting Dates, Washington* (Washington Agricultural Statistics Service 1999). This document was published by the USDA NASS (see Section 4.1.4.1 for source justification). This information was selected because it is representative of agricultural practices in Washington.

Growing season for winter wheat and spring barley are from the *1995 Crop Rotation Budgets for Eastern Whitman County, Washington* (Painter et al. 1995, Tables A1 and A4), published by Washington State University Cooperative Extension. Season length was calculated as the length of time between the midpoints of planting and harvesting months. This source was selected because it provides crop- and site-specific information for the county where two future-climate analog weather stations (Rosalia and St. Johns) are located.

Growing season for apples, grapes, strawberries, feed corn, oats, and oat hay are from the *1999 Annual Bulletin: Usual Planting & Harvesting Dates, Washington* (Washington Agricultural Statistics Service 1999), published by the USDA NASS. The midpoints of “Usual Planting Dates” and “Most Active Usual Harvesting Dates” are used to define planting and harvest dates, respectively. These data were selected because they are representative of agricultural practices in Washington.

Alfalfa - Growth initiation dates, final harvest dates, and cutting schedules that are typical for alfalfa grown in the Intermountain West are reported in Schmierer et al. (1997, pp. 9 through 18) and Orloff and Marble (1997, pp. 106 through 107). This information was used in Appendix D to establish cut schedules and growing season lengths for alfalfa and in Section 6.4 to develop the Growing Time distribution for cattle forage. This source was required because information on alfalfa was not included in the primary data sources for growing season lengths used in this analysis (i.e., state Cooperative Extension Services and the USDA NASS).

Initiation of growth and cutting schedules for alfalfa from *Intermountain Alfalfa Management* (Schmierer et al. 1997, pp. 9 through 18; Orloff and Marble 1997, pp. 106 through 107) are for conditions that are similar to those in eastern Washington (future climate analog). Recommendations for initiation of spring growth or planting, and the last harvest of the growing season are based on temperatures (Schmierer et al. 1997 pp. 9 through 18) and are corroborated by Allen et al. (1998, Table 11, p. 107). This allows the use of future climate information (Section 4.1.5) to determine appropriate dates for initiation of spring growth and the date of the last harvest. This is an appropriate source because it provides information that can be used with site specific data to determine initiation of growth and harvest dates, and it is corroborated by another published and technically defensible source (Allen et al. 1998, see Section 4.1.4.1 for source justification). Use of this information, and discussions of uncertainty associated its use, is further described in Appendix D and Section 6.4.

4.1.5 Climate Information

The primary source for climate information for upper bound monsoon, lower bound future, and future climates is the National Oceanic and Atmospheric Administration (NOAA) and its agencies (e.g., National Climatic Data Center and the Western Regional Climate Center). This source is appropriate because the National Climatic Data Center serves as the repository for all NOAA meteorological information collected routinely from governmental agencies (e.g., Department for Commerce and Department of Defense) and private sources (e.g., National Cooperative Observer Program). The meteorological information undergoes quality control processing before being made available for public, private, or commercial use. This organization is recognized as the best source of national meteorological data by all agencies of the U.S. Government, and the data are accepted in the U.S. courts as interpreted by qualified experts.

4.1.5.1 Current Climate

Climate data collected at Yucca Mountain meteorological monitoring Site 9, were used to calculate reference evapotranspiration (ET_o , see Appendix C) for current climatic conditions at Yucca Mountain. This site is at an elevation of 838 m (2,750 feet) (CRWMS M&O 1999a, Table 1-1 on p. 6), near the southwestern corner of the Nevada Test Site. The following data were used: mean, minimum, and maximum temperature; minimum and maximum relative humidity; solar radiation; mean precipitation (DTN: MO9903CLIMATOL.001); and mean wind speed (DTN: MO9811DEDCRMCR.000). Average monthly values were based on five years (1993-1997) of data for temperature, relative humidity, radiation, and precipitation and on four years (1993-1996) of data for wind speed. These data are appropriate because they were collected at the southernmost Yucca Mountain meteorological site, located in the valley bottom in northern Amargosa Valley and therefore are consistent with the current arid conditions of the Yucca Mountain region. The data are presented in Table 4.1-2.

4.1.5.2 Upper Bound Monsoon Climate

Information from Nogales and Tucson, Arizona weather stations were used to calculate ET_o for the upper bound monsoon climate. Average monthly values were based on eight (wind speed) and 29 (remaining variables) years of information for Nogales, and 48 years of information for Tucson. Mean, minimum, and maximum temperature, mean precipitation, and mean wind speed were used from Nogales. Mean sunshine duration was used from Tucson. This information is appropriate because it is from the upper bound monsoon climate analog weather station having the longest and most complete record (USGS 2001, p. 66) and from a nearby weather station. The information for both sites was obtained from the Western Regional Climate Center (2003a, b, and c), which is cooperatively run by the Desert Research Institute of the University of Nevada, Reno, and the National Climatic Data Center of the National Oceanic and Atmospheric Administration. The information is presented in Table 4.1-3.

4.1.5.3 Lower Bound Future Climate

Information from Delta, Utah and Milford, Utah weather stations was used to calculate ET_o for the lower bound glacial transition climate. Average monthly values based on 30 years of information for Delta and eight years of information for Milford were used. Mean minimum, and maximum temperature, mean dewpoint temperature, and mean precipitation were used from Delta. Mean temperature was calculated from the mean minimum and mean maximum temperatures. Mean sunshine duration and mean wind speed were used from Milford. This information is appropriate because it is from the future-climate analog weather station having the longest and most complete record (USGS 2001, p. 66) and from a nearby weather station. The information for Delta was obtained from the National Weather Service (2003) and the Western Regional Climate Center (2003c). The information for Milford was obtained from the Western Regional Climate Center (2003d). The information is presented in Table 4.1-4.

4.1.5.4 Future Climate

Average monthly values based on 36 to 48 years of weather information collected at the Spokane International Airport were used to calculate ET_o for glacial transition climate (see Appendix C).

The following information was used: mean, minimum, and maximum temperature; mean, minimum, and maximum relative humidity; mean sunshine duration; mean wind speed; and mean precipitation. This information is appropriate because it is from the future-climate analog weather station having the longest and most complete record (USGS 2001, p. 66). The information was obtained from the Western Regional Climate Center (1997), which is cooperatively run by the Desert Research Institute of the University of Nevada, Reno, and the National Climatic Data Center of the National Oceanic and Atmospheric Administration. The weather information is presented in Table 4.1-5.

4.1.6 Soil Infiltration Rate

Information from the USDA Natural Resources Conservation Service (NRCS) on infiltration rates (i.e., permeability) of soils in Amargosa Valley was used in Section 6.6 to develop a distribution of irrigation intensity. The infiltration rates are from an unpublished soil survey of Amargosa Valley and were obtained directly from the Nevada Office of the NRCS (Dollarhide 1999). The infiltration rates are appropriate because they are specific to soils in northern Amargosa Valley and because they were collected by the federal agency with expertise in evaluating and describing soils. The infiltration rates are presented in Section 6.6.

4.1.7 Salinity of Irrigation Water

Electrical conductivity (*EC*) is the most common measure of water and soil salinity. Wells in the Amargosa and Yucca Mountain areas were drilled and monitored for salinity levels (among other variables) for the Nye County Early Warning Drilling Program (DTN: LA0206AM831234.001). Electrical conductivity was sampled on three dates from three well zones at Well number NC-EWDP-19D, located in the southwest corner of the Nevada Test Site (within the region being evaluated for the receptor population). Average well water salinity ($EC = 0.44$ dS/m, DTN: LA0206AM831234.001) rounded up to the nearest tenth ($EC = 0.50$ dS/m) from these samples was used in the calculations of crop leaching requirements (Appendix E). Units for *EC* were converted from $\mu\text{S}/\text{cm}$ to dS/m for the analysis using the equation $\text{dS}/\text{m} = 0.001(\mu\text{S}/\text{cm})$. The leaching requirement uses the salinity of irrigation water and crop tolerance to salts to calculate the amount of water needed to flush salts below the rooting zone. It is used as the Overwatering Rate when precipitation does not meet leaching requirements (Section 6.9 and Appendix E). It is also added to the Annual Average and Daily Average Irrigation Rates when precipitation does not meet leaching requirements (Sections 6.5, 6.8, and Appendix E).

The *EC* data from this source are corroborated by salinity measurements from 31 irrigation or domestic wells located in the village of Amargosa Valley (formerly Lathrop Wells) or west of State Route 373 and south of Highway 95 in Amargosa Valley (McKinley et al. 1991, pp. 9 through 17). Average well water salinity for these 31 wells was 0.51 dS/m (converted from $\mu\text{S}/\text{m}$). Thus, the data from the Nye County Early Warning Drilling Program are representative of local conditions. Additionally, irrigation calculations are relatively insensitive to salinity values that are below the tolerance levels of the crops under consideration. Salinity tolerances for the crops used in this analysis ranged from 1.0 dS/m for carrots and strawberries to 8.0 dS/m for barley (Allen et al. 1998, Table 23, pp. 178 through 180). Therefore, the mean well water salinity value was lower than the salinity tolerances for the crops under consideration, making leaching requirements minimal.

4.1.8 Crop Yield

Information from the USDA NASS (USDA 1998a, b; 1999a; 1999c; 2000a, b; 2001a, b; 2002c [see Section 4.1.4.1 for source justification]) was used to develop distributions of yield, as described in Section 6.11. Yields of commercially produced crops during five years (1995 – 1999) from up to four states (Arizona, California, Nevada, and Washington) with arid to semi-arid conditions were selected. These yield values are appropriate because they were developed from a large dataset of information on crop production (yield) over a wide range of semi-arid to arid conditions and therefore include variation due to changes in weather and agricultural practices. Information from Arizona and California were used in addition to that from Nevada and Washington because sufficient information for many crops was not available from Nevada and Washington. Information from gardens was not used because the methods used to develop the limited available information generally were not defined and the yield values therefore were of unknown quality. The yield values and the USDA sources are presented in Tables 6.11-1 through 6.11-6.

4.1.9 Tillage Depth

Information from the University of Georgia, the University of Ohio, and Washington State University Cooperative Extension Services was used to develop the distribution for tillage depth, as described in Section 6.10 (see Section 4.1.4.1 for source justification). Conventional tillage depth is cited as 25 to 30 cm (Lang et al., 1999, p. 3; Granberry et al. 2000, p. 8; and Johnson, 1999, Chapter 8, p. 1). This information is appropriate because it shows that there is little variation in conventional tillage depths, and that common tillage or plowing implements are designed to mix the soil to depths of 25 to 30 cm. Additionally, information on tillage depths from these non-site specific sources is appropriate because the use of irrigation and fertilizer in the Amargosa Valley would tend to make the site less distinguishable from other, more temperate areas.

4.1.10 Irrigation Methods

Information from USDA Cooperative Extension Service State Extension Offices was used in Section 6.3 to determine methods commonly used to irrigate commercial and garden crops (see Section 4.1.4.1 for source justification). Information on irrigation methods for leafy vegetables and other vegetables was selected from Martin et al. (1999a,b,c), Mayberry (2000a,b), Teegerstrom and Umeda (2001), Teegerstrom et al. (2001), and Hinman et al. (1997). Information on irrigation methods for fruits was selected from Klonsky and DeMoura (2001), Mayberry (2000c,d), Teegerstrom and Umeda (2001), Teegerstrom et al. (2001), Uriu and Magness (1967, pp. 697 – 698), and Wolf and Johnson (1999, p. 5). This information was selected because it comes from a variety of arid and semi-arid conditions and was prepared by agriculture professionals. The irrigation methods are described in Section 6.3.

Data collected on irrigation methods in Amargosa Valley during surveys conducted for the Radiological Monitoring Program (DTN: MO0208SPAMETHO.004) were used in Section 6.3 to determine methods commonly used to irrigate grains and cattle forage. This information was selected because it is site specific for the Amargosa farming community. The data are presented in Table 4.1-6

4.1.11 Rooting Depth

Ranges for maximum effective rooting depths (m) for crops used in this analysis were taken from Allen et al. (1998, Table 22, pp. 163 through 165). The low end of each range was selected for each crop. The ranges are presented in Table 4.1-7. Maximum effective rooting depths were used to develop the distribution for rooting depth in Section 6.12, and in Appendix E to calculate effective precipitation, available water in the root zone, Irrigation Application, and Overwatering Rates.

Crop Evapotranspiration (Allen et al. 1998, FAO Irrigation and Drainage Paper 56, see Section 4.1.4.1 for source justification) describes comprehensive guidelines for determining crop water requirements. Ranges of maximum effective rooting depths for most of the representative crops and turf used in this analysis are provided in Table 22, pp. 163 through 165. Allen et al. (1998) recommended using the smaller range values for irrigation scheduling because a large percentage of root biomass and activity occurs in the upper portion of the rooting zone. Therefore, the smaller values for rooting depth were selected for this analysis. This source is appropriate for use in this analysis because it is one of several *Irrigation and Drainage Papers* published by the FAO, a leading agency for agriculture in the United Nations system. Additionally, similar rooting depths to those reported in Allen et al. (1998) are described as “typical” by the American Society of Civil Engineers (Jensen et al. 1990, Table 2.7, pp. 22 through 23), and are supported by Bishop and Beetham (1989, Table 20, no page number), and Hagen et al. (1967, various chapters).

4.2 CRITERIA

Table 4.2-1 lists the requirements from the *Project Requirements Document* (Canori and Leitner, 2003) that are applicable to this analysis. These requirements are for compliance with applicable portions of 10 CFR 63, which is described in more detail in Section 4.3.

Table 4.2-2 lists the acceptance criteria from Section 2.2.1.3.14 (Biosphere Characteristics) of the *Yucca Mountain Review Plan, Draft Final Report* (NRC 2003) based on meeting the requirements of 10 CFR 63.114, 63.305, and 63.312 as they relate to biosphere characteristics modeling. These criteria are listed to further describe how the requirements referenced in Table 4.2-1 should be met. Only those bulleted items from Section 4.2.1.3.14 of the *Review Plan* that apply to this analysis are included here. Similar acceptance criteria and descriptions from Section 4.2.1.3.13 (Redistribution of Radionuclides in Soil) of the *Review Plan* also apply to portions of this analysis.

4.3 CODES AND STANDARDS

The following requirements in the Nuclear Regulatory Commission’s regulations for disposal of spent nuclear fuel and high level radioactive wastes in the geologic repository at Yucca Mountain (10 CFR 63, *Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada*. 2002) are relevant to this analysis.

63.305 Required characteristics of the reference biosphere.

(a) Features, events, and processes that describe the reference biosphere must be consistent with present knowledge of the conditions in the region surrounding the Yucca Mountain site.

(b) DOE should not project changes in society, the biosphere (other than climate), human biology, or increases or decreases of human knowledge or technology. In all analyses done to demonstrate compliance with this part, DOE must assume that all of those factors remain constant as they are at the time of submission of the license application.

(c) DOE must vary factors related to the geology, hydrology, and climate based upon cautious, but reasonable assumptions consistent with present knowledge of factors that could affect the Yucca Mountain disposal system over the next 10,000 years.

(d) Biosphere pathways must be consistent with arid or semi-arid conditions.

63.312 Required characteristics of the reasonably maximally exposed individual.

The reasonably maximally exposed individual is a hypothetical person who meets the following criteria: ...

(b) Has a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada. DOE must use projections based upon surveys of the people residing in the Town of Amargosa Valley, Nevada, to determine their current diets and living styles and use the mean values of these factors in the assessments conducted for 63.311 and 63.321.

Table 4.1-1. Technical Product Inputs Used in Analysis

Input Data	Source	Analysis Parameter and TDMS ^a Parameter	Presented In
Water Content of Food	USDA (2002a)	Dry to Wet Ratios	Table 6.2-1
Dry to Wet Ratios (alfalfa, corn silage, and oat hay)	Till and Meyer (1983, Table 5.16, with oat hay =forage)	Dry to Wet Ratios	Section 4.1.2, Table 6.2-1
Harvest Indices	Neitsch et al. (2002, Table A-8, pp. 381 through 384)	Dry Biomass	Table 6.1-1
Current Climate Growing Seasons	Mills et al. (no date) Call (1999); Morris and Johnson (1991, pp. 3 and 4); USDA (2002b, pp. 16 and 17); Allen et al. 1998 (Table 11, p.104 - 108); MO0210SPAGRO06.029.	Irrigation Application Annual Irrigation Rate Daily Irrigation Rate Overwatering Rate TDMS Parameter: Grow Time	Section 4.1.4, Table D-1
Future Climate Growing Seasons	Washington State University Cooperative Extension (2002, p. 2); Antonelli et al. (1998, Table 2); Washington Agricultural Statistics Service (1999); Painter et al. (1995, Tables A1 and A4); Schmierer et al. (1997, pp. 9 through 18); Orloff and Marble (1997, pp. 106 through 107).	Irrigation Application Annual Irrigation Rate Daily Irrigation Rate Overwatering Rate	Table D-2
Weather – Current Climate Conditions	MO9903CLIMATOL.001 MO9811DEDCRMCR.000	Irrigation Application Annual Irrigation Rate Daily Irrigation Rate Overwatering Rate TDMS Parameters: Precipitation quantity Relative humidity Solar Flux Temperature Wind Speed	Table 4.1-2
Weather – Upper Bound Monsoon Climate Conditions	Western Regional Climate Center (2003a, b, and c)	Annual Irrigation Rate	Table 4.1-3
Weather – Lower Bound Future Climate Conditions	National Weather Service (2003); Western Regional Climate Center (2003c); Western Regional Climate Center (2003d).	Annual Irrigation Rate	Table 4.1-4

Table 4.1-1. Technical Product Inputs Used in Analysis (Continued)

Input Data	Source	Analysis Parameter and TDMS ^a Parameter	Presented In
Weather – Upper Bound Future Climate Conditions	Western Regional Climate Center (1997)	Irrigation Application Annual Irrigation Rate Daily Irrigation Rate Overwatering Rate	Table 4.1-5
Soil Infiltration Rate	Dollarhide (1999)	Irrigation intensity	Section 6.6
Well Water Salinity	LA0206AM831234.001	Irrigation Application Annual Irrigation Rate Daily Irrigation Rate Overwatering Rate TDMS Parameter: Electrical Conductivity	Section 4.1.7
Crop Yield – Leafy Vegetables	USDA (1998a, Tables 4-14, 4-15, 4-21, 4-22, 4-33, 4-35, and 4-54); USDA (1999c, Tables 4-14, 4-15, 4-21, 4-22, 4-33, 4-35, and 4-54); USDA (2000a, Tables 4-14, 4-15, 4-21, 4-22, 4-33, 4-35, and 4-54); USDA (2001a, Tables 4-14, 4-15, 4-21, 4-22, 4-34, 4-36, and 4-55).	Yield	Table 6.11-1
Crop Yield – Other Vegetables	USDA (1998a, Tables 4-18, 4-26, 4-40, 4-43, and 4-47); USDA (1999c, Tables 4-18, 4-26, 4-40, 4-43, and 4-47); USDA (2000a, Tables 4-18, 4-26, 4-40, 4-43, and 4-47); USDA (2001a, Tables 4-18, 4-26, 4-41, 4-44, and 4-48).	Yield	Table 6.11-2
Crop Yield - Fruits	USDA (1998a, Tables 4-17, 4-32, 4-61, 4-73, and 5-70); USDA (1999c, Tables 4-17, 4-32, 4-61, 4-72, and 5-72); USDA (2000a, Tables 4-17, 4-32, 4-61, 4-72, and 5-72); USDA (2001a, Tables 4-17, 4-33, 4-62, 4-71, and 5-76).	Yield	Table 6.11-3

Table 4.1-1. Technical Product Inputs Used in Analysis (Continued)

Input Data	Source	Analysis Parameter and TDMS ^a Parameter	Presented In
Crop Yield – Apples and Grapes	USDA (1998b, Tables “Apples, Commercial: Bearing Acreage and Yield by State and United States, 1995-97” and “Grapes: Bearing Acreage and Yield by Type, State, and United States, 1995-97”); USDA (1999a, Tables on pages 8 and 40); USDA (2000b, Tables on pages 8 and 40); USDA (2001b, Tables on pages 10 and 44); USDA (2002c, Tables on pages 10 and 46). For all years, grapes = all types.	Yield	Table 6.11-6
Crop Yield – Cattle Forage	USDA (1998a, Tables 1-41, 6-3, and 6-4); USDA (1999c, Tables 1-41, 6-3, and 6-4); USDA (2000a, Tables 1-41, 6-3, and 6-4); USDA (2001a, Tables 1-39, 6-3, and 6-4).	Yield	Table 6.11-4
Crop Yield - Grain	USDA (1998a, Tables 1-8, 1-40, 1-50, and 1-56); USDA (1999c, Tables 1-8, 1-40, 1-51, and 1-57); USDA (2000a, Tables 1-8, 1-39, 1-51 and 1-57); USDA (2001a, Tables 1-8, 1-37, 1-49, and 1-55).	Yield	Table 6.11-5
Tillage Depth	Lang et al., 1999, p. 3; Granberry et al. 2000, p. 8; Johnson, 1999, Chapter 8, p. 1.	Tillage Depth	Section 6.10
Irrigation Methods	Martin et al. (1999a,b,c); Mayberry (2000a,b,c,d); Teegerstrom and Umeda (2001); Teegerstrom et al. (2001); Hinman et al. (1997); Klonsky and DeMoura (2001); Uriu and Magness (1967, pp. 697 – 698); Wolf and Johnson (1999, p. 5); MO0208SPAMETHO.004.	Fraction of Overhead Irrigation TDMS Parameter: Agricultural Statistics	Section 6.3 Table 4.1-6

Table 4.1-1. Technical Product Inputs Used in Analysis (Continued)

Input Data	Source	Analysis Parameter and TDMS ^a Parameter	Presented In
Rooting Depth	Allen et al. (1998, Table 22, pp. 163 through 165)	Rooting Depth Irrigation Application Annual Irrigation Rate Daily Irrigation Rate Overwatering Rate	Table 4.1-7

Notes: ^aTechnical Data Management System

Table 4.1-2. Weather Data for Current Climate^a

Month	Average Monthly Temperature ^b (°C)			Average Monthly Relative Humidity ^b (%)		Solar Radiation ^b (MJ/m ² /day)	Wind Speed ^c (m/s)	Precipitation ^{b,d} (mm)
	Mean	Max	Min	Max	Min			
January	7.1	13.5	1.3	61.9	39.0	9.5	3.8	23.4
February	9.6	16.6	3.1	55.2	27.6	13.9	4.2	17.0
March	13.6	21.5	6.1	48.3	19.9	19.4	4.4	11.7
April	16.7	24.6	8.1	37.9	13.7	24.6	4.8	3.0
May	22.1	30.1	13.1	38.7	14.2	27.5	4.7	5.6
June	27.4	35.3	18.4	27.9	8.7	29.9	4.7	7.6
July	31.0	39.2	21.5	23.7	7.3	29.4	4.6	0.5
August	30.5	38.9	20.9	24.2	8.0	27.0	4.7	0.2
September	25.4	33.7	16.7	30.7	11.4	22.6	4.4	9.1
October	17.7	26.0	10.0	33.2	13.8	17.4	4.1	5.3
November	10.6	18.3	3.6	47.6	23.5	11.9	4.1	7.1
December	6.9	13.9	0.8	54.4	28.0	9.6	4.0	11.7

Notes: ^a Data were collected at Yucca Mountain Meteorological Monitoring Site 9.

^b DTN: MO9903CLIMATOL.001

^c DTN: MO9811DEDCRMCR.000 (from CRWMS M&O 1997a, Table A-9, p. A-11)

^d Precipitation was converted from inches to millimeters (mm = inches x 2.54 x 10)

Table 4.1-3. Weather Data for Upper Bound Monsoon Climate

Month	Average Monthly Temperature ^a (°C)			Percent of Possible Sunshine	Wind Speed ^b (m/s)	Precipitation ^c (mm)
	Mean	Max	Min			
January	7.5	17.7	-2.7	80	2.01	33.3
February	9.2	19.5	-1.2	82	2.95	27.7
March	11.5	21.8	1.1	86	3.00	25.4
April	14.7	25.7	3.6	92	2.95	12.4
May	18.7	30.1	7.3	93	3.04	8.1
June	23.9	35.4	12.4	93	2.95	13.7
July	26.1	34.6	17.5	78	2.32	108.5
August	25.3	33.4	17.2	80	2.06	107.7
September	22.8	32.3	13.2	87	2.24	42.7
October	17.1	27.8	6.4	88	2.46	46.7
November	11.2	22.0	0.3	85	1.92	19.8
December	7.8	18.1	-2.4	79	2.24	37.3

Notes: Source: Western Regional Climate Center (2003a [temperature and precipitation from Nogales, Arizona], 2003b [percent of possible sunshine from Tucson, Arizona], and 2003c [wind speed from Nogales, Arizona])

^a Temperature was converted from °F to °C ($^{\circ}\text{C} = [^{\circ}\text{F}-32]/1.8$)

^b Wind speed was converted from mph to m/s ($\text{m/s} = 0.447\text{mph}$)

^c Precipitation was converted from inches to millimeters ($\text{mm} = \text{inches} \times 2.54 \times 10$)

Table 4.1-4. Weather Data for Lower Bound Future Climate

Month	Average Monthly Temperature ^a (°C)			Average Monthly Dew Point Temperature ^a (°C)	Percent of Possible Sunshine	Wind Speed ^c (m/s)	Precipitation ^d (mm)
	Mean ^b	Max	Min				
January	-3.1	3.9	-10.0	-8.3	58	4.87	15.7
February	-0.3	6.7	-7.2	-6.7	64	4.74	14.5
March	4.2	11.7	-3.3	-5.6	63	5.10	20.8
April	9.7	17.8	1.7	-1.7	69	5.05	20.1
May	14.7	23.3	6.1	1.1	73	5.45	21.3
June	19.4	28.9	10.0	1.7	82	5.54	12.7
July	24.7	34.4	15.0	7.8	77	5.36	6.6
August	23.6	33.3	13.9	5.6	79	4.92	10.7
September	18.3	28.3	8.3	2.8	80	4.43	10.4
October	11.1	20.0	2.2	-0.6	76	4.65	20.8
November	2.8	10.6	-5.0	-3.9	62	4.20	11.4
December	-1.4	5.6	-8.3	-6.7	60	4.38	16.8

Notes: Sources: National Weather Service (2003 [temperatures and precipitation from Delta, Utah]); Western Regional Climate Center (2003c [wind speed from Milford, Utah]); Western Regional Climate Center (2003d [percent of possible sunshine from Milford, Utah])

^a Temperature was converted from °F to °C (°C = [°F-32]/1.8)

^b Mean temperature was calculated from the maximum and minimum temperatures

^c Wind speed was converted from mph to m/s (m/s = 0.447mph)

^d Precipitation was converted from inches to millimeters (mm = inches x 2.54 x 10)

Table 4.1-5. Weather Data for Upper Bound Future Climate

Month	Average Monthly Temperature ^a (°C)			Average Monthly Relative Humidity (%)		Percent of Possible Sunshine	Wind Speed ^b (m/s)	Precipitation ^c (mm)
	Mean	Max	Min	Max	Min			
January	-2.7	0.7	-6.2	86	79	28	3.93	50.3
February	0.7	4.8	-3.4	85	69	41	4.11	37.8
March	3.7	8.7	-1.3	81	54	55	4.29	37.8
April	7.7	13.9	1.5	77	44	61	4.47	30.0
May	12.2	18.8	5.5	77	40	65	4.11	35.8
June	16.7	23.7	9.6	75	36	67	4.16	32.0
July	20.4	28.4	12.4	65	28	80	3.84	17.0
August	20.2	28.1	12.4	63	28	78	3.71	18.3
September	14.9	22.2	7.7	71	34	72	3.66	18.5
October	8.5	14.8	2.2	79	49	55	3.66	25.2
November	1.7	5.2	-1.8	87	76	29	3.89	54.6
December	-2.3	1.0	-5.7	88	83	23	3.89	61.5

Notes: Source: Western Regional Climate Center (1997)

^a Temperature was converted from °F to °C (°C = [°F-32]/1.8)

^b Wind speed was converted from mph to m/s (m/s = 0.447mph)

^c Precipitation was converted from inches to millimeters (mm = inches x 2.54 x 10)

Table 4.1-6. Acres Irrigated in Amargosa Valley

Crop Type	Sprinkler	Drip	Surface	No Data	Total
Grains and Forage	1,697.5		225.5	43.1	1,966.1
Fruits and Nuts		37.0	2.0	83.9	122.9
Leafy and other Vegetables				0.3	0.3
To be Planted	58.0		87.1		145.1
Fallow	420.3			204.5	624.8
Sod	126.2			69.2	195.4
Total	2,302.0	37.0	314.6	401.0	3,054.5

Notes: DTN: MO0208SPAMETHO.004

Table 4.1-7. Maximum Effective Rooting Depths (m)

Crop	Depth (Range)	Crop	Depth (Range)
Alfalfa	1.0 – 2.0	Grapes	1.0 – 2.0
Apples	1.0 – 2.0	Lettuce ^a	0.3 – 0.5
Barley	1.0 – 1.5	Melons	0.8 – 1.5
Bell peppers	0.5 – 1.0	Oats	1.0 – 1.5
Bermuda grass	0.5 – 1.0	Onions	0.3 – 0.6
Broccoli	0.4 – 0.7	Potatoes	0.4 – 0.6
Cabbage	0.5 – 0.8	Spinach	0.3 – 0.5
Carrots	0.5 – 1.0	Squash	0.6 – 1.0
Cauliflower	0.4 – 0.7	Strawberries	0.2 – 0.3
Celery	0.3 – 0.5	Sweet corn	0.8 – 1.2
Field corn	1.0 – 1.7	Tomatoes	0.7 – 1.5
Corn silage	1.0 – 1.7	Winter wheat	1.5 – 1.8
Cucumbers	0.7 – 1.2		
Fescue	0.5 – 1.0		

Notes: Source: Allen et al. (1998, Table 22, pp. 163 through 165)

^a Head lettuce or leaf lettuce not specified

Table 4.2-1. Requirements Applicable to this Analysis

Requirement Number	REQUIREMENT TITLE	Related Regulation
PRD-002/T-015	Requirements for Performance Assessment	10 CFR 63.114
PRD-002/T-026	Required Characteristics of the Reference Biosphere	10 CFR 63.305
PRD-002/T-028	Required Characteristics of the Reasonably Maximally Exposed Individual	10 CFR 63.312

Notes: From Canori and Leitner (2003, Table 2-3).

Table 4.2-2. Acceptance criteria from the *Yucca Mountain Review Plan, Draft Final Report* (NRC 2003) applicable to this analysis.

Acceptance Criterion 1 – System Description and Model Integration Are Adequate.
<ol style="list-style-type: none"> 1. Total system performance assessment adequately incorporates important site features, physical phenomena, and couplings, and consistent and appropriate assumptions throughout the biosphere characteristics modeling abstraction process; 2. The total system performance assessment model abstraction identifies and describes aspects of the biosphere characteristics modeling that are important to repository performance, and includes the technical bases for these descriptions. For example, the reference biosphere should be consistent with the arid or semi-arid conditions in the vicinity of Yucca Mountain; 3. Assumptions are consistent between the biosphere characteristics modeling and other abstractions. For example, the U.S. Department of Energy should ensure that the modeling of features, events, and processes, such as climate change, soil types, sorption coefficients, volcanic ash properties, and the physical and chemical properties of radionuclides are consistent with assumptions in other total system performance assessment abstractions;
Acceptance Criterion 2 – Data Are Sufficient for Model Justification.
<ol style="list-style-type: none"> 1. The parameter values used in the license application are adequately justified (e.g., behaviors and characteristics of the residents of the Town of Amargosa Valley, Nevada, characteristics of the reference biosphere, etc.) and consistent with the definition of the reasonably maximally exposed individual in 10 CFR Part 63. Adequate descriptions of how the data were used, interpreted, and appropriately synthesized into the parameters are provided; and 2. Data are sufficient to assess the degree to which features, events, and processes related to biosphere characteristics modeling have been characterized and incorporated in the abstraction. As specified in 10 CFR Part 63, the U.S. Department of Energy should demonstrate that features, events, and processes, which describe the biosphere, are consistent with present knowledge of conditions in the region, surrounding Yucca Mountain. As appropriate, the U.S. Department of Energy sensitivity and uncertainty analyses (including consideration of alternative conceptual models) are adequate for determining additional data needs, and evaluating whether additional data would provide new information that could invalidate prior modeling results and affect the sensitivity of the performance of the system to the parameter value or model.

Table 4.2-2. Acceptance criteria from the *Yucca Mountain Review Plan, Draft Final Report* (NRC 2003) applicable to this analysis (Continued).

Acceptance Criterion 3 – Data Uncertainty Is Characterized and Propagated Through the Model Abstraction.

1. Models use parameter values, assumed ranges, probability distributions, and bounding assumptions that are technically defensible, reasonably account for uncertainties and variabilities, do not result in an under-representation of the risk estimate, and are consistent with the definition of the reasonably maximally exposed individual in 10 CFR Part 63;
2. The technical bases for the parameter values and ranges in the abstraction, such as consumption rates, plant and animal uptake factors, mass-loading factors, and biosphere dose conversion factors, are consistent with site characterization data, and are technically defensible;
3. Process-level models used to determine parameter values for the biosphere characteristics modeling are consistent with site characterization data, laboratory experiments, field measurements, and natural analog research;
4. Uncertainty is adequately represented in parameter development for conceptual models and process-level models considered in developing the biosphere characteristics modeling, either through sensitivity analyses, conservative limits, or bounding values supported by data, as necessary. Correlations between input values are appropriately established in the total system performance assessment, and the implementation of the abstraction does not inappropriately bias results to a significant degree;
5. Where sufficient data do not exist, the definition of parameter values and conceptual models is based on appropriate use of expert elicitation, conducted in accordance with appropriate guidance, such as NUREG-1563. If other approaches are used, the U.S. Department of Energy adequately justifies their uses; and
6. Parameters or models that most influence repository performance, based on the performance measure and time period of compliance specified in 10 CFR Part 63, are identified.

Notes: From NRC 2003 (Section 4.2.1.3.14, Biosphere Characteristics). Only those acceptance criteria and related explanations that apply to this analysis are listed. Note that similar acceptance criteria in Section 4.2.1.3.13 (Redistribution of Radionuclides in Soils) also apply to this analysis.

5. ASSUMPTIONS

No assumptions were used to develop the distributions in this analysis.

6. ANALYSIS

This section describes the analyses conducted to develop average values and distributions for the twelve parameters considered in this report. The recommended parameter values are intended for use as inputs in the ERMYN biosphere model for the calculation of BDCF's for the modern interglacial (current) and glacial transition (future) climates for both the biosphere groundwater exposure scenario and volcanic ash exposure scenario.

Seven of the parameters (Dry Biomass, Dry to Wet Ratios, Fraction of Overhead Irrigation, Growing Time, Irrigation Application, Daily Irrigation Rate, and Yield) require separate distributions for the five crop types used in the biosphere model (leafy vegetables, root and other vegetables [hereafter called other vegetables], fruits, grain, and cattle forage). Five of the parameters (Annual Irrigation, Irrigation Intensity, Overwatering Rate, Tillage Depth, and Rooting Depth), are composite values with a single distribution representative of all crop types and turf.

Much of the variation in these parameters is from differences among crops within a crop type and much of the uncertainty is due to lack of knowledge about the specific crops a farmer or gardener will choose to grow (for example, see Section 6.5.2). To ensure that this variation and uncertainty is adequately addressed, the first step in this analysis was to select a set of crops for each crop type that is representative of the variation in types of plants likely to be grown under current and future climatic conditions. Selection of these representative crops was based on an evaluation of crops currently grown in southern Nye County, Nevada and eastern Washington, national patterns of food consumption, and variation in the growing season for commonly grown and consumed crops. This analysis is described in Appendix A and the recommended crops are listed in Table 6-1. Average parameter values were calculated using these representative crops throughout the analysis. Development of the parameter distributions was based on values calculated for the representative crops, which resulted in the use of uniform, fixed, normal, and cumulative probability distributions. Minimum and maximum values were required for most of the parameter distributions to preserve biological meaning and avoid selection of nonsensical values. For example, minimum and maximum values were necessary for irrigation parameters so that values likely to result in yield reduction or crop mortality would not be selected. Minimum values tended to be closer to the mean than maximum values because of crop sensitivity to water stress. This would have resulted in non-symmetrical truncation of normal distributions and shifts in the calculated mean. When this occurred, cumulative distribution functions were used to better represent the available data.

To calculate means and develop probabilities for cumulative distribution intervals for cattle forage, a 3 to 1 weighting process was used for alfalfa (3), oat hay (1), and corn silage (1). In Amargosa Valley, alfalfa totaled 67 to 97 percent of the acreage planted in hay for 1996 through 1999 (Table A-1). In Whitman and Spokane County, Washington (future climate analogs) alfalfa totaled 59 and 69 percent (respectively) of the acreage planted in hay, with very low percentages planted in oat hay and corn silage (Table A-3). Inclusion of values for oat hay and corn silage were necessary to account for uncertainties associated with crop selection and crop differences in parameter values. In some cases (e.g., dry biomass and yield), corn silage had very different parameter values compared to alfalfa. Because of this, and the importance of alfalfa compared to corn silage and oat hay, weighting of means and probabilities was necessary

to calculate averages and generate distributions for cattle forage. Weighting was not necessary for other crop types or for parameters developed from all 26 crops and turf because there was no information indicating that some crops were more common than others, or values within a crop type were similar, making weighting unnecessary.

Information from literature and field surveys was used to determine appropriate and reasonable values for each crop for dry biomass, dry to wet ratios, growing time, tillage depth, rooting depth, and yield. The methods outlined in the Food and Agriculture Organization of the United Nations Irrigation and Drainage Papers 56 (Allen et al. 1998) and 24 (Doorenbos and Pruitt 1977) were used to calculate crop water and irrigation supply requirements, respectively. Allen et al. (1998) provides energy balance and mass transfer equations to calculate reference evapotranspiration (ET_o) and lists crop coefficients (K_c), which are used to determine crop water requirements. These equations were recommended as the international standard for calculating ET_o (Allen et al. 1998) following an evaluation of several methods used to calculate evapotranspiration across a variety of climatic conditions (Jensen et al. 1990). Members of the International Commission for Irrigation and Drainage and the World Meteorological Organization were among the panel of experts that made the recommendations for revisions and improvements for calculation of ET_o . The methods for calculating net irrigation and seasonal irrigation requirements in Doorenbos and Pruitt (1977) are widely accepted and were used to complete the analysis to determine irrigation rates. Alternate technical methods and justification for use of the methods in Allen et al. (1998) and Doorenbos and Pruitt (1977) are in Appendix B. Variation and uncertainty associated with K_c are discussed in Section 6.5.2. Variation and uncertainty associated with ET_o are discussed in Sections 6.5.2, 6.7.2, 6.8.2, and 6.9.2.

6.1 DRY BIOMASS

6.1.1 Use in Biosphere Model

Dry Biomass (DB_j , kg/m^2) is a measure of the total, above-ground standing crop biomass per unit area, for each crop type. It is used in the plant submodel in the calculations of water and dust interception fractions. In both calculations, it represents the amount of plant material available to intercept contaminated water or dust.

Water Interception Fraction—Dry biomass is one of three parameter inputs to the calculation of the water interception fraction (Rw_j) (Eq. 6.1-1, BSC 2003b, p. 95), that is based on experiments of Beryllium-7 (7Be) and Iodine-131 (^{131}I). This fraction, which can vary from zero to one, represents the percentage of radionuclides in irrigation water sprayed on plants that is intercepted and deposited on plant leaves.

$$Rw_j = K_1 DB_j^{K_2} IA_j^{K_3} I_j^{K_4} \quad (\text{Eq. 6.1-1})$$

where

K_1 , K_2 , K_3 , and K_4 = empirical constants, depending on the plant-type and contaminant form. The recommended values are as follows:

$$K_1 = 2.29 \text{ for beryllium (Be}^+), 1.54 \text{ for iodine (I)},$$

$$K_2 = 0.695 \text{ for beryllium (Be}^+), 0.697 \text{ for iodine (I)},$$

$$K_3 = -0.29 \text{ for beryllium (Be}^+), -0.909 \text{ for iodine (I)},$$

$$K_4 = -0.341 \text{ for beryllium (Be}^+), -0.049 \text{ for iodine (I)},$$

IA_j = Irrigation Application (see Section 6.7),

I_j = Irrigation Intensity (see Section 6.6).

Because biomass is raised to the power of approximately 0.7 in this equation, there is a linear, positive relationship between biomass and water interception over a likely range of biomass values. For example, for dry biomass values ranging from 0.1 to 1.5 kg/m², the water interception fraction for Be⁺ changes approximately linearly from about 0.1 to about 0.7 (with $IA_j = 30$ mm and $I_j = 4$ cm/hour). The interception values for I only changes from about 0.01 to 0.08 over that range. Thus, interception for the cationic Be⁺ is sensitive to changes in biomass, but interception for the anionic I is insensitive to those changes

Dust Interception Fraction—Dry biomass is one of two variables in the calculation of dust interception, Ra_j (Eq. 6.1-2, BSC 2003b, p. 98), which represents the percentage (expressed as a number from zero to one) of suspended dust that is intercepted by the leaves of a plant.

$$Ra_j = 1.0 - e^{-a_j DB_j} \quad (\text{Eq. 6.1-2})$$

where

a_j = an empirical factor in units of square meter per kilogram of dry plant biomass (2.9 for leafy vegetables, fresh forage feed and grain, 3.6 for other vegetables and fruit).

Changes in biomass ranging from 0.15 to 0.7 kg/m² result in changes in the dust interception fraction from about 0.4 to 0.9 (Figure 6.1-1). Values of dry biomass greater than about 0.8 cause little change in the interception fraction, as the fraction asymptotes toward 1.0 at high values of dry biomass. Thus, the dust interception fraction is sensitive to changes in dry biomass ranging from 0.1 to 0.8, but insensitive to higher values.

6.1.2 Parameter Development

Dry Biomass of leafy vegetables and cattle forage was calculated by multiplying yield of each representative crop (Section 6.11) by the dry to wet ratio for that crop (Section 6.2). Because the total aboveground portions of leafy vegetables and cattle forage are weighed to determine yield, the resulting values are valid measurements of total aboveground dry biomass (Table 6.1-1).

Dry Biomass for grains, other vegetables, and fruits were calculated by multiplying yield of each representative crop (Section 6.11) by the dry to wet ratio for that crop (Section 6.2) and dividing the resulting value by a harvest index (Table 6.1-1). Harvest index inputs are described in Section 4.1.3 and presented in Table 6.1-1. Harvest indices for grains, other vegetables, and fruits were selected from Neitsch et al. (2002, Table A-8, pp. 381 through 384) because they are appropriate for use with USDA measurements of yield and dry to wet ratios. Values for the optimal harvest index were selected from Table A-8. Squash and corn were not included in the

dry biomass distribution for other vegetables because yield data were not available (see Section 6.11). Apples were not included in the dry biomass distribution for fruits because a high percentage of aboveground biomass is invested in woody structures compared to leaves and fruit.

A harvest index is a measure of the ratio of seed, fruit, or tuber dry biomass to total aboveground dry biomass. It was first used in plant breeding studies to identify cultivars and select for desirable traits that would improve crop yield (Hay 1995, p. 198; Prince et al. 2001, p. 1196). More recently it has been used to estimate net primary production for cropped land (Prince et al. 2001), assess dry matter partitioning responses of horticultural crops to fertilizer or irrigation treatments (Scholberg et al. 2000; Van Delden 2001), and estimate aboveground biomass from published yield values (Prince et al. 2001, p. 1196). For crops with aboveground yield (e.g., bell peppers and strawberries) the harvest index is less than 1.0 (Neitsch et al. 2002, p. 381). For crops with belowground yield (e.g., onions and carrots) the harvest index may be greater than 1.0 (Neitsch et al. 2002, p. 381).

The average for each crop type is the mean biomass of representative crops, with the exception of the weighted mean used for cattle forage (Table 6.1-2).

A cumulative distribution function is recommended for each crop type (Table 6.1-2). Ninety percent of the probability distribution is between the minimum and maximum biomass of representative crops within a crop type (e.g., biomass for leafy vegetables ranges from 0.13 [head lettuce] to 0.42 kg/m² [celery], Table 6.1-1). The distribution between the minimum and maximum crop biomass is divided into intervals of equal probability (summing to 90 percent), with the exception of cattle forage (see below). The number of intervals is one less than the number of representative crops and the upper limits are crop-specific values of biomass. The probabilities for the two intervals for cattle forage were weighted 3:1 for the range between oat hay and alfalfa ($p = 0.675$) versus the range between alfalfa and corn silage ($p = 0.225$) (see Section 6 for justification). This results in a higher probability for selection of values that are similar to alfalfa. To account for variation and uncertainty that could result in values beyond the range of crop specific values, intervals of five percent probability each were added to the lower and upper ends of the distribution. Yield (Section 6.11) was evaluated for crops within a crop type having low and high dry biomass values to determine appropriate bounds for the distributions. The lowest yield value reported for crops with relatively low dry biomass was used with dry to wet ratios and harvest indices (when appropriate) to recalculate dry biomass. The resulting value was rounded down to the nearest tenth and used as the lower bound. For example, broccoli and head lettuce had the lowest reported dry biomass for leafy vegetables; however, broccoli had a lower yield value and was selected to calculate the lower bound. Using the minimum yield reported for broccoli (1.08 kg/m², Table 6.11-1) and the dry to wet ratio reported for broccoli (0.093, Table 6.2-1) the lower bound for leafy vegetables is $1.08 \times 0.093 = 0.10$. Carrots, strawberries, oats, and alfalfa were used to calculate the lower bounds for other vegetables, fruits, grains, and cattle forage, respectively. The upper bounds were determined with the same method using the highest yield value reported for crops with high biomass. The resulting values were rounded up to the nearest tenth (Table 6.1-2). Celery, onions, strawberries, corn, and corn silage were used to calculate the upper bounds for leafy vegetables, other vegetables, fruits, grains, and cattle forage, respectively. It should be noted that potatoes had a higher yield than onions for other vegetables (6.61 kg/m² versus 6.50 kg/m²). However, the low dry to wet ratios for potatoes resulted in a lower dry biomass than that calculated for the highest

yield of onions. Therefore, the yield for onions was more appropriate for calculating the upper bound. The wide range in yield values for strawberries made their use appropriate for calculation of both lower and upper bounds for fruits (see Table 6.11-3)

Much of the variation in this parameter is due to variation in yield (i.e., wet biomass of harvest). As discussed in Section 6.11, the distributions of yield adequately incorporate variation and uncertainty due to climate or farming conditions, farming and gardening practices, and selection of crops and crop types. There is little uncertainty in the measurements of dry to wet ratios (Section 6.2); thus, they contribute little to the uncertainty in dry biomass. Harvest indices tend to be conservative unless crops are grown under extreme stress conditions (Prince et al. 2001, p. 1196). Most published measurements of harvest indices reviewed by Prince et al. (2001, p. 1197) varied by no more than ± 0.06 from the values used in this analysis. Increasing or decreasing the values of harvest indices of grain by 0.06 would result in mean dry biomass values of about 1.0 and 1.3, respectively, well within the bounds of the recommended distribution (range = 0.50 to 2.20 kg/m²). Thus, there is little variation or uncertainty associated with harvest indices for grains. Uncertainty in harvest index values for other vegetables and fruits was accounted for by selection of four to five crops per crop type. The distributions for dry biomass are more sensitive to variation in yield than harvest indices (see selection of distribution bounding values above). Therefore, changes in the accuracy of harvest index for representative crops has little influence on the distribution bounds of dry biomass for each crop type.

The same distributions are recommended for both climate scenarios and for use in both the biosphere groundwater and volcanic ash exposure scenarios (see Section 1). Distributions for yield and dry to wet ratios were developed from a variety of crops and climate conditions, including arid conditions representative of current climate and cooler conditions representative of future climates (see Sections 6.2 and 6.11). Therefore, yield, dry to wet ratios, or other physical characteristics of crops that influence dry biomass account for influences that climate change or a volcanic eruption at Yucca Mountain would have.

6.2 DRY TO WET RATIOS

6.2.1 Use in Biosphere Model

The Dry to Wet Ratio (DW_j , unitless) is a measure of the ratio of dry mass to wet mass of edible foodstuffs per crop type. It is used in the plant submodel in the calculation of radionuclide concentrations in plant foodstuffs contributed from plant root uptake ($C_{p_{root\ i,j}}$) (Eq. 6.2-1, BSC 2003b, p. 92). The dry to wet ratio is included in this equation because the transfer factors are based on the dry weight of food.

$$C_{p_{root\ i,j}} = C_{s_{m,i}} F_{s \rightarrow p\ i,j} DW_j \quad (\text{Eq. 6.2-1})$$

where

$C_{s_{m,i}}$ = concentration of radionuclide i in the surface soil per unit area for a crop type j in units of Bq per square meter,

$F_{s \rightarrow p\ i,j}$ = the soil-to-plant transfer factor, per crop type.

In this equation, the dry to wet ratio has a positive, linear effect on radionuclide concentrations. Thus, plant root uptake will be greater for drier foodstuffs within a crop type (i.e., those with a larger ratio) than it will be for wetter plants.

6.2.2 Parameter Development

Information on the water content of food products compiled by the USDA (2002a) (see Section 4.1.1), and dry to wet ratios for alfalfa, corn silage, and oat hay from Till and Meyer (1983, Table 5.16, pp. 5 through 48) (see Section 4.1.2) were used to develop distributions of Dry to Wet Ratios (Table 6.2-1).

The average for each crop type is the mean Dry to Wet Ratio of representative crops, with the exception of the weighted mean used for cattle forage (Table 6.2-2).

A cumulative distribution function is recommended for each crop type (Table 6.2-2). The probability distribution ranges between the minimum and maximum dry to wet ratios of representative crops within a crop type (e.g., dry to wet ratios for leafy vegetables range from 0.041 [head lettuce] to 0.093 [broccoli], Table 6.2-1). The distribution between the minimum and maximum crop dry to wet ratios is divided into intervals of equal probability, with the exception of cattle forage. The number of intervals is one less than the number of representative crops and the upper bounds are crop-specific values of dry to wet ratios (Table 6.2-2). The probabilities for the two cattle forage intervals were weighted 3:1 for the range between oat hay and alfalfa ($p = 0.75$) versus the range between alfalfa and corn silage ($p = 0.25$) (see Section 6 for justification). This results in a higher probability of selection of values that are similar to alfalfa.

The number of samples used by USDA to calculate water content per crop generally is large (10 to more than 200 measurements for all but cucumbers [3 measurements], leaf lettuce [estimated], potatoes [9], and barley [7]). The standard errors of their estimates of average percent water content per crop are very small (range = 0.06 to 1.0 percent). Because dry to wet ratios are a simple conversion of crop water content ($1 - [\% \text{ water} / 100]$) the variation per crop in dry to wet ratios is also very small. Thus, there is so little variation or uncertainty about the dry to wet ratio per crop that it was not necessary to extend the distribution beyond crop specific values.

The important sources of variation and uncertainty for this parameter are related to variation among crops within a crop type and uncertainty in the types of locally grown crops planted and consumed. These are adequately accounted for through the use of three or more representative crops within a crop type.

Values of the dry to wet ratios for alfalfa (0.227), corn silage (0.238), and oat hay (0.182) were selected for this analysis (see Section 4.1.2). Comparable values used in radiological assessments include 0.19 for alfalfa (IAEA 1994, Table 5), 0.22 for fresh forage (Kennedy and Strenge 1992, Table 6.17), 0.20 for fresh forage (Napier et al. 1988, Table 4.25 on p. 4.71), and 0.22 for beef cattle fresh forage (LaPlante and Poor 1997, Table B-1 on p. B-9). In addition, Orloff (1997, p. 109) states that the moisture content of alfalfa is generally between 75 and 80 percent, the midpoint of which equals a dry to wet ratio of 0.225. These values are within the

range of those selected, indicating that there is little uncertainty about the dry to wet ratios of forage. Therefore, the recommended distributions are adequate for each crop-type.

The same distributions are recommended for both climate scenarios and for use in both the biosphere groundwater and volcanic ash exposure scenarios (see Section 1) because climate change and a volcanic eruption at Yucca Mountain will not result in a change in the moisture content of foods or forage.

6.3 FRACTION OF OVERHEAD IRRIGATION

6.3.1 Use in Biosphere Model

The fraction of a crop type that is irrigated using sprinkler or spray irrigation ($f_{o,j}$, unitless) is used in the plant submodel in the calculation of uptake into foodstuffs of radionuclides deposited on the plant surface via water (Equation 6.3-1, BSC 2003b, p. 94). This equation, without $f_{o,j}$, is also used to calculate the interception of soil on the surface of plants.

$$Cp_{water\ i,j} = \frac{Dw_{i,j} f_{o,j} R_{w_j} T_j}{\lambda_w Y_j} (1 - e^{-\lambda_w t_{g,j}}) \quad (\text{Eq. 6.3-1})$$

where

$Cp_{water\ i,j}$ = concentration of radionuclide i in a specific plant foodstuff contributed from plant leaf uptake. There are two deposition mechanisms, irrigation water ($Cp_{water\ i,j}$) and dust ($Cp_{dust\ i,j}$),

$Dw_{i,j}$ = the deposition rate from irrigation water ($Dw_{i,j}$) or resuspended dust ($Da_{i,j}$) onto crop type j in units of Bq per square meter per day,

$f_{o,j}$ = the probability that overhead sprinklers or spray is used to irrigate a crop type j , dimensionless; this parameter only applies to uptake from irrigation water and does not appear in the equation for deposition via dust,

R_{w_j} = the interception fraction for irrigation water ($R_{w_{i,j}}$) or air dust ($R_{a_{i,j}}$), (dimensionless) for crop type j ,

T_j = the translocation factor for crop type j , (dimensionless),

λ_w = the weathering constant in units of per day,

Y_j = yield per crop type (see Section 6.9),

$t_{g,j}$ = growing time that plants are exposed to contaminated soil or water for crop type j in units of days (see Section 6.4).

The fraction of overhead irrigation is included in the model to account for the portion of crops that are not watered using overhead sprinklers and to propagate uncertainty in irrigation methods. A change in this fraction results in a proportional change in the numerator of Equation 6.3-1.

6.3.2 Parameter Development

There are three basic methods used to irrigate field crops, orchards, and gardens: surface irrigation, drip systems, and sprinkler systems. Surface irrigation includes ditch and furrow irrigation and other flood methods that saturate part, or all, of the soil surface. Drip irrigation includes the use of bubblers, drip emitters, drip tubing, micro sprays, or other methods that deliver water to the soil surface at or near the base of plants. Sprinkler systems include stationary and mobile sprinklers (e.g., center pivot, side roll sprinklers) that spray water over plants, and lawn-type sprinklers and garden hoses sprayed over gardens. Overhead spraying is the only method that will result in groundwater contaminated with radionuclides being applied to the surface leaves (i.e., uptake by foliar interception of irrigation water). Because the rate of removal of radionuclides from the surface of plants (i.e., the weathering factor) is relatively fast (see Section 6.4.1), the method of irrigation used during the month prior to harvesting is more important than that used during germination or early growth stages.

Distributions of the probability of leafy vegetables, other vegetables, and fruits being irrigated with overhead spray or sprinkler irrigation were developed from descriptions of irrigation methods commonly used to grow the representative crops in arid and semi-arid environments from USDA Cooperative Extension Service State Extension Offices. Distributions of the probability of grains and cattle forage being irrigated with overhead spray or sprinkler irrigation were developed from observations of irrigation methods in Amargosa Valley. These observations were recorded in 1998 during surveys conducted for the Radiological Monitoring Program (DTN MO0208SPAMETHO.004, Section 4.1.10, Table 4.1-6). Most (86 percent of grains and forage and at least 75 percent of all acreage) agricultural fields in Amargosa Valley during 1998 were irrigated with overhead sprinklers (Table 4.1-6). Because few fruits and vegetables are commercially grown in Amargosa Valley, and because there is little irrigation of crops in eastern Washington (Table A-3), much of the following information on irrigation practices for fruits and vegetables comes from Arizona and California. There is no information available on the prevalence of irrigation methods used in gardens, although recommended methods are described in publications such as Antonelli et al. (1998, p. 11) and Call (1999, Chapter 18).

Because there is much variation and uncertainty associated with this parameter for most crop types, recommended distributions, which are summarized in Table 6.3-1, have relatively large standard deviations.

The same distributions are recommended for both climate scenarios because irrigation methods would not change appreciably due to changes in climate (in part because irrigation methods are substantially influenced by water availability, economics, and crop selection) and because increases or decreases of human knowledge and technology over time are not to be considered in this analysis, per 10 CFR 63.305(b). This parameter is not used in the biosphere volcanic ash exposure scenario; therefore, changes resulting from a volcanic eruption at Yucca Mountain are not considered in this analysis.

Leafy Vegetables and Other Vegetables—Surface irrigation (flood, ditch, and furrow) is commonly used for commercial production of most leafy vegetables and other vegetables (e.g., lettuce, carrots, and onions in Arizona—Martin et al. 1999a,b,c; lettuce in California—Mayberry

2000a; numerous vegetables in central and western Arizona—Teegerstrom and Umeda 2001; Teegerstrom et al. 2001), although some vegetables may be grown using drip irrigation (e.g., bell peppers in California—Mayberry 2000b). Use of overhead sprinkler irrigation for vegetables is uncommon in the southwestern U.S., but is used at least some in semiarid regions of the Pacific Northwest (e.g., potatoes and sweet corn in south central Washington—Hinman et al. 1997). Surface, drip, or sprinkler irrigation may be used in gardens.

To ensure that leaf interception of radionuclides is not underestimated, a normal distribution with a mean of 0.75 is recommended for leafy vegetables and other vegetables. To account for the large amount of uncertainty in this parameter, a standard deviation of 0.1 is recommended, with a minimum of 0.49 and a maximum of 1.0 (Table 6.3-1). The minimum value was based on the ninety-ninth percentile of the low end of the distribution (calculated as $0.75 - [2.58 \times 0.1]$).

Fruits—Surface irrigation (melons in central and southwestern Arizona—Teegerstrom and Umeda 2001; Teegerstrom et al. 2001; cantaloupe in California—Mayberry 2000c) and drip irrigation (watermelons in California—Mayberry 2000d, strawberries in California—Klonsky and DeMoura 2001) are commonly used for commercial production of melons and berries. Grapes are grown using drip or flood irrigation, in part because wetting leaves with overhead spraying causes leaf diseases (Wolf and Johnson 1999, p. 5). Fruit and nut trees may be irrigated using stationary sprays on risers (Uriu and Magness 1967, pp. 697–698); however, the water is sprayed under the canopy, and fruits do not get wet. Therefore, spray irrigation that would contaminate fruits is uncommon for commercial production of fruits. Surface, drip, or sprinkler irrigation may be used in gardens for melons, berries, and other low-growing fruits.

A normal distribution with a mean of 0.5, a standard deviation of 0.1, a minimum of 0.24, and a maximum of 1.0 is recommended for fruits (Table 6.3-1). The minimum value was based on the ninety ninth percentile of the low end of the distribution (calculated as $0.5 - [2.58 \times 0.1]$). The mean of this distribution is lower than that recommended for vegetables because leaf interception is not an important process for fruit and nut trees and because spray irrigation is uncommon for commercial production of other fruits.

Grains and Cattle Forage—At least 86 percent of 1,966 acres of grains and forage grown in Amargosa Valley during 1998 was irrigated using center pivot, side roll, or other types of sprinklers. About 12 percent was surface irrigated, and the method used to irrigate the remainder was not recorded (Table 4.1-6). Surface and sprinkler irrigation also are used elsewhere to irrigate grains and forage (Hinman et al. 1997; Orloff et al. 1997, p. 36–37; Teegerstrom and Clay 1999).

Because overhead sprinkler irrigation is used most often, but not exclusively, in Amargosa Valley for commercial crops, a normal distribution with a mean of 0.9, a minimum of 0.77, and a maximum of 1.0 is recommended for grains and cattle forage. Because there is less uncertainty about the type of irrigation used for these crops in Amargosa Valley than for other crops, a smaller standard deviation of 0.05 is recommended. The minimum value was based on the ninety ninth percentile of the low end of the distribution (calculated as $0.9 - [2.58 \times 0.05]$).

6.4 GROWING TIME

6.4.1 Use in Biosphere Model

Growing Time for crop type j ($t_{g,j}$, days/growing season) is a measure of the amount of time crops are growing and exposed to contaminated water and dust. It is used in the biosphere model in the calculation of the uptake into foodstuffs of radionuclides deposited on the plant surface via water and dust interception (Eq. 6.3-1).

Growing Time is in a “one minus” exponential term that accounts for the weathering of radionuclides on plant surfaces. This term approaches one (i.e., no effect on radionuclide concentration as weathering of radionuclides on the leaf approach equilibrium conditions) as growing time increases. For a weathering half life of 14 days ($\lambda_w = 0.05$, calculated as \ln_2 /weathering half life), the weathering decay term equals 0.92 when $t_{g,j} = 50$ days, 0.98 when $t_{g,j} = 75$ days, and 0.99 when $t_{g,j} = 90$ days. Therefore, weathering approaches equilibrium at 50 to 100 days, and leaf uptake is not sensitive to values of growing time greater than about 50 to 75 days.

6.4.2 Parameter Development

Selection of values for growing season length of representative crops is described in Section 2.1 of Appendix D and summarized in Table 6.4-1. The data from which these values were derived are described in Section 4.1.4.

Different values are presented for each climate because differences in temperature, planting season, and selection of varieties adapted to those climates result in differences in season length for some crops. For example, barley is always grown as a winter/spring crop in southern Nevada and therefore has a long growing season, but can be grown in a much shorter time during spring and summer in eastern Washington (Appendix A, Figures A-1 and A-2).

The values in Table 6.4-1 represent the typical number of days that the representative crops must be irrigated (because they were selected primarily for calculations of irrigation rates). Thus, they are valid measurements of growing time for water interception calculations. They are also valid measurements of soil exposure time for annual crops (i.e., all representative vegetables and grains), cattle forage, and perennial fruits in southern Nevada, because these crops are irrigated throughout the entire growing season. However, irrigation time is not equal to soil exposure time for perennial fruits in eastern Washington (grapes, apples, and strawberries) because these crops are only irrigated until fruit harvest, but the leaves of these plants remain and are exposed to dust throughout the entire growing season. Because the average value of growing time for fruits for the future climate is greater than 100 (and the model is insensitive to higher values, see Section 6.4.1) separate values for the soil interception calculation are not required.

Because leaf uptake is insensitive to changes in growing times greater than about 75 days, fixed values are recommended for this parameter, and recommended values were selected by rounding the average growing time per crop type to the nearest value divisible by five (Table 6.4-1). Rounding to the nearest value divisible by five was done to simplify presentation of data and because a higher level of accuracy was not necessary.

Deposition and redistribution of a thin layer of ash expected from a volcanic eruption at Yucca Mountain would not cause long-term changes in climate or soil that would result in substantial changes in crop growing time (see Section 1); therefore, the same distribution is recommended for both the biosphere groundwater and volcanic ash exposure scenarios.

6.5 IRRIGATION RATE–ANNUAL AVERAGE

6.5.1 Use in Biosphere Model

Irrigation rate (IR , m/year) is a measure of the average rate at which contaminated groundwater is applied to soils to irrigate plants. It is used in the soil submodel to calculate radionuclide concentrations in soil (Equation 6.5-1, BSC 2003b, p. 76), and in a very similar equation in the carbon-14 submodel. Changes in land use and crop rotation practices make it possible that a variety of plants, including garden crops, commercial crops, and horticultural plants could be grown on a plot of land over a long period. Because of this, the distribution for annual irrigation rate is based on all 26 representative crops and turf (Table 6.1). Using several plant types to develop the distribution for annual irrigation rate accounts for uncertainty in crop selection and rotation.

The equation used to calculate radionuclide concentrations in soil is:

$$\frac{dC_{s_i}(t)}{dt} = C_{w_i}(t)IR(t) - (\lambda_{di} + \lambda_{li} + \lambda_e)C_{s_i}(t) \quad (\text{Eq. 6.5-1})$$

where

$C_{s_i}(t)$ = activity concentration of radionuclide i in surface soil per unit area at time t (Bq/m^2),

t = time (years),

i = index of primary radionuclide,

$C_{w_i}(t)$ = radionuclide concentration in groundwater used for irrigation at time t (Bq/m^3),

λ_{di} = radionuclide decay constant for radionuclide i (1/year),

λ_{li} = leaching removal constant for radionuclide i (1/year),

λ_e = the surface soil erosion removal constant (1/year).

Changes in annual average irrigation rate have a linear effect on soil concentrations and therefore may be an important parameter in calculating BDCFs.

6.5.2 Parameter Development

Methods in Allen et al. (1998) and Doorenbos and Pruitt (1977) published by the Food and Agriculture Organization of the United Nations (FAO) were used to calculate IR and are justified in Appendix B (Section 2). Background information on plant water use is also included in Appendix B (Section 1). The methodology is based on determination of crop water requirements, which are calculated from evapotranspiration of a grass reference surface and adjusted with a crop-specific coefficient (Appendices C and D).

Parameter inputs were growing season lengths (Section 4.1.4), average monthly weather data for current, upper bound monsoon, lower bound future and upper bound future climates (Section 4.1.5), and salinity of irrigation water (Section 4.1.7). Growing season lengths were used in Appendices D and E to adjust growth stage lengths and calculate seasonal water requirements, respectively. Average monthly weather data were used in Appendix C to calculate reference evapotranspiration (ET_o) and in Appendix E to calculate effective precipitation. Salinity of irrigation water (Section 4.1.7) was used in Appendix E to determine the leaching requirement used to calculate seasonal water requirements.

Reference evapotranspiration was calculated for a grass reference surface and represents the effects of climate on crop evapotranspiration (ET_c). The reference surface as defined by Allen et al. (1998, p. 15) is a “hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23”. It is assumed to be of uniform height, actively growing, completely shading the ground, with an adequate water supply. Climatic variables that drive ET_o include air temperature, humidity, radiation, and wind speed. The FAO Penman-Monteith equation (Allen et al. 1998, Equation 6, p. 24) was used to calculate ET_o (calculations and examples are in Appendix C). Mean monthly ET_o was calculated for current, upper bound monsoon, lower bound future, and upper bound future climates (Appendix C, Table C-5). Variation and uncertainty in ET_o that could affect irrigation parameter values are discussed in Sections 6.5.2, 6.7.2, 6.8.2, and 6.9.2.

The crop coefficient (K_c) integrates the effects of four primary crop characteristics that differ from the reference grass surface (crop height, albedo, canopy resistance, and evaporation from soil). Changes in crop characteristics (i.e., leaf area, stomatal conductance, developmental stages) over the growing season also affect K_c ; therefore, growth stage information was used to derive crop specific values (calculations and examples are in Appendix D). Locally determined values for K_c were not available for this analysis and so values published in Allen et al. 1998 (Table 12, pp. 104 through 108) were used for the 26 representative crops and turf. To reduce uncertainty associated with published K_c , these values were adjusted to local conditions using relative humidity and wind speed for the four climate states (Appendix D, Tables D-5 and D-6). A monthly mean K_c was calculated to correspond with monthly mean ET_o (Appendix D).

Variation in K_c is primarily influenced by differences in crop specific characteristics (Allen et al. 1998, p. 90). This allows standard K_c values to be used across geographical locations and different climates, and has been the main reason for general acceptance and usefulness of the K_c methodology. There is little variation in K_c values among crops within a crop type (Allen et al. 1998, p. 109). Use of a variety of representative crops and crop types adequately accounts for variation and uncertainty in K_c for this analysis.

Crop evapotranspiration was used with information on timing of growing seasons to determine average monthly crop water requirements. Average daily ET_c ($ET_{c \text{ daily}}$) for each month (Appendix D, Section 5, Tables D-7 and D-8) was calculated according to Allen et al. (1998, Equation 58 on p. 103):

$$ET_{c \text{ daily}} = K_c \times ET_o$$

The resulting value was multiplied by the number of growing season days per month to get mean monthly ET_c ($ET_{c \text{ monthly}}$) needed to estimate seasonal water requirements.

Seasonal crop water requirements (W_s , Appendix E, Section 2.4) were calculated using the following equation from Doorenbos and Pruitt (1977, p. 79):

$$W_s = \frac{\sum_{i=1}^n (ET_{c \text{ monthly}} - Pe)}{1 - LR}$$

where

$ET_{c \text{ monthly}}$ = monthly mean crop evapotranspiration ,
 Pe = monthly mean effective precipitation (see Appendix E for calculation methods),
 LR = leaching requirement,
 n = months in growing season.

Seasonal irrigation requirements (In) were calculated from one of the following equations from Doorenbos and Pruitt (1977, p. 70). The first equation was used if precipitation met the seasonal LR (Appendix E, Section 2.4). The second equation was used if irrigation was required to meet the seasonal LR (Appendix E, Section 2.4).

$$In = \sum_{i=1}^n ET_{c \text{ monthly}} - (\sum_{i=1}^n Pe + Ge + Wb)$$

$$In = W_s - (Ge + Wb)$$

where

$ET_{c \text{ monthly}}$ = monthly mean crop evapotranspiration,
 Pe = monthly mean effective precipitation,
 Ge = groundwater contribution to the water requirement (see Appendix E for calculation methods),
 Wb = stored soil moisture in the root system (see Appendix E for calculation methods),
 W_s = seasonal crop water requirement
 n = months in growing season.

For each crop and turf, annual average irrigation rate (IR) was equal to In (Appendix E, Sections 1 through 2.4 and Table 6.5-1) and used in development of the distribution for IR for current and future climates, and used to calculate the means for current, upper bound monsoon, lower bound future, and upper bound future climates. For two season crops and alfalfa, average values of IR were summed across growing seasons to get a total for the year (Table 6.5-1).

Upper bound monsoon and lower bound future climates were only considered in this analysis for calculation of IR . This was done to develop an average estimate for these intermediate climate states that could be used to help define sampling limits for Biosphere Dose Conversion Factors (BDCFs) that would include variation within climate states. The averages for IR were 0.52

m/year and 0.88 m/year for upper bound monsoon and lower bound future climate conditions, respectively (Table 6.5-1).

The averages for *IR* for current and future climate conditions were 0.94 m/year and 0.50 m/year, respectively (Table 6.5-2). Two distributions for *IR* are included in this analysis for both current and future climates so that the more appropriate distribution can be selected for use in the biosphere model. *IR* differs from other parameters in this analysis because it is used for long-term radionuclide accumulation in soil. Because of this, the biosphere model could require *IR* values that are representative of long-term averages which do not include the entire range of possible variation. In this case, normal distributions with the calculated means and standard errors are recommended for both climates (Table 6.5-3). To avoid extreme values that are not representative of long-term averages, the ninety-ninth percentiles are recommended as the minimum and maximum values for the distributions. For current climate, this results in a distribution with values that range from 0.73 to 1.15 m/year (Table 6.5-3). For future climate, the distribution values range from 0.40 to 0.60 m/year (Table 6.5-3).

If the biosphere model requires an *IR* distribution that includes yearly variation and a wider range of uncertainty, then cumulative distribution functions are recommended for current and future climates (Table 6.5-4). Ninety percent of the probability distribution is between the minimum and maximum *IR* of representative crops (e.g., range = 0.40 [squash] to 1.94 [alfalfa] m/year for current climate). The distribution between the minimum and maximum crop *IR* is divided into five intervals of equal probability (summing to 90 percent, Table 6.5-4), with 5 or 6 crops per interval. To account for variation and uncertainty beyond the range of crop specific values, intervals of five-percent probability each were added to the lower and upper ends of the distribution. To avoid *IR* values that could result in yield reduction or plant mortality due to water stress, recommended minimum bounds for current and future climate distributions are 0.33 m/year and 0.14 m/year, respectively (Table 6.5-4). To include variation and uncertainties associated with season length and excessive irrigation, maximum bounds of 2.29 m/year and 0.98 m/year are recommended for current and future climates, respectively (Table 6.5-4). Minimum and maximum bounds are justified in the analysis below.

This parameter is not used in the biosphere volcanic ash exposure scenario; therefore, changes resulting from a volcanic eruption at Yucca Mountain are not considered in this analysis.

Variation and Uncertainty—Variation in *IR* is primarily from differences in water use among crops, variation in growing season length among crops, differences between minimum and maximum season lengths for each crop, and yearly variation in climate variables that drive *ET_o*. Uncertainty in the distribution of *IR* is due to lack of knowledge about which crops a farmer will choose to grow and about water management practices (i.e., excessive watering or under watering during a growing season).

Variation among crops and uncertainty about which crops a farmer will grow are adequately accounted for through use of 26 crops and turf. Selection was based on an evaluation of crops currently grown in southern Nye County, Nevada and eastern Washington, national patterns of food consumption, and variation in the growing season for commonly grown and consumed crops (see Appendix A).

Within Crop Variation in Season Length—Generally, the midpoint of minimum and maximum season lengths gathered from several sources was selected as a representative and reasonable growing season length for each crop (Appendix D, Tables D-1 and D-2). For the current climate, within crop differences between the minimum and maximum season lengths ranged from 10 to 60 days with a mean difference of 32 days ($SD = 15.2$, calculated from Table D-1). For the future climate, within crop differences between the minimum and maximum season lengths ranged from 5 to 70 days with a mean difference of 24 days ($SD = 15.2$, calculated from Table D-2). Even though the ranges in minimum and maximum season lengths appear to be considerable, in most cases, season lengths were constrained by mean monthly temperatures for the two climates (i.e., temperatures below crop tolerance levels) or by growing two-season crops. These constraints resulted in relatively little variation in *IR* due to within crop differences in potential growing season lengths compared to variation in *IR* among crops. Examples are illustrated below.

Crops with the lowest *IR*s were evaluated to establish low bounds for the distributions that would encompass the potential variation caused by minimum season lengths for a crop. Squash and strawberries had the lowest *IR* for current and future climates, respectively (Table 6.5-2). However, there was no information on minimum and maximum ranges for season length for strawberries. Therefore, squash was used to evaluate the low end of the distributions for both climate conditions. Squash season length for current climate was 58 days, and the minimum season length was 50 days (Appendix D, Table D-1). Re-calculation of *IR* based on the minimum season length showed a reduction from 0.40 m/year to 0.33 m/year. This value was selected as the minimum for the recommended distribution because it included variation in *IR* due to season length for a single-season, low water-use crop, and also encompassed uncertainties regarding under-watering (discussed below).

Squash season length for future climate was 58 days, and the minimum season length was 50 days (Appendix D, Table D-2). Re-calculation of *IR* based on the minimum season length showed a reduction from 0.18 m/year to 0.14 m/year. This value was selected as the minimum for the recommended distribution because it included variation in *IR* due to season length for a low water-use crop, and also encompassed uncertainties regarding under-watering (discussed below).

Bounds for the high end of the distributions were evaluated using crops with high water-use, or a wide range between minimum and maximum growing season lengths. Alfalfa, apples, bermudagrass, and celery were considered for current climate, and alfalfa, fescue, carrots, and feed corn were considered for future climate.

Alfalfa had the highest *IR* for current climate (1.94 m/year, Table 6.5-2) compared to other crops. Additionally, six cuttings were used, making the total growing time 336 days. Because of the time required for each cutting, and the short winter dormant period, additional cuttings or a longer time between cuttings were not possible. Thus, 1.94 m/year is the maximum amount of water that alfalfa can use based on maximum growing season length. Apples also had relatively high water requirements (1.82 m/year); however, apples are usually drip irrigated making the *IR* less important to the distribution than alfalfa which is sprinkler irrigated. Bermudagrass (turf) also had a relatively high *IR* (1.61 m/year); however, its growing season was 365 days and could not be increased. The mean difference between minimum and maximum growing season lengths

of 32 days for current climate was added to early celery because a range specific to celery was not available (Appendix D, Table D-1). A 32-day increase is similar to the ranges in growing season length for other leafy vegetables (Appendix D, Table D-1), and does not overlap the planting time for late season celery. Addition of days to the late season celery crop would do little to increase the irrigation requirement because of the very low evaporative demand in January and February. The resulting irrigation requirement for celery (early and late season) was 1.95 m/year, an increase of 0.45 m/year. This is similar to *IR* for alfalfa (1.94 m/year). Therefore, variation due to season length for two-season and multi-season high water-use crops is accounted for in the range of crop specific *IR* for current climate conditions.

Tall fescue (turf grass) and alfalfa had the highest *IR* (0.83 m/year) for future climate compared to the remaining 25 crops. Growing season length was constrained by dormancy and occurrence of killing frost from November through the end of March, making it unreasonable to extend the growing seasons. Based on maximum growing season lengths, it is reasonable to conclude that 0.83 m/year is the maximum amount of water that fescue or alfalfa would normally use. Maximum season lengths for carrots and feed corn were examined to determine whether variable growing season length or variable onset of growth (with no increase in season length) should be used to establish upper bounds for the future climate distribution of *IR*. These crops were chosen because they have relatively high *IR* (carrots = 0.71 m/year and feed corn = 0.73 m/year)

Moving the planting date for carrots from April 23 to April 15 (Appendix D, Table D-2) resulted in an eight-day extension at the beginning of the growing season. Extension of the harvest date was not possible because of constraints imposed by the planting date for the late season crop (July 13 for carrots). Because of low evaporative demands in April, the 8-day extension of the growing season resulted in an *IR* increase of only 0.02 m/year for carrots. This illustrates that use of two season crops encompasses the variation that might occur from within crop variation in growing season length at the high end of the distribution.

The planting and harvest dates for feed corn were moved forward 26 days to illustrate the impact of a change in timing of growth for a relatively high water-use crop (0.73 m/year). The change in timing changed several parameters, including precipitation and evaporative demands, and resulted in an *IR* of 0.85 m/year. This value is similar to those for fescue and alfalfa. Therefore, potential variation in *IR* due to within-crop variation in timing of growth is encompassed by variation in *IR* among crops for future climate conditions.

Yearly Variation in Climate—Variation in *IR* from yearly variation in mean monthly climate variables that drive ET_o was not directly calculated because the datasets that were used did not include this information. While hourly or daily variations in ET_o can be large, ET_o averaged for monthly time periods tend to be conservative from year to year (Tanner 1967, Chapter 29, p. 557). Error in estimates of ET_o using empirical formulas have been shown to decrease by two to three times as the period of estimation increased from one week to one month (Tanner 1967, Chapter 29, p. 557). Variation from the expected monthly average in ET_o was estimated using air temperature data as a meteorological index representing variation in evaporative demands. Monthly mean, average maximum, and average minimum air temperatures with standard deviations for 26 to 29 years in Amargosa Valley, Nevada were obtained from the Western Regional Climate Center (2002a, 2002b, 2002c, Table 6.5-5). The coefficient of variation ($CV =$

SD/mean) showed little yearly variation occurred in the three temperature parameters each month (Table 6.5-5). Yearly variation ranged from 3.0 percent to 10.0 percent depending on the temperature parameter and month (Table 6.5-5). It should be noted that the data for current climate were averaged over 5 years and the *CV* would be higher than that for data averaged over 26 to 29 years. More variation in *IR* occurred due to variation among crops (44 percent and 38 percent for current and future climates, respectively, Table 6-5.2) than would occur due to yearly variation in monthly mean *ET_o*. Therefore, it is reasonable to conclude that the recommended distributions encompass the variation in *IR* that could be caused by yearly variation in mean monthly climate variables that drive *ET_o*.

Uncertainty in Water Management Practices—Uncertainty in the distribution of *IR* due to lack of knowledge about water management practices (i.e., excessive irrigation or under-watering during a growing season) can be bounded by assessing practices that would result in reductions in crop yield.

Excessive irrigation—When irrigation exceeds the storage capacity of soil in the root zone, water percolates past the root zone, or runs off site and is unavailable for use by the plant, or will accumulate and waterlog poorly drained soils (Viets 1967, Chapter 24, p. 466). Such situations affect nutrient availability and therefore crop yield. Excessive percolation leaches nitrates and other mineral nutrients that are essential to plant growth (Viets 1967, Chapter 24, p. 466). In poorly drained soils, or if water is ponded at the surface for an extended period, water will replace oxygen in soil pores resulting in oxygen deficiencies for root growth and microbial activity (Viets 1967, Chapter 24, pp. 466 and 478). Microbes compete with plant roots for oxygen, and reduce available nitrate through denitrification (nitrate converted to unusable gaseous nitrogen) in wet soils (Viets 1967, Chapter 24, p. 478). Excessive irrigation can also increase annual weeds and perennial grasses which causes reduction in yield for most crops. Overwatering increases pumping costs and is limited by water permits. A farmer or gardener would probably respond to signs of excessive irrigation and modify their water management practices to avoid losses in yield or increases in pumping costs.

To determine reasonable upper bounds for *IR* distributions, impacts of overwatering alfalfa were evaluated. Overwatering alfalfa causes root and shoot diseases, nutrient losses through leaching, weed encroachment, and does not increase yield (Orloff et al. 1997, p. 25). Environmental problems such as stream, river, or groundwater pollution can be a direct result of leaching fertilizers due to excessive irrigation of alfalfa (or other crops). Values for yield reduction caused by overwatering suggest that an approximate 18 percent increase in irrigation over crop requirements can result in yield reduction of about 0.4 tons per acre (Keller and Carlson 1967, Figure 31-2, p. 612). Orloff et al. (1997) suggest that alfalfa does not tolerate wet soils during periods of active growth, and wet soils have the potential to shorten stand life. Therefore, it is reasonable to suggest that farmers would not over irrigate alfalfa by more than about 18 percent of the crop water requirement. This percent increase results in *IR* values of 2.29 m/year and 0.98 m/year for alfalfa under current and future climate conditions, respectively. To include uncertainty associated with excessive watering practices, these values were used as the upper bounds for the distributions of *IR* for current and future climates.

Under-watering—Moisture stress occurs if precipitation and/or irrigation do not meet crop water requirements (see Appendix B). The level of moisture stress can vary from minor, where crop

leaves wilt during the day but recover at night, to severe, where recovery is not possible and leaf desiccation occurs. Reductions in crop yield and quality can occur at various levels of water stress depending on the sensitivity of the crop. For example, grain crops tend to be more tolerant of water stress than potatoes or leafy vegetables (Robins et al. 1967, p. 635 and 636; Vittum and Flocker 1967, p. 676 and 677). As with excessive irrigation, it is likely that a farmer or gardener would respond to signs of under-watering by modifying their water management practices to avoid losses in quality and yield.

To evaluate the impacts that under-watering might have on the distribution of *IR*, soil moisture storage capacity of the root zone and crop sensitivity to soil moisture stress were considered for crops at the low end of the recommended distributions (Appendix E, Section 2.6). The methods used to calculate Irrigation Application (Section 6.7 and Appendix E, Section 2.5) were modified to reflect under-watering conditions that would likely cause stress. Soil moisture was allowed to stay at a level that would impose stress for two days prior to each scheduled irrigation event over a 30-day time period (scheduling of irrigation events differed according to crop requirements). Two days was chosen as a likely time interval that would cause some level of crop stress without causing mortality. The resulting number of days the crop would experience stress and the percent reduction in applied water was determined (Appendix E, Section 2.6). The results of this exercise showed that small percent decreases in irrigation could cause several (non-consecutive) days of water stress in the 30 day time period (Appendix E, Table E-14). Based on this analysis, a 10 percent reduction in irrigation parameters was selected to determine whether under-watering should be used to determine lower bounds for the distributions, and to avoid selection of a lower bound that would cause yield reduction or crop mortality. Squash was chosen for the *IR* analysis for current climate and strawberries were chosen for future climate. These two crops had the lowest *IR* values for the two climate conditions (Table 6.5-1).

Using a 10 percent reduction in *IR* for squash resulted in a decrease from 0.40 m/year to 0.36 m/year. 0.36 m/year was only slightly higher than the recommended minimum value for the distribution based on variation in season length (0.33 m/year). Thus, the recommended distribution accounts for uncertainty in water management practices without including values that would result in crop mortality.

For future climate conditions, a 10 percent reduction in *IR* for strawberries resulted in a decrease from 0.16 m/year to 0.14 m/year. This value was equal to the recommended minimum for the distribution of *IR* based on variation in season length. Therefore, the recommended distribution for future climate also accounts for uncertainty in water management practices without including values that would result in crop mortality.

6.6 IRRIGATION INTENSITY

6.6.1 Use in Biosphere Model

Irrigation Intensity (I , cm/hour) is a measure of the rate at which contaminated groundwater is applied to a crop type each time a crop is irrigated. It is used in the plant submodel in the calculation of the water interception fraction (Eq. 6.1-1). In that equation, Irrigation Intensity is raised to the power of a negative fraction; thus, increasing the rate at which water is applied decreases the interception fraction (because the plant surface becomes saturated more rapidly and

more contaminated water runs off of the leaves). Changing Irrigation Intensity from 0.5 to 10 cm/hour results in a decrease in the interception fraction of beryllium from 0.57 to 0.21 (Figure 6.6-1, with biomass = 0.4 kg/m² and irrigation application = 40 mm). The interception fraction is much more sensitive to values of Irrigation Intensity less than about 4.0 cm/hour because the fraction asymptotes at higher intensities (Figure 6.6-1). Irrigation Intensity has no effect on the interception fraction for iodine because the parameter is raised to the power of -0.05 for that anion.

6.6.2 Parameter Development

Irrigation Intensity can vary substantially depending on the method of irrigation used. High irrigation intensity is achieved in gardens using hoses and lawn sprinklers and in agricultural fields using large gun sprayers. Low rates can be achieved on garden and commercial sprinkler systems (e.g., center pivot, side roll, or stationary spray systems) by selecting nozzles with low flow rates and increasing the spacing between nozzles. Irrigation Intensity for sprinkler types and typical spacing used in commercial agriculture can range from less than 0.5 cm per hour to more than 10 cm per hour (Doorenbos and Pruitt 1977, Table 44, p. 77; Ley 1992, Table 2; Hansen and Trimmer 1997, Figures 1 and 2; Kranz 2002, Figure 2).

One of the most important factors considered when determining the rate at which water can be applied using agricultural sprinkler systems is the soil texture and associated infiltration rate (Christiansen and Davis, 1967, pp. 896 and 897; Hansen and Trimmer 1997; Kranz 2002). On clay soils, which have infiltration rates of about 0.1 to 1.5 cm/hour (Doorenbos and Pruitt 1977, Table 40, p. 91), water must be applied slowly to avoid ponding, runoff, and erosion. In contrast, sandy and sandy loam soils have high infiltration rates (1.5 to 7.5 cm/hour for sandy loam and 2.5 to 25 cm/hour for sandy soils, Doorenbos and Pruitt 1977, Table 40, p. 91) and can be irrigated at relatively high rates.

Information on the infiltration rates of soils in northern Amargosa Valley was obtained from the USDA Natural Resources Conservation Service and examined to determine the feasible range of Irrigation Intensity for soils in that area. The common soils in northern Amargosa Valley (Arizo, Corbilt, Sanwell, Shamock, Yermo) are sandy to sandy loam, well drained, and have a moderate to rapid permeability (CRWMS M&O 1999b; Figure 1 and pp. C-1, C-2, C-25, C-27, C-39, C-40). The infiltration rate of the upper layers of these soils is about 5 to 15 cm per hour (Dollarhide 1999, Table Physical Properties of Soils, Column Permeability).

Because of the high infiltration rate of soils in northern Amargosa Valley, systems with low Irrigation Intensity would not be required and likely would be avoided because they are more expensive to operate. For example, evaporation is higher when using low spray rates, which decreases irrigation efficiency and increases costs, especially in hot, dry, windy conditions such as those experienced in Amargosa Valley during summer. Also, it takes a long time to deliver sufficient water at low application rates, which increases labor and pumping costs. At an irrigation efficiency of 70 percent, it takes almost 18 hours to apply 3 cm of water at an irrigation intensity of 0.25 cm per hour, and about 9 hours to apply that amount at an intensity of 0.5 cm per hour (Ley 1992, Table 3).

Based on this information, 4.3 cm per hour (midpoint of the distribution), and a uniform distribution of Irrigation Intensity with a minimum of 1.0 cm per hour and a maximum of 7.5 cm per hour are recommended. A minimum value less than the minimum infiltration rate of soils in Amargosa Valley (2 to 15 cm/hour) is recommended to account for uncertainty about irrigation methods used and irrigation efficiency in Amargosa Valley. Although application rates higher than the maximum recommended value are possible for most soils in Amargosa Valley (and are quite likely for some irrigation methods such as gardens irrigated with a hose), a higher maximum is not recommended because higher values have little influence on the calculation of leaf interception fraction (see Section 6.6.1). A uniform distribution is recommended because there is no information to indicate which rates within this range are more likely.

The same distribution is recommended for all crop types because sprinklers producing a wide range of application rates are available for both garden and commercial crops, and soil conditions would not differ substantially for garden and commercial crops. Likewise, the same distribution is recommended for current and future climates, because soil infiltration rates would not change and available sprinkler equipment do not differ between arid and semiarid regions.

There is uncertainty in the development of a distribution for Irrigation Intensity because there is limited information on irrigation methods used in Amargosa Valley, there is a wide range of irrigation methods available, and irrigation systems can be modified easily to change Irrigation Intensity. The bounds of the distribution recommended in this analysis were selected to ensure that these uncertainties are propagated in the biosphere model.

This parameter is not used in the biosphere volcanic ash exposure scenario; therefore, changes resulting from a volcanic eruption at Yucca Mountain are not considered in this analysis.

6.7 IRRIGATION APPLICATION

6.7.1 Use in Biosphere Model

Irrigation application (IA_j , mm) is a measure of the amount of contaminated water applied to a crop type each time crops are irrigated during the last 30 days of growth. It is used in the plant submodel in the calculation of the water interception fraction (Eq. 6.1-1). In that equation, irrigation application is raised to the power of a negative fraction (see Section 6.1.1); thus, increasing the amount of water applied during each application decreases the interception fraction (because the plant surface becomes saturated and more contaminated water runs off of the leaves). Changing the irrigation amount from 15 to 65 mm results in an approximately linear change in the interception fraction of beryllium from about 0.34 to 0.23 (with biomass = 0.4 kg/m² and irrigation intensity = 4 cm/hour). The interception fraction for iodine changes from about 0.06 to about 0.02. Thus, the water interception fraction is relatively insensitive to changes in irrigation application.

6.7.2 Parameter Development

Methods for calculating crop water requirements that were published by FAO (Allen et al. 1998) were used to calculate ET_o (Appendix C), K_c (Appendix D), and ET_c (Appendix D). Methods are justified in Appendix B (Section 2). Background information on plant water use is also in Appendix B (Section 1). Mean daily ET_c averaged for one-month time periods and soil moisture

balance over a 30 day period prior to harvest were used to calculate IA for each crop (see Appendix E, Section 2.5.2 for methods and example calculations). Several irrigation events were required during the last 30 days of growth for most crops. The average application amount for all irrigation events (per crop) was determined and these values were used to calculate the average per crop type (Table 6.7-1). The average application amount for two seasons was used where applicable. Application amounts were averaged across cuttings for alfalfa.

Parameter inputs were rooting depth (Section 6.12), growing season lengths (Section 4.1.4) and average monthly weather data (Section 4.1.5) for current and future climates. Rooting depth was used in soil water balance calculations in Appendix E. Growing season lengths were used in Appendix D to calculate mean monthly K_c and in Appendix E to determine when the last 30 days of growth occurred for each crop. Average monthly weather data were used in Appendix C to calculate ET_o . Average monthly precipitation was used in Appendix E to calculate effective precipitation. Effective precipitation for 30 days prior to harvest was used in the calculations of IA (Appendix E, Section 2.5.2).

The average for each crop type is the mean IA_j of the representative crops, with the exception of the weighted mean used for cattle forage (Tables 6.7-2 and 6.7-3).

A cumulative distribution function is recommended for each crop type for both current and future climates (Tables 6.7-2 and 6.7-3). Ninety percent of the probability distribution is between the minimum and maximum IA of representative crops within a crop type (e.g., IA for leafy vegetables ranges from 7.4 [spinach] to 23.6 mm [cabbage] for current climate, Table 6.7-1). The distribution between the minimum and maximum crop IA_j is divided into intervals of equal probability (summing to 90 percent), with the exception of cattle forage (see below). The number of intervals is one less than the number of representative crops and the upper limits are crop-specific values of IA (Table 6.7-2). The probabilities for the two intervals for the distribution of cattle forage were weighted 3:1 for the range between oat hay and alfalfa ($p = 0.675$) versus the range between alfalfa and corn silage ($p = 0.225$) (see Section 6 for justification). This results in a higher probability for selection of values that are similar to alfalfa. To account for variation and uncertainty that could result in values beyond the range of crop specific values, intervals of five percent probability each were added to the lower and upper ends of the distribution. The bounds are based on crop water stress calculations and overwatering potentials and are justified in the analysis below.

This parameter is not used in the biosphere volcanic ash exposure scenario; therefore, changes resulting from a volcanic eruption at Yucca Mountain are not considered in this analysis.

Variation and Uncertainty - Much of the variation and uncertainty associated with the distributions of IA_j were accounted for through selection of three or more representative crops per crop type (see Section 6.5 and Appendix A). Variation that was not accounted for includes year to year variation in monthly climate variables. Uncertainty not accounted for is due to lack of knowledge about water management practices (i.e., excessive irrigation or under-watering during the 30 days prior to harvest).

Yearly Variation in Climate –Year to year variation in mean monthly climatic variables affect IA_j through calculation of ET_o (Appendix C). Variation in IA_j from yearly variation in mean

monthly climate variables was not directly calculated because the data were not available. While daily or hourly fluctuations in ET_o can be large, monthly means tend to be conservative from year to year (see Section 6.5.2.1). Variation from the expected monthly average ET_o was calculated using air temperature data as a meteorological index representing variation in evaporative demands (Section 6.5.2). Monthly mean, monthly average maximum, and monthly average minimum air temperatures with standard deviations for 26 to 29 years in Amargosa Valley, Nevada were obtained from the Western Regional Climate Center (2002a, 2002b, 2002c Table 6.5-5). Small coefficients of variation ($CV = SD/mean$) indicates little yearly variation in the average monthly temperature parameters (Table 6.5-5). Yearly variation ranged from 3.0 percent to 10.0 percent depending on the temperature parameter and month (Table 6.5-5). Variation in IA_j among crops within a crop type ranged from 3 percent to 52 percent for current climate and from 10 percent to 51 percent for future climate (Table 6.7-1). Therefore, variation in IA_j among crops within a crop type is generally greater than the variation in IA_j expected from yearly changes in mean monthly climate variables. It is reasonable to conclude that the recommended distributions sufficiently account for yearly variations in monthly mean climate.

Uncertainty in Water Management Practices—Uncertainty in the distribution of IA_j due to lack of knowledge about water management practices (i.e., excessive irrigation or under watering during a growing season) can be bounded similarly to IR , by assessing practices that would result in crop stress.

Excessive Irrigation—Problems caused by excessive irrigation are discussed in Section 6.5.2. These include nutrient loss from the root zone through leaching, water loss through percolation below the root zone or runoff, oxygen deficiencies for root growth and microbial activity, denitrification, and infestation by weeds (Section 6.5.2). These processes can result in loss of yield, reduced crop quality, pollution, and increased water pumping costs. In Section 6.5.2 it was concluded that overwatering alfalfa by about 18 percent would result in yield reduction through a variety of mechanisms, including those mentioned above. It is reasonable to conclude that an 18 percent increase in IA_j would have similar effects on other representative crops and pumping costs. To establish appropriate upper bounds for the distributions of IA_j that would encompass uncertainties associated with excessive irrigation, maximum values (within a crop type) were increased by 18 percent (Tables 6.7-2 and 6.7-3). Cabbage, sweet corn, apples, winter wheat, and corn silage were used to establish upper bounds in the current climate analysis. Cabbage, sweet corn, apples, barley, and corn silage were used in the future climate analysis.

Under watering—Moisture stress occurs if irrigation water does not meet crop water requirements (see Appendix B). The level of moisture stress can vary from minor, where crop leaves wilt during the day but recover at night, to severe where recovery is not possible and leaf desiccation occurs. Reductions in both crop yield and quality can occur at various levels of water stress depending on the sensitivity of the crop. For example, grain crops tend to be more tolerant of water stress than potatoes or leafy vegetables (Robins et al. 1967, pp. 635 and 636, and Vittum and Flocker 1967, pp. 676 and 677). It is likely that a farmer or gardener would respond to signs of under watering by modifying their water management practices to avoid losses in crop quality and yield.

The methods used to determine percent reduction in the total amount of irrigation applied for other irrigation parameters (see Appendix E for example) were not applicable to IA_j . This is

because stress was imposed by withholding water for 2 days after scheduled irrigation events, then enough water was added to bring the volume in the root zone to the level where stress would be alleviated. This often resulted in fewer applications but increased application amounts. However, the results of the exercise indicated that a 10 percent reduction in irrigation would likely cause water stress. Therefore, it is reasonable to use the 10 percent reduction recommended for other irrigation parameters to determine lower bounds for the distributions of IA_j .

Spinach, onions, strawberries, barley, and oat hay were chosen for the current climate analysis because these crops had the lowest IA within their crop type (Table 6.7-1). IA was reduced by 10 percent for each of these crops and used as minimum bounds for the distributions for crop types (Table 6.7-2). The recommended minimum values were rounded down to the nearest mm.

Spinach, onions, strawberries, feed corn, and oat hay were chosen for the future climate analysis because these crops had the lowest IA within their crop type (Table 6.7-1). IA was reduced by 10 percent for each of these crops and used as minimum bounds for the distributions for crop types (Table 6.7-3). The recommended minimum values were rounded down to the nearest mm.

6.8 IRRIGATION RATE – DAILY

6.8.1 Use in Biosphere Model

Daily irrigation rate (IRD_j , mm/day) is a measure of the average amount of contaminated groundwater applied per day over the growing season (over all growing seasons for multiple season crops) for a crop type. It is used in the plant uptake submodel to calculate the rate of deposition of radionuclides onto the surface of plants (Dw_{ij} , BSC 2003b, p. 94):

$$Dw_{i,j} = Cw_i IRD_j \quad (\text{Eq. 6.8-1})$$

where Cw_i is the concentration of radionuclide i in the groundwater (Bq/m^2). The deposition rate is then used in the calculation of leaf uptake of radionuclides, as shown in Equation 6.3-1. Because values of daily irrigation rate directly influence the concentration of radionuclides in leaves, this parameter may have an important influence on BDCFs. It is also used in a similar equation in the carbon-14 submodel to calculate the concentration of carbon-14 (^{14}C) in surface soils (by multiplying irrigation rate by ^{14}C concentration in water and dividing by decay and removal constants).

6.8.2 Parameter Development

Distributions for IRD_j were developed for each of the five crop types for current and future climates. Daily irrigation rates for each crop were determined by dividing IR by growing season days (Table 6.8-1). Therefore, IRD_j is directly related to IR making inputs and calculation methods the same as those described in Section 6.5 and Appendix E.

IRD_j for each crop and averages per crop type are in Table 6.8-1 for current and future climates. The average for each crop type is the mean IRD_j of the representative crops, with the exception of the weighted mean used for cattle forage (Tables 6.8-2 and 6.8-3).

A cumulative distribution function is recommended for each crop type for both climate conditions (Tables 6.8-2 and 6.8-3). Ninety percent of the probability distribution is between the minimum and maximum *IRD* of representative crops within a crop type (e.g., *IRD* for leafy vegetables ranges from 5.11 [spinach] to 5.98 mm/day [celery] for current climate Table 6.8-1). The distribution between the minimum and maximum crop *IRD* is divided into intervals of equal probability (summing to 90 percent), with the exception of cattle forage (see below). The number of intervals is one less than the number of representative crops and the upper limits are crop-specific values of *IRD*, with the exception of leafy vegetables for both climate conditions. Head and leaf lettuce for current climate, and broccoli and cabbage for future climate have equal *IRD* values (Table 6.8-1). Therefore, probabilities were doubled for those intervals with upper limits of 5.46 and 3.86 for current and future climates, respectively. This resulted in two less intervals than the number of representative crops for leafy vegetables for both climates. The probabilities for the two intervals for the distribution of cattle forage were weighted 3:1 for the range between alfalfa and oat hay ($p = 0.675$) versus the range between oat hay and corn silage ($p = 0.225$) (see Section 6. for justification). This results in a higher probability for selection of values that are similar to alfalfa. To account for variation and uncertainty that could result in values beyond the range of crop specific values, intervals of five percent probability each were added to the lower and upper ends of the distributions (Tables 6.8-2 and 6.8-3). The bounds are based on crop water stress calculations and overwatering potentials and are justified in the analysis below.

This parameter is not used in the biosphere volcanic ash exposure scenario; therefore, changes resulting from a volcanic eruption at Yucca Mountain are not considered in this analysis.

Variation and Uncertainty—Variation and uncertainties associated with IRD_j are the same as those associated with *IR* (see Section 6.5.2). Much of the variation and uncertainty in *IR* was accounted for through selection of several representative crops (see Appendix A and Section 6.5). Variation that was not accounted for includes differences between minimum and maximum season length for each crop, and year to year variation in monthly climate variables. Uncertainty not accounted for is due to lack of knowledge about water management practices (i.e., excessive watering or under watering during a growing season).

Within Crop Variation in Season Length— IRD_j is conservative with respect to changes in season length (i.e., there is little response to changes). This is because increases or decreases in *IR* caused by changing the season lengths are offset in IRD_j through division by the number of days in the season. For example, in Section 6.5.2, *IR* was recalculated for celery based on a 32 day increase in the growing season for current climate. This resulted in an increase in *IR* from 1.50 m/year to 1.95 m/year. The concurrent increase in IRD_j was only 0.5 mm/day (6.0 mm/day to 6.5 mm/day). Other crops showed similar or smaller changes in IRD_j in response to changes in season length. Additionally, season lengths were constrained by mean monthly temperatures for the two climates (i.e., temperatures below crop tolerance levels) or by growing two season crops. It was shown in Section 6.5.2 that the use of two season crops encompassed much the variation in *IR* that could be caused by changing growing season lengths. Therefore, variation caused by changes in season lengths is included by the recommended distributions of IRD_j .

Yearly Variation in Climate—Year to year variation in mean monthly climate variables affect IRD_j through ET_o in the calculation of *IR* (see Section 6.5.2). While daily or hourly fluctuations in ET_o can be large, monthly means tend to be conservative from year to year (Section 6.5.2).

Variation in *IR* from yearly variation in mean monthly climate variables was not directly calculated because the data were not available. Variation from the expected monthly average *ET_o* was calculated using air temperature data as a meteorological index representing variation in evaporative demands (Section 6.5.2). Monthly mean, monthly average maximum, and monthly average minimum air temperatures with standard deviations for 26 to 29 years in Amargosa Valley, Nevada were obtained from the Western Regional Climate Center (2002a, 2002b, 2002c, Table 6.5-5). The coefficient of variation ($CV = SD/mean$) showed little yearly variation in the average monthly temperature parameters (Table 6.5-5). Yearly variation ranged from 3 percent to 10 percent depending on the temperature parameter and month (Table 6.5-5). Variation in *IRD_j* among crops within a crop type ranged from 5 percent to 44 percent for current climate and from 8 percent to 28 percent for future climate (Table 6.8-1). Therefore, variation in *IRD_j* that could be caused by yearly variation in mean monthly climate variables is generally encompassed by variation among crops within a crop type.

Uncertainty in Water Management Practices—Uncertainty in the distribution of *IRD_j* due to lack of knowledge about water management practices (i.e., excessive irrigation or under-watering during a growing season) can be bounded similarly to *IR*, by assessing practices that would result in crop yield reductions.

Excessive Irrigation—Problems caused by excessive irrigation are discussed in Section 6.5.2. These include nutrient loss from the root zone through leaching, water loss through percolation below the root zone or runoff, oxygen deficiencies for root growth and microbial activity, denitrification, and infestation by weeds. These processes can result in loss of yield, reduced crop quality, and increased water pumping costs.

In Section 6.5.2 it was established that over watering alfalfa by about 18 percent would result in yield reduction through a variety of mechanisms, including those mentioned above. It is reasonable to conclude that an 18 percent increase in *IRD_j* would have similar effects on other representative crops and pumping costs. To establish appropriate upper bounds for the distributions of *IRD_j* that would include uncertainties associated with over irrigating, maximum values (within a crop type) were increased by 18 percent (Tables 6.8-2 and 6.8-3). Celery, bell peppers, tomatoes, corn, and corn silage were used for current climate. Celery, sweet corn, melons, corn, and corn silage were used for future climate.

Under-watering—Moisture stress occurs if irrigation water does not meet crop water requirements (see Appendix B). The level of moisture stress can vary from minor, where crop leaves wilt during the day but recover at night, to severe where recovery at night is not possible and leaf desiccation occurs. Reductions in both crop yield and quality can occur at various levels of water stress depending on the sensitivity of the crop. For example, grain crops tend to be more tolerant of water stress than potatoes or leafy vegetables (Robins et al. 1967, pp. 635 and 636, and Vittum and Flocker 1967, pp. 676 and 677). It is likely that a farmer or gardener would respond to signs of under-watering by modifying their water management practices to avoid losses in quality and yield.

Water storage capacity of the root zone and crop sensitivity to soil moisture stress were considered for crops with low *IRD* to establish reasonable lower bounds for the distributions (see Appendix E, Section 2.6). The methods used to calculate Irrigation Application (Section 6.7 and

Appendix E, Section 2.5) were modified to reflect under-watering conditions that would likely cause stress. The resulting percent decrease that might be tolerated was calculated (Appendix E, Section 2.6). Soil moisture was allowed to stay at a level that would impose stress for two days following each scheduled irrigation event over a 30-day time period (scheduling of irrigation events differed according to crop requirements). Two days was chosen as a likely time interval that would cause some level of crop stress without causing mortality. The resulting number of days the crop would experience stress and the percent reduction in applied water was determined (Appendix E, Section 2.6). The results of this exercise showed that small percent decreases in irrigation could cause several (non-consecutive) days of water stress in the 30 day time period (Appendix E, Table E-14). Based on this analysis, a 10 percent reduction in IRD_j was selected to establish lower bounds for the distributions.

Spinach, onions, grapes, barley, and alfalfa were chosen for the current climate bounds because these crops had the lowest IRD within their crop type (Table 6.8-1). IRD for each crop was reduced by 10 percent and those values were used as the lower limits of the recommended distributions for each crop type (Table 6.8-2). The calculated minimum values were rounded down to the nearest mm.

Spinach, squash, strawberries, winter wheat, and oats were chosen for the future climate analysis because these crops had the lowest IRD within their crop type (Table 6.8-1). IRD for each crop was reduced by 10 percent and those values were used as the lower limits of the recommended distributions for each crop type (Table 6.8-3). The calculated minimum values were rounded down to the nearest mm.

6.9 OVERWATERING RATE

6.9.1 Use in Biosphere Model

The overwatering rate (OW , m/year) is the amount of irrigation water intentionally applied to soil to leach salts, and the amount of precipitation that percolates below the root zone. It is used in the surface soil submodel to calculate the radionuclide specific (j) leaching removal constant ($\lambda_{i,j}$) (Equation 6.9-1, BSC 2003b, p. 82), which is used in the calculation of radionuclide concentration in soil (Equation 6.6-1). Because soil concentrations are calculated for long-term, equilibrium conditions, one overwatering rate representative of all irrigated plants is used, rather than crop-type specific rates.

$$\lambda_{i,j} = \frac{OW}{d \times \theta \left(1 + \frac{\rho}{\theta} Kd_i\right)} \quad (\text{Eq. 6.9-1})$$

Where

d = the depth of surface soil (m),

θ = the volumetric water content of soil, dimensionless,

ρ = the soil bulk density for surface soil (kg/m^3),

Kd_i = the surface soil solid/liquid partition coefficient for radionuclide i (m^3 liquid/kg solid).

The range of values of Kd_i is quite large (at least one order of magnitude) (Sheppard and Thibault 1990) compared to overwatering rates, which greatly reduces the influence of variation on OW on the leaching rate. Therefore, BDCFs are not sensitive to variation in overwatering. Depth of surface soil (d , m) is either Tillage Depth (T_d , Section 6.10) or Rooting Depth (Z_r , Section 6.12)

6.9.2 Parameter Development

The distribution for OW was either developed from the crop leaching fraction (LF) or from deep percolation (DP) of precipitation below the crop root zone, depending on which of the two values were greatest for a crop (Appendix E, Section 2.2). The leaching requirement (LR) is the fraction of infiltrated water that must pass through the root zone to remove excess salts. It is a function of the salinity of irrigation water and salt tolerance of individual crops (Doorenbos and Pruitt 1977, p. 77). LF is the actual amount of water that must be applied in addition to crop water requirements to meet the LR . It is determined from ET_c , LR , and effective precipitation (Appendix E, Sections 2.3 and 2.4). Deep percolation occurs when precipitation is great enough to cause the soil moisture to reach field capacity and drain below the root zone (Allen et al. 1998, p. 156). It is calculated from storage capacity of the soil, monthly precipitation, and monthly ET_c using soil water balance methods and information on growing season length (see Appendix E, section 2.4 for calculation methods). Deep percolation did not occur for any crops under current climate conditions because of low monthly precipitation and high evaporative demands. Thus, LR was used to develop the OW distribution for current climate. For future climate, enough precipitation occurred during the winter that deep percolation occurred for some two-season and short-season crops. This resulted in use of both deep percolation and LR to develop the distribution for OW for future climate conditions. If DP occurred, but did not meet the leaching requirement, it was accounted for by subtracting it from W_s (seasonal crop water requirement), and LF was used for OW .

The distributions for OW were developed from 26 representative crops and turf grass for current and future climates (Table 6.9-1). Seasonal crop water requirements were needed to calculate both LR and DP (calculation methods and examples are in Appendix E, Sections 2.2.1 through 2.3). Parameter inputs for W_s were average monthly weather data (Section 4.1.5) and growing season lengths for current and future climates (Section 4.1.4). Average monthly weather data was used to calculate ET_o in Appendix C (see Section 6.5 for relationship of ET_o to ET_c and W_s). Growing season lengths were used in Appendices D and E to adjust growth stage lengths and calculate W_s , respectively. Salinity of irrigation water was derived from inputs in Section 4.1.7.

The OW means of representative crops and turf for current and future climate conditions were 0.079 and 0.067 m/year, respectively, (Table 6.9-1).

A cumulative distribution function is recommended for current and future climate OW (Table 6.9-2). Ninety-five percent of the probability distribution is between the minimum and maximum OW of representative crops (e.g., range = 0.009 [oat hay] to 0.233 [strawberries] m/year for current climate). The distribution between the minimum and maximum crop OW is divided into five equal intervals of equal probability (summing to 95 percent, Table 6.9-2). To account for variation and uncertainty beyond the range of crop specific values, an upper bound interval of five-percent probability was added to the upper end of the distributions for both

climate conditions. The upper bounds are 0.275 m/year for current climate and 0.177 m/year for future climate (Table 6.9-2). These bounds are based on excessive irrigation and are justified in the analysis below. Because the low crop specific values for OW are for crops with relatively high salinity tolerance (and therefore low LR and OW), those values are used to bound the low ends of the distributions. Because there is little uncertainty regarding this low bound, addition of an interval of five-percent probability was not required for the lower ends of the OW distributions.

This parameter is not used in the biosphere volcanic ash exposure scenario; therefore, changes resulting from a volcanic eruption at Yucca Mountain are not considered in this analysis.

Variation and Uncertainty - Variation in OW that could arise due to differences in salinity tolerance, water requirements, or growing season lengths among crops is adequately accounted for through use of 26 crops and turf. Selection was based on an evaluation of crops currently grown in southern Nye County, Nevada and eastern Washington, national patterns of food consumption, and variation in the growing season for commonly grown and consumed crops (see Appendix A).

Overwatering rates that are based on LR are dependent on seasonal crop water requirements (W_s , Appendix E, Equations E-5 and E-6). Therefore, variation in W_s caused by differences in minimum and maximum growing season lengths for a crop and yearly variation in climate variables that drive ET_o could potentially influence the distribution of OW .

Uncertainty in the distribution of OW is from lack of knowledge about which crops a farmer will choose to grow and about water management practices (i.e., excessive irrigation during a growing season). Uncertainty regarding crops is accounted for through selection of 26 crops and turf.

Variation in Minimum and Maximum Season Lengths—Ranges in minimum and maximum season lengths for crops within a crop type appear to be considerable, suggesting a potentially large influence on the distribution parameters for irrigation (Section 6.5.2). However, it was shown in Section 6.5.2 that season lengths were constrained by mean monthly temperatures for the two climates (i.e., temperatures below crop tolerance levels) or by growing two-season crops. Thus, potential variation in IR due to minimum and maximum growing season lengths was encompassed by the use of two-season crops and constraints on growing season length caused by temperatures (Section 6.5.2). Therefore, any influence of this variation on the distribution of OW would also be adequately accounted for through the use of two-season crops and constraints on growing season length caused by temperatures.

Yearly Variation in Climate Variables—Climate variables affect OW through the effects of ET_o on IR . Variation caused by mean monthly climate variables was not directly calculated because the information was not available. However, it was shown in Section 6.5.2 that variation in IR caused by differences in crop water-use was greater than that caused by potential yearly variation in climate variables. It is reasonable to suggest that the influence of variation in monthly mean climate variables on the distribution of OW would be accounted for in the variation among crops in IR and salt tolerance. Additionally, for both climates the CV for OW was greater than the CV for temperature data used in Section 6.5.2 (73 percent and 65 percent for current and future

climate, respectively, versus 10 percent for yearly variation in monthly mean temperature). This suggests that the recommended distribution encompasses the variation in OW that could be caused by yearly variation in mean monthly climate variables.

Uncertainty in Water Management Practices—Uncertainty in the distributions of OW due to lack of knowledge about water management practices can be bounded similarly to the distributions for IR (Section 6.5.2) by assessing practices that could result in reductions in crop yield or water waste. Minimum values that were selected for the distributions of OW would not be affected by under watering so only excessive irrigation practices are considered.

Excessive Irrigation—Problems caused by excessive irrigation are discussed in Section 6.5.2. These include loss of nutrients from the root zone through leaching, water loss through percolation below the root zone or runoff, oxygen deficiencies for root growth and microbial activity, denitrification, and infestation by weeds. These processes can result in loss of yield, reduced crop quality, and increased water pumping costs.

In Section 6.5.2 it was established that over watering alfalfa by about 18 percent would result in yield reduction through a variety of mechanisms, including those mentioned above. To establish reasonable upper bounds associated with excessive irrigation, maximum crop specific OW values were increased by 18 percent for both climate conditions. Strawberries and head lettuce were used for current and future climates, respectively. An 18 percent increase in OW for strawberries (0.233 m/year) resulted in an upper bound of 0.275 m/year for current climate. An 18 percent increase in OW for head lettuce (0.150 m/year) resulted in an upper bound of 0.177 m/year for future climate (Table 6.9-2).

6.10 TILLAGE DEPTH

6.10.1 Use in Biosphere Model

Tillage depth (T_d , in units of m) is the depth of the soil layer where mechanical plowing or tilling occurs. Either tillage depth or rooting depth (see Section 6.12) will be used as soil surface depth in the biosphere model. In the soil submodel, soil surface depth is used to calculate the radionuclide leaching removal constant (λ_{li}) (Equation 6.9-1) and to estimate surface soil density (when multiplied by soil bulk density) in the calculation of the saturation activity concentration of radionuclides in surface soil per unit mass (Equation 6.10-1, BSC 2003b, p. 78):

$$Cs_{m,i} = \frac{Cs_i}{\rho \times d} \quad (\text{Eq. 6.10-1})$$

where

- $Cs_{m,i}$ = activity concentration of radionuclide i in surface soil per unit mass (Bq/kg),
- Cs_i = saturation activity concentration of radionuclide i in surface soil per unit area (Bq/m²),
- ρ = bulk density for surface soil (kg/m³),
- d = depth of surface soil.

Soil surface depth is used in a similar manner in the air, carbon-14, and external exposure biosphere submodels. In the biosphere model for the groundwater exposure scenario, radionuclide concentration in the soil is assumed to be at equilibrium (i.e., at saturated conditions that do not change over time or within the surface soil, for a given concentration of radionuclides in irrigation water). Therefore, surface soil depth has no influence on radionuclide concentration at equilibrium for the biosphere groundwater exposure scenario, but it does influence the time it would take to reach equilibrium conditions. For the biosphere volcanic ash exposure scenario, it is assumed that contaminated ash on agricultural fields and gardens is evenly mixed (i.e., diluted) throughout the surface soil. Therefore, deeper tillage depths will result in a decrease in radionuclide concentrations in the surface soil (and in resuspended soil deposited on plants) for the biosphere volcanic ash exposure scenario.

6.10.2 Parameter Development

Tillage is any mechanical manipulation of soil that is performed to prepare seed beds, control weeds, incorporate fertilizers, or mix organic residues into the soil. Conventional tillage for forage crops and vegetables is accomplished using a moldboard plow or chisel plow and is often supplemented by a disc plow. These plows are designed to till to a depth of approximately 25 to 30 cm, which is the recommended range for conventional tillage depths (Lang et al. 1999, p. 3; Granberry et al. 2000, p. 8; Johnson, 1999, Chapter 8, p. 1, see Section 4.1.9 for input information). However, conventional tillage practices can result in high rates of soil erosion, soil compaction, and water runoff. Conservation tillage causes less compaction and protects the soil surface from erosion. Conservation tillage methods are designed to till to depths of approximately 5 to 10 cm and leave at least 30% residue on the soil surface (Brady and Weil, 1999, pp. 579 through 587). A growing percentage of farmed area uses conservation tillage methods (Brady and Weil, 1999, pp. 579 through 587).

Based on this information, a reasonable estimate of 25 cm, and a uniform distribution of tillage depth with a minimum of 5 cm and a maximum of 30 cm is recommended. Tillage depth is constrained at the low end by seeding depth and seedbed preparation requirements. It is unlikely that depths greater than 30 cm would be used due to environmental concerns such as soil loss through erosion and use of herbicides to control weeds. While recent general trends suggest an increase in conservation tillage (Brady and Weil, 1999, pp. 579 – 587) there is no information regarding central tendencies. Therefore, the recommended distribution is reasonable and encompasses uncertainty regarding use of different tillage methods. The same distribution is recommended for both current and future climates because climate change will not influence tillage depth.

Deposition and redistribution of a thin layer of ash on agricultural fields expected from a volcanic eruption at Yucca Mountain (see Section 1) would not cause long-term changes in the methods used to till agricultural fields and gardens; therefore, the distribution described above is recommended for both the biosphere groundwater and volcanic ash exposure scenarios.

6.11 YIELD

6.11.1 Use in Biosphere Model

Yield (Y_j , kg/m²) is a measure of the wet mass per unit area of the edible portion of each crop type. It is used in the calculation of the uptake into foodstuffs of radionuclides deposited on the plant surface via water and dust interception (Eq. 6.3-1). It represents the amount of foodstuffs into which the radionuclides are concentrated. Yield has a negative, linear effect on leaf uptake values, as any increase in yield results in a dilution, or decrease, in the concentration in foodstuffs contributed from leaf uptake.

6.11.2 Parameter Development

Distributions of yield were developed from measurements of commercial crops. The data used were gathered and compiled by the USDA National Agricultural Statistics Service (Section 4.1.8). Data from five years (1995–1999) and up to four states (Arizona, California, Nevada, and Washington) were used (Tables 6.11-1 through 6.11-6). Data from Arizona and California were included because some representative crops are not grown commercially in Nevada and California in sufficient quantities to be reported. Yield is reported per growing season for vegetables, so if more than one crop is grown in a year on the same acreage, production for both crops are reported (USDA 1999b, p. D-4). For example, if a spring and fall crop of carrots are grown on 25 acres, production for carrots would be reported for 50 acres for that year. Information on crop yields from gardens was not used because little such information is available, much of the information that is available is presented in units that are useful for home gardeners (e.g., heads of lettuce per 10-foot row, Antonelli et al. 1998, Table 2) but not for this analysis, and the methods used to develop the data are not defined.

Yields for leafy vegetables (Table 6.11-1), fruits (Table 6.11-3), grain (Table 6.11-5), and cattle forage (Table 6.11-4) were based on all representative crops per group. Yield of corn was not included in the calculations for other vegetables (Table 6.11-2) because commercial yield of corn is measured with the husk on. Squash also was not included because production per state is not reported by the National Agricultural Statistics Service. For cattle forage, yield of oat hay was represented by “other hay” because oat hay was not presented separately by National Agricultural Statistics Service and because many other hays are grown in southern Nevada and eastern Washington (Tables A-2 and A-3). Yield of other hay and corn silage was based on one cutting. For alfalfa yield, if multiple cuttings are made they are included in the total production that is reported. However, National Agricultural Statistics Service does not include information on how many cuttings occur per year. For this analysis, yield of alfalfa was calculated based on four cuttings per year. The number of cuttings used here for alfalfa differs from those used in the calculations of irrigation rates because alfalfa yield data comes from four states with a large variation in growing conditions. Four cuttings was selected to represent the average for all areas, based on information in Orloff and Marble (1997). This is a reasonable average for current and future climate conditions.

The average for each crop type is the mean yield of representative crops, with the exception of the weighted mean used for cattle forage (Table 6.11-7).

A cumulative distribution function is recommended for each crop type (Table 6.11-7). Ninety percent of the probability distribution is between the average minimum and maximum yield of representative crops within a crop type (e.g., yield for leafy vegetables ranges from 1.46 [broccoli] to 7.79 kg/m² [celery], Table 6.11-1). The distribution between the average minimum and maximum yield is divided into intervals of equal probability (summing to 90 percent), with the exception of cattle forage. The number of intervals is one less than the number of representative crops and the upper limits are average crop-specific values of yield (Table 6.11-7). The probabilities for the two intervals for the distribution of cattle forage were weighted 3:1 for the range between alfalfa and oat hay ($p = 0.675$) versus the range between oat hay and corn silage ($p = 0.225$) (see Section 6 for justification). This results in a higher probability for selection of values that are similar to alfalfa. To account for variation and uncertainty that could result in values beyond the range of mean crop specific values, intervals of five percent probability each were added to the lower and upper ends of the distribution. The lowest and highest yield values reported within a crop type over a five year period were selected as the lower and upper bounds of the distributions (Tables 6.11-1 through 6.11-6).

The distributions presented in Table 6.11-7 are recommended for the current and future climates for the following reasons. Most of the uncertainty in yield per crop type is due to crop and variety selection and farming or gardening practices. Farmers and gardeners are likely to select crops and varieties of crops that are most productive for their growing conditions, and distributions of yield for a crop type therefore should not vary much due to climate change. In addition, the distributions were developed using data from a variety of crops and climatic conditions, including arid conditions representative of current climate (e.g., data from Arizona and parts of Nevada and California) and cooler conditions representative of future climates (e.g., data from Washington and parts of Nevada and California).

The distributions for some vegetables and fruits matched well with the limited data available for production from gardens. For example, production of broccoli (10–12 lb per 10- × 2-ft row, or 2.7 kg/m², calculated as production per 10-ft row ÷ [10-ft row length × 2-ft row spacing] × 1 kg/2.2 lb × 10.76 ft²/m²), cabbage (10–15 lb per 10- × 2-ft row, 3.1 kg/m²), and potatoes (20 lb per 10- × 2-ft row, 4.1 kg/m²) in eastern Washington gardens (Antonelli et al. 1998, Table 2) match the distributions based on commercial production (Tables 6.9-1 through 6.9-3). However, values for carrots (12 lb per 10- × 1-ft row, 5.9 kg/m²), tomatoes (30–50 lb per 10- × 3-ft row, 6.5 kg/m²), and onions (10 lb per 10- × 0.5-ft row, 43.5 kg/m²) were higher than commercial yields. Because methods of calculation are not presented, these high garden values are less reliable than those based on yields reported for thousands of acres of commercial farms.

Deposition and redistribution of a thin layer of ash expected from a volcanic eruption at Yucca Mountain (see Section 1) onto agricultural fields and gardens in northern Amargosa Valley would not cause a long-term change in the yield of crops. Therefore, the distributions of yield in Table 6.11-7 are intended for both the biosphere groundwater and volcanic ash exposure scenarios.

6.12 ROOTING DEPTH

6.12.1 Use in Biosphere Model

Mean maximum effective rooting depth (Z_r) is the proportion of maximum rooting depth where approximately 80 to 90 percent of a plant's feeder roots occur. Either tillage depth or rooting depth will be used as soil surface depth in the biosphere model (see Section 6.10). Soil surface depth is used to calculate the radionuclide leaching removal constant (λ_{l1}) (Equation 6.9-1) and to estimate surface soil density (when multiplied by soil bulk density) in the calculation of the saturation activity concentration of radionuclides in surface soil per unit mass (Equation 6.10-1).

In the biosphere model for the groundwater exposure scenario, radionuclide concentration in the soil is assumed to be at equilibrium (i.e., at saturated conditions that do not change over time or within the surface soil, for a given concentration of radionuclides in irrigation water). Therefore, surface soil depth has no influence on radionuclide concentration at equilibrium for the biosphere groundwater exposure scenario, but it does influence the time it would take to reach equilibrium conditions. For the biosphere volcanic ash exposure scenario, it is assumed that contaminated ash on agricultural fields and gardens is evenly mixed (i.e., diluted) throughout the surface soil. Therefore, deeper rooting depths will result in a decrease in radionuclide concentrations in the surface soil (and in resuspended soil deposited on plants) for the volcanic ash exposure scenario.

6.12.2 Parameter Development

Information on rooting depth for 24 of the 26 crops and turf from Allen et al. (1998, Table 22, pp. 163 through 165) (see Section 4.1.11 for input information) was used to develop the distribution for rooting depth. Allen et al. (1998) did not distinguish between depths for leaf lettuce and head lettuce, provided one value for field corn (includes feed corn and corn silage), and one value for oats (includes oat feed and oat hay). This resulted in 24 values for rooting depth calculations.

Allen et al. (1998, Table 22, pp. 163 through 165) present ranges for maximum effective rooting depths (Table 4.1-7). The smaller values for each range are recommended for irrigation scheduling because a large percentage of root biomass and activity occurs in the upper portion of the rooting zone. Effective rooting depth is less than the absolute maximum rooting depth of a mature plant because root density typically decreases near the lower part of the root zone (Jensen et al., 1990, p. 22, Bishop and Beetham, 1989, p. 51). Generally, 80 to 90 percent of a plant's roots occur in the upper 60 to 75 percent of the root zone (Jensen et al. 1990, p. 22). For example, even though maximum rooting depth of sweet corn could be as great as 1.2 m, most of the root activity will occur within 0.8 to 0.9 m. Therefore, the smaller values for rooting depth recommended by Allen et al. (1998, Table 22, pp. 163 through 165) represent general rooting depths that are adequate for this analysis.

The mean Z_r of representative crops was 0.65 (Table 6.12-1).

A cumulative distribution function is recommended for Z_r (Table 6.12-2). Ninety percent of the probability distribution is between the minimum and maximum Z_r of representative crops (range = 0.2 [strawberries] to 1.5 m [winter wheat]). The distribution between the minimum and

maximum crop Z_r is divided into five equal intervals of equal probability (summing to 90 percent, Table 6.12-2). To account for variation and uncertainty beyond the range of crop specific values, intervals of five-percent probability each were added to the lower and upper ends of the distribution. To avoid unreasonably low values that would not likely support a healthy plant, a minimum bound of 0.15 is recommended (Table 6.12-2). The high value of 2.0 m for the range of Z_r reported for alfalfa in Allen et al. (1998 Table 22, p. 165) is recommended as the maximum bound for the distribution (Table 6.12-2). The same distribution is recommended for current and future climates.

Genetic and environmental controls regulate root growth of agricultural crops. Maximum rooting depths can differ among varieties within a species, and among different crop species (Bishop and Beetham 1989, Table 20). Important soil properties that influence root growth include texture, structure, and bulk density (Bishop and Beetham 1989, p. 14 through 17; Jensen et al. 1990, pg. 22). Soil moisture availability, temperature, aeration, and nutrient supply also regulate root growth. Use of several crops and turf accounts for uncertainties associated with choice of crop, and variation associated with differences in rooting depths among crops.

Deposition and redistribution of a thin layer of ash expected from a volcanic eruption at Yucca Mountain (see Section 1) onto agricultural fields and gardens in northern Amargosa Valley would not cause a change in growth characteristics of crops (i.e., root to shoot ratios). Therefore, the recommended distribution of rooting depth is intended for both the biosphere groundwater and volcanic ash exposure scenarios.

Table 6-1. Representative Crops

Crop Type	Crop Type
Representative Crops^a	Representative Crops
Leafy Vegetables	Fruits
Broccoli	Apples
Cabbage	Grapes
Cauliflower	Melons
Celery	Strawberries
Head Lettuce	Tomatoes
Leaf Lettuce	
Spinach	Grains
Other Vegetables	Barley
Bell Peppers	Feed Corn
Carrots	Oats
Cucumbers	Wheat
Onions	Cattle Forage
Potatoes	Alfalfa
Squash	Corn silage
Sweet Corn	Oat hay
	Home Irrigation
	Current – Bermudagrass
	Future – Fescue

Notes: ^a See Appendix A for information on selection of representative crops.

Table 6.1-1. Dry Biomass (kg/m²)

Crop Type					Crop Type				
Crop	Yield^a	Ratio^b	HI^c	Biomass^d	Crop	Yield^a	Ratio^b	HI^c	Biomass^d
Leafy Vegetables					Fruits				
Broccoli	1.46	0.093	-	0.14	Grapes ^e	1.51	0.194	0.45	0.65
Cabbage	3.83	0.078	-	0.30	Melons	2.92	0.102	0.50	0.60
Cauliflower	2.01	0.081	-	0.16	Strawberries	3.63	0.084	0.45	0.68
Celery	7.79	0.054	-	0.42	Tomatoes	3.0	0.062	0.33	0.56
Head Lettuce	3.25	0.041	-	0.13	Average				0.62
Leaf Lettuce	2.98	0.060	-	0.18	SD ^f				0.05
Spinach	1.78	0.084	-	0.15					
Average				0.21	Grains				
SD ^f				0.11	Barley	0.44	0.906	0.54	0.74
					Corn	1.10	0.896	0.50	1.97
Other Vegetables					Oats	0.28	0.918	0.42	0.61
Bell Peppers	3.37	0.078	0.60	0.44	Winter wheat	0.54	0.891	0.40	1.20
Carrots	3.64	0.122	1.12	0.40	Average				1.13
Cucumbers	3.56	0.035	0.27	0.46	SD ^f				0.61
Onions	4.92	0.103	1.25	0.41	Cattle Forage				
Potatoes	5.15	0.08	0.95	0.43	Alfalfa hay	1.02	0.227	-	0.23
Average				0.43	Corn silage	5.78	0.238	-	1.38
SD ^f				0.02	Oat hay	1.87	0.182	-	0.34
					Average				0.65
					SD ^f				0.63

Notes: Source: USDA 2002a

^a Wet yield (kg/m²), See Tables 6.11-1 through 6.11-6 .

^b Dry:wet ratio, See Table 6.2-1.

^c Harvest Index (dry yield to dry biomass, see Section 4.1.3. A dash means no index was required, optimal harvest index values from Neitsch et al. 2002, Table A-8, pp. 381 through 384)

^d kg/m², calculated as (yield x dry:wet ratio) ÷ harvest index.

^e HI for strawberries was used for grapes.

^f Standard deviation calculated using the STDEV function of EXCEL.

Table 6.1-2. Averages and Cumulative Distributions for Dry Biomass (kg/m²)

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability
Leafy Vegetables	0.21	0.10	0.00	Fruits	0.62	0.10	0.00
		0.13	0.05			0.56	0.05
		0.14	0.20			0.60	0.35
		0.15	0.35			0.65	0.65
		0.16	0.50			0.68	0.95
		0.18	0.65			1.30	1.00
		0.30	0.80				
		0.42	0.95				
Other Vegetables	0.43	0.30	0.00	Grains	1.13	0.50	0.00
		0.40	0.05			0.61	0.05
		0.41	0.28			0.74	0.35
		0.43	0.51			1.20	0.65
		0.44	0.73			1.97	0.95
		0.46	0.95			2.20	1.00
		0.60	1.00				
			Cattle Forage^c	0.48	0.10	0.00	
					0.23	0.05	
					0.34	0.73	
					1.38	0.95	
					1.50	1.00	

Notes: ^a Mean dry biomass for a crop type from Table 6.1-1, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as $(3 \times 0.23 \text{ [dry biomass for alfalfa]} + 1 \times 1.38 \text{ [dry biomass for corn silage]} + 1 \times 0.34 \text{ [dry biomass for oat hay]}) / 5 = 0.48$.

^b Limits determined from crop specific biomass (see Table 6.1-1).

^c For 90 percent of the distribution between the minimum and maximum crop biomass, the probabilities for the two cattle forage intervals were weighted 3:1 for the range between oat hay to alfalfa ($p = 0.68$) and alfalfa to corn silage ($p = 0.22$).

Table 6.2-1. Dry to Wet Ratios^a

Crop Type Crop	NDB No. ^b	% Water	Dry:Wet Ratio ^c	Crop Type Crop	NDB No. ^b	% Water	Dry:Wet Ratio ^c
Leafy Vegetables				Fruits			
Broccoli	11090	90.69	0.093	Apples	09004	84.46	0.155
Cabbage	11109	92.15	0.078	Grapes	09132	80.56	0.194
Cauliflower	11135	91.91	0.081	Melons	09181	89.78	0.102
Celery	11143	94.64	0.054	Strawberries	09316	91.57	0.084
Head Lettuce	11252	95.89	0.041	Tomatoes	11529	93.76	0.062
Leaf Lettuce	11253	94.00	0.060	Average			0.120
Spinach	11457	91.58	0.084	SD ^d			0.054
Average			0.070				
SD ^d			0.019	Grains			
Other Vegetables				Barley	20004	9.44	0.906
Bell peppers	11333	92.19	0.078	Corn	20014	10.37	0.896
Carrots	11124	87.79	0.122	Oats	20038	8.22	0.918
Cucumbers	11206	96.49	0.035	Wheat flour	20076	10.94	0.891
Onions	11282	89.68	0.103	Average			0.903
Potatoes	11352	92.02	0.080	SD ^d			0.012
Squash	11641	93.68	0.063	Cattle Forage			
Corn	11167	75.96	0.240	Alfalfa hay ^e			0.227
Average			0.103	Corn silage ^e			0.238
SD ^d			0.067	Oat hay ^e			0.182
				Average			0.216
				SD ^d			0.030

- Notes: ^a Source for vegetables, fruits, and grains: USDA (2002a).
^b USDA (2002a) nutrient database number (NDB) for a foodstuff.
^c Calculated as 1- (% water ÷ 100) for most vegetables, fruits, and grains.
^d Standard deviation calculated using the STDEV function of EXCEL.
^e Source: Till and Meyer (1983, Table 5.16, with oat hay = forage).

Table 6.2-2. Averages and Cumulative Distribution Functions for Dry to Wet Ratios

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability
Leafy Vegetables	0.070	0.041	0.00	Fruits	0.120	0.062	0.00
		0.054	0.17			0.084	0.25
		0.060	0.33			0.102	0.50
		0.078	0.50			0.155	0.75
		0.081	0.67			0.194	1.00
		0.084	0.83				
		0.093	1.00				
Other Vegetables	0.103	0.035	0.00	Grains	0.903	0.891	0.00
		0.063	0.17			0.896	0.33
		0.078	0.33	Cattle Forage^c	0.220	0.906	0.67
		0.080	0.50			0.918	1.00
		0.103	0.67			0.182	0.00
		0.122	0.83			0.227	0.75
		0.240	1.00			0.238	1.00

Notes: ^a Mean dry to wet ratio for a crop type from Table 6.2-1, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as (3 x 0.227 [dry to wet ratio for alfalfa] + 1 x 0.238 [dry to wet ratio for corn silage] + 1 x 0.182 [dry to wet ratio for oat hay]) / 5 = 0.220.

^b Limits determined from crop specific dry to wet ratios (see Table 6.2-1).

^c The probabilities for the two cattle forage intervals were weighted 3:1 for the range between oat hay and alfalfa (p = 0.75) versus the range between alfalfa and corn silage (p = 0.25).

Table 6.3-1. Recommended Distributions for Fraction of Overhead Irrigation

Crop Type	Type of Distribution	Average	Standard Deviation	Minimum	Maximum
Leafy Vegetables	Normal	0.75	0.1	0.49	1.0
Other Vegetables	Normal	0.75	0.1	0.49	1.0
Fruits	Normal	0.50	0.1	0.24	1.0
Grains	Normal	0.90	0.05	0.77	1.0
Cattle Forage	Normal	0.90	0.05	0.77	1.0

Table 6.4-1. Growing Time^a (days)

Crop Type	Current Climate	Future Climate	Crop Type	Current Climate	Future Climate
Crop			Crop		
Leafy Vegetables			Fruits		
Broccoli	80	83	Apples	240	166
Cabbage	85	75	Grapes	183	105
Cauliflower	80	63	Melons	100	103
Celery	125	110	Strawberries	205	64
Head Lettuce	60	78	Tomatoes	80	88
Leaf Lettuce	60	58	Average	161	105
Spinach	50	55	Recommended ^b	160	105
Average	77	75			
Recommended ^b	75	75	Grains		
Other Vegetables			Barley	243	91
Bell peppers	78	100	Corn	154	178
Carrots	75	80	Oats	160	141
Cucumbers	60	68	Winter wheat	243	334
Onions	110	155	Average	200	186
Potatoes	110	115	Recommended ^b	200	185
Squash	58	65	Cattle Forage		
Sweet corn	82	105	Alfalfa hay	56	70
Average	82	98	Corn silage	93	137
Recommended ^b	80	100	Oat hay	75	57
			Average	75	88
			Recommended ^b	75	90

Notes: ^a Midpoint of season length, from Tables D-1 (current climate) and D-2 (future climate), except alfalfa, which is calculated as the average of all cutting.

^b Recommended values are the average per crop type, rounded to the nearest number divisible by five.

Table 6.5-1. Average Annual Irrigation Rates^a (*IR*, m/year) for 26 Crops and Turf Grass for Upper Bound Monsoon and Lower Bound Future Climates

Crop	Upper Bound Monsoon Climate	Lower Bound Future Climate	Crop	Upper Bound Monsoon Climate	Lower Bound Future Climate
Alfalfa	1.07	1.36	Head lettuce	0.36	1.09
Apples	1.00	1.18	Lettuce	0.37	0.80
Barley	0.54	0.56	Melons	0.29	0.76
Bell Peppers	0.35	0.80	Oat feed	0.34	0.92
Broccoli	0.48	1.11	Oat hay	0.26	0.39
Cabbage	0.52	1.05	Onions	0.90	1.05
Carrots	0.55	1.29	Potatoes	0.51	0.90
Cauliflower	0.47	0.80	Spinach	0.27	0.66
Celery	0.85	0.86	Squash	0.15	0.43
Feed Corn	0.44	1.15	Strawberries	0.81	0.39
Corn silage	0.31	1.08	Sweet corn	0.46	0.88
Cucumbers	0.16	0.51	Tomatoes	0.32	0.74
Grapes	0.52	0.58	Turf Grass	1.05	1.26
			Winter Wheat	0.57	1.22
			Average	0.52	0.88
			SD ^b	0.26	0.29
			CV ^c	0.51	0.32

Notes: ^aIrrigation rates from Tables E-6 and E-7 for upper bound monsoon and lower bound future climates, respectively. See Appendix E for calculation methods and examples.

^bStandard deviation calculated using the STDEV function of EXCEL.

^cCoefficient of variation (SD ÷ Average)

Table 6.5-2. Average Annual Irrigation Rates^a (*IR*, m/year) for 26 Crops and Turf Grass for Current and Future Climates

Crop	Current Climate	Future Climate	Crop	Current Climate	Future Climate
Alfalfa	1.94	0.83	Head lettuce	0.66	0.63
Apples	1.82	0.73	Lettuce	0.66	0.46
Barley	0.84	0.31	Melons	0.84	0.49
Bell Peppers	0.72	0.42	Oat feed	0.57	0.55
Broccoli	0.83	0.64	Oat hay	0.46	0.21
Cabbage	0.92	0.58	Onions	1.33	0.54
Carrots	1.00	0.71	Potatoes	0.84	0.47
Cauliflower	0.83	0.44	Spinach	0.51	0.37
Celery	1.50	0.46	Squash	0.40	0.18
Feed Corn	1.18	0.73	Strawberries	1.43	0.16
Corn silage	0.83	0.69	Sweet corn	0.67	0.52
Cucumbers	0.50	0.21	Tomatoes	0.69	0.38
Grapes	0.98	0.36	Turf Grass	1.61	0.83
			Winter Wheat	0.94	0.67
			Average	0.94	0.50
			SD ^b	0.41	0.19
			CV ^c	0.44	0.38

Notes: ^aIrrigation rates from Tables E-5 and E-8 for current and future climates, respectively. See Appendix E for calculation methods and examples.

^bStandard deviation calculated using the STDEV function of EXCEL.

^cCoefficient of variation (SD ÷ Average)

Table 6.5-3. Averages and Normal Distributions for Long-Term Average Annual Irrigation Rates (*IR* m/year)

	Average^a	Standard Error	Minimum	Maximum
Current Climate	0.94	0.08	0.73	1.15
Future Climate	0.50	0.04	0.40	0.60

Notes: ^aMean *IR* of 26 representative crops and turf calculated from Table 6.5-2

Table 6.5-4. Averages and Cumulative Distributions for Annual Average Irrigation Rates (*IR* m/year) for Current and Future Climates

	Average^a	Upper Limit of Interval	Cumulative Probability		Average^a	Upper Limit of Interval	Cumulative Probability
Current Climate	0.94	0.33	0.00	Future Climate	0.50	0.14	0.00
		0.40	0.05			0.16	0.05
		0.66	0.23			0.36	0.23
		0.83	0.41			0.46	0.41
		0.92	0.59			0.54	0.59
		1.33	0.77			0.69	0.77
		1.94	0.95			0.83	0.95
		2.29	1.00			0.98	1.00

Notes: ^aMean *IR* of 26 representative crops and turf calculated from Table 6.5-2.

Table 6.5-5. Monthly Mean Air Temperatures (°F) for Amargosa, Nevada

	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Mean Temperature ^a	45.9	50.2	55.5	62.3	71.7	80.0	85.9	84.9	77.2	66.0	52.9	45.4
SD ^b	2.6	3.3	3.0	3.9	3.4	3.0	2.3	2.2	2.7	3.6	3.1	3.0
CV ^c	0.06	0.07	0.05	0.06	0.05	0.04	0.03	0.03	0.03	0.05	0.06	0.07
Years ^d	27.0	29.0	29.0	29.0	28.0	28.0	28.0	27.0	27.0	26.0	26.0	28.0
Maximum Temperature ^a	60.5	65.4	71.3	79.3	88.8	97.5	103.2	102.0	95.0	83.8	69.3	60.9
SD ^b	3.9	4.8	4.8	4.0	4.8	4.0	3.2	2.6	2.9	3.4	4.4	4.4
CV ^c	0.06	0.07	0.07	0.05	0.05	0.04	0.03	0.03	0.03	0.04	0.06	0.07
Years ^d	27.0	29.0	29.0	29.0	29.0	28.0	28.0	28.0	27.0	27.0	26.0	28.0
Minimum Temperature ^a	31.4	35.0	39.6	45.3	54.6	62.4	68.6	67.8	59.4	48.2	36.5	30.0
SD ^b	2.8	3.1	2.7	3.5	3.4	3.2	2.6	2.5	3.2	3.6	3.0	2.9
CV ^c	0.09	0.09	0.07	0.08	0.06	0.05	0.04	0.04	0.05	0.07	0.08	0.10
Years ^d	27.0	29.0	29.0	29.0	28.0	28.0	28.0	27.0	27.0	26.0	26.0	28.0

Notes: ^a Source: Western Regional Climate Center (2002a, 2002b, 2002c)

^b Standard deviation

^c Coefficient of variation (CV = SD/mean)

^d Number of years that data were collected

Table 6.7-1. Irrigation Application^a (I_A , mm)

Crop Type Crop	Current Climate	Future Climate	Crop Type Crop	Current Climate	Future Climate
Leafy Vegetables			Fruits		
Broccoli	22.0	19.3	Apples	49.2	54.4
Cabbage	23.6	26.1	Grapes	48.4	43.2
Cauliflower	20.8	22.0	Melons	35.5	34.6
Celery	8.4	8.0	Strawberries	6.0	7.3
Head Lettuce	10.9	9.0	Tomatoes	30.2	31.4
Leaf Lettuce	10.0	10.1	Average	33.9	34.2
Spinach	7.4	7.8	SD ^b	17.6	17.5
Average	14.7	14.6	CV ^c	0.52	0.51
SD ^b	7.1	7.6			
CV ^c	0.48	0.5			
Other Vegetables			Grains		
Bell peppers	19.7	17.7	Barley	48.7	66.7
Carrots	21.2	20.1	Corn	50.3	32.2
Cucumbers	34.9	37.2	Oats	50.1	46.2
Onions	9.0	11.3	Winter wheat	77.9	59.9
Potatoes	18.7	14.4	Average	56.8	51.3
Squash	32.9	34.1	SD	14.1	15.3
Sweet corn	41.2	40.3	CV	0.25	0.30
Average	25.4	25.0			
SD ^b	11.3	11.8	Cattle Forage		
CV ^c	0.44	0.5	Alfalfa hay	57.5	52.5
			Corn silage	60.2	61.9
			Oat hay	56.5	48.3
			Average	58.1	54.2
			SD ^b	1.9	7.0
			CV ^c	0.03	0.1

Notes: ^aIrrigation application amounts from Tables E-13 and E-14 for current and future climates, respectively. See Appendix E for calculation methods and examples.

^bStandard deviation calculated using the STDEV function of EXCEL.

^cCoefficient of variation (SD ÷ Average).

Table 6.7-2. Averages and Cumulative Distributions for Irrigation Application (I_A , mm) for Current Climate

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability		
Leafy Vegetables	14.7	6.0	0.00	Fruits	33.9	5.0	0.00		
		7.4	0.05			6.0	0.05		
		8.4	0.20			30.2	0.28		
		10.0	0.35			35.5	0.51		
		10.9	0.50			48.4	0.72		
		20.8	0.65			49.2	0.95		
		22.0	0.80			58.1	1.00		
		23.6	0.95						
Other Vegetables	25.4	27.8	1.00	Grains	56.8	43.0	0.00		
						48.7	0.05		
				8.0	0.00			50.1	0.35
				9.0	0.05			50.3	0.65
				18.7	0.20			77.9	0.95
				19.7	0.35			91.9	1.00
				21.2	0.50				
				32.9	0.65	Cattle Forage^c	57.8	50.0	0.00
				34.9	0.80			56.5	0.05
				41.2	0.95			57.5	0.72
		48.6	1.00	60.2	0.95				
						71.0	1.00		

Notes: ^a Mean I_A for a crop type from Table 6.7-1, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as $(3 \times 57.5 [I_A \text{ for alfalfa}] + 1 \times 60.2 [I_A \text{ for corn silage}] + 1 \times 56.5 [I_A \text{ for oat hay}]) / 5 = 57.8$.

^b Limits determined from crop specific I_A (see Table 6.7-1).

^c For 90% of the distribution between the minimum and maximum crop specific I_A , the probabilities for the two cattle forage intervals were weighted 3:1 for the range between oat hay to alfalfa ($p = 0.68$) and alfalfa to corn silage ($p = 0.22$).

Table 6.7-3. Averages and Cumulative Distributions for Irrigation Application (I_A , mm) for Future Climate

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	
Leafy Vegetables	14.6	7.0	0.00	Fruits	34.2	6.0	0.00	
		7.8	0.05			7.3	0.05	
		8.0	0.20			31.4	0.28	
		9.0	0.35			34.6	0.51	
		10.1	0.50			43.2	0.72	
		19.3	0.65			54.4	0.95	
		22.0	0.80			64.2	1.00	
		26.1	0.95					
Other Vegetables	25.0	30.8	1.00	Grains	51.3	28.0	0.00	
						32.2	0.05	
		10.0	0.00			46.2	0.35	
		11.3	0.05			59.9	0.65	
		14.4	0.20			66.7	0.95	
		17.7	0.35			78.7	1.00	
		20.1	0.50					
		34.1	0.65	Cattle Forage^c		53.5	43.0	0.00
		37.2	0.80			48.3	0.05	
		40.3	0.95			52.5	0.73	
47.6	1.00	61.9	0.95					
				73.0	1.00			

Notes: ^a Mean I_A for a crop type from Table 6.7-1, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as $(3 \times 52.5 [I_A \text{ for alfalfa}] + 1 \times 61.9 [I_A \text{ for corn silage}] + 1 \times 48.3 [I_A \text{ for oat hay}]) / 5 = 53.5$.

^b Limits determined from crop specific I_A (see Table 6.7-1).

^c For 90% of the distribution between the minimum and maximum crop specific I_A , the probabilities for the two cattle forage intervals were weighted 3:1 for the range between corn silage to oat hay ($p = 0.22$) and oat hay to alfalfa ($p = 0.68$).

Table 6.8-1. Daily irrigation rate^a (IRD_j , mm/day)

Crop Type Crop	Current Climate	Future Climate	Crop Type Crop	Current Climate	Future Climate
Leafy Vegetables			Fruits		
Broccoli	5.19	3.86	Apples	7.56	4.38
Cabbage	5.38	3.86	Grapes	5.38	3.48
Cauliflower	5.21	3.51	Melons	8.35	4.79
Celery	5.98	4.18	Strawberries	7.00	2.51
Head Lettuce	5.46	4.02	Tomatoes	8.60	4.33
Leaf Lettuce	5.46	3.92	Average	7.38	3.90
Spinach	5.11	3.34	SD ^b	1.28	0.91
Average	5.40	3.81	CV ^c	0.17	0.23
SD ^b	0.29	0.29	Grains		
CV ^c	0.05	0.08	Barley	3.44	3.42
Other Vegetables			Corn	7.67	4.11
Bell peppers	9.18	4.16	Oats	3.58	3.93
Carrots	6.65	4.43	Winter wheat	3.86	1.99
Cucumbers	8.32	3.08	Average	4.64	3.36
Onions	6.05	3.48	SD	2.03	0.96
Potatoes	7.62	4.08	CV	0.44	0.28
Squash	6.85	2.73	Cattle Forage		
Sweet corn	8.19	4.95	Alfalfa hay	5.84	4.01
Average	7.55	3.84	Corn silage	9.00	5.03
SD ^b	1.10	0.78	Oat hay	6.18	3.64
CV ^c	0.14	0.20	Average	7.00	4.23
			SD ^b	1.74	0.59
			CV ^c	0.25	0.14

Notes: ^aDaily irrigation rates derived from seasonal net irrigation requirements (Tables E-5 and E-8) divided by the number of days in the growing season (mid season length in Tables D-1 and D-2).

^bStandard deviation

^cCoefficient of variation = SD/mean.

Table 6.8-2. Recommended Cumulative Distributions for Daily Irrigation Rate (IRD_j mm/day) for Current Climate

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	
Leafy Vegetables	5.40	4.00	0.00	Fruits	7.38	4.00	0.00	
		5.11	0.05			5.38	0.05	
		5.19	0.20			7.00	0.28	
		5.21	0.35			7.56	0.51	
		5.38	0.50			8.35	0.72	
		5.46	0.80			8.60	0.95	
		5.98	0.95			10.15	1.00	
Other Vegetables	7.55	5.00	0.00	Grains	4.64	3.00	0.00	
			6.05			0.05	3.44	0.05
			6.65	0.20	3.58	0.35		
			6.85	0.35	3.86	0.65		
			7.62	0.50	7.67	0.95		
			8.19	0.65	9.05	1.00		
			8.32	0.80	Cattle Forage ^c	6.54	5.00	0.00
			9.18	0.95			5.84	0.05
			10.83	1.00			6.18	0.73
							9.00	0.95
				10.62	1.00			

Notes: ^a Mean IRD_j for a crop type from Table 6.7-1, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as $(3 \times 5.84 [IRD \text{ for alfalfa}] + 1 \times 9.00 [IRD \text{ for corn silage}] + 1 \times 6.18 [IRD \text{ for oat hay}]) / 5 = 6.54$.

^b Limits determined from crop specific IRD (see Table 6.8-1).

^c For 90 percent of the distribution between the minimum and maximum crop specific IRD_j values, the probabilities for the two intervals for the distribution of cattle forage were weighted 3:1 for the range between alfalfa and oat hay ($p = 0.68$) versus the range between oat hay and corn silage ($p = 0.22$).

Table 6.8-3. Averages and Cumulative Distributions for Daily Irrigation Rate (IRD_j mm/day) for Future Climate

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability
Leafy Vegetables	3.81	3.00	0.00	Fruits	3.90	2.00	0.00
		3.34	0.05			2.51	0.05
		3.51	0.20			3.48	0.28
		3.86	0.50			4.33	0.51
		3.92	0.65			4.38	0.72
		4.02	0.80			4.79	0.95
		4.18	0.95			5.65	1.00
Other Vegetables	3.84	2.00	0.00	Grains	3.36	1.00	0.00
		2.73	0.05			1.99	0.05
		3.08	0.20			3.42	0.35
		3.48	0.35	3.93	0.65		
		4.08	0.50	4.11	0.95		
		4.16	0.65	4.85	1.00		
		4.43	0.80	Cattle Forage^c	4.14	3.00	0.00
		4.95	0.95			3.64	0.05
		5.84	1.00			4.01	0.73
						5.03	0.95
				5.94	1.00		

Notes: ^a Mean IRD_j for a crop type from Table 6.7-1, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as $(3 \times 4.01 [IRD \text{ for alfalfa}] + 1 \times 5.03 [IRD \text{ for corn silage}] + 1 \times 3.64 [IRD \text{ for oat hay}]) / 5 = 4.14$.

^b Limits determined from crop specific IRD (see Table 6.8-1).

^c For 90 percent of the distribution between the minimum and maximum crop specific IRD values, the probabilities for the two intervals for the distribution of cattle forage were weighted 3:1 for the range between oat hay and alfalfa ($p = 0.68$) versus the range between corn silage and oat hay ($p = 0.22$).

Table 6.9-1. Average Overwatering Rates^a (OW, m/year) for 26 Crops and Turf Grass for Current and Future Climates

Crop	Current Climate	Future Climate	Crop	Current Climate	Future Climate
Alfalfa	0.149	0.064	Head lettuce	0.080	0.150
Apples	0.166	0.066	Lettuce	0.080	0.142
Barley	0.015	0.006	Melons	0.058	0.034
Bell Peppers	0.075	0.082	Oat feed	0.014	0.014
Broccoli	0.045	0.098	Oat hay	0.009	0.004
Cabbage	0.079	0.089	Onions	0.177	0.085
Carrots	0.162	0.134	Potatoes	0.076	0.072
Cauliflower	0.045	0.095	Spinach	0.039	0.121
Celery	0.128	0.104	Squash	0.024	0.044
Feed Corn	0.101	0.063	Strawberries	0.233	0.125
Corn silage	0.071	0.059	Sweet corn	0.061	0.047
Cucumbers	0.030	0.020	Tomatoes	0.042	0.030
Grapes	0.103	0.038	Turf Grass	0.035	0.018
			Winter Wheat	0.023	0.016
			Average	0.079	0.067
			SD ^b	0.058	0.044
			CV ^c	0.734	0.647

Notes: ^a Overwatering rates from Tables E-5 and E-8 for current and future climates, respectively. See Appendix E for calculation methods and examples.
^b Standard Deviation
^c Coefficient of variation = SD/mean.

Table 6.9-2. Averages and Cumulative Distributions for Overwatering Rates (OW m/year) for Current and Future Climates

	Average ^a	Upper Limit of Interval	Cumulative Probability		Average ^a	Upper Limit of Interval	Cumulative Probability
Current Climate	0.079	0.009	0.00	Future Climate	0.067	0.004	0.00
		0.030	0.19			0.020	0.19
		0.045	0.38			0.047	0.38
		0.076	0.57			0.072	0.57
		0.128	0.76			0.104	0.76
		0.233	0.95			0.150	0.95
		0.275	1.00			0.177	1.00

Notes: ^a Mean OW of 26 representative crops and turf calculated from Table 6.9-1.

Table 6.11-1. Commercial Yield of Leafy Vegetables

Leafy Vegetable	State	Area Harvested (1,000 Acres) ^a					Production (1,000 Cwt) ^a					Yield (kg/m ²) ^b					Average Per Crop	
		1995	1996	1997	1998	1999	1995	1996	1997	1998	1999	1995	1996	1997	1998	1999		5-Yr Avg
Broccoli	AZ	8.6	10.0	11.0	12.3	17.1	946	960	1,357	1,538	3,420	1.23	1.08	1.38	1.40	2.24	1.47	
	CA	115.0	122.0	119.0	121.0	130.0	14,375	14,640	15,470	15,730	18,200	1.40	1.34	1.46	1.46	1.57	1.45	1.46
Cabbage	CA	10.0	10.0	13.8	14.0	12.5	3,700	3,500	4,692	4,620	4,000	4.15	3.92	3.81	3.70	3.59	3.83	3.83
Cauliflower	AZ	4.5	4.4	3.9	3.4	3.9	788	770	780	714	1,170	1.96	1.96	2.24	2.35	3.36	2.38	
	CA	40.7	41.5	37.5	39.0	41.0	5,088	6,310	5,790	5,850	6,355	1.40	1.70	1.73	1.68	1.74	1.65	2.01
Celery	CA	24.5	24.5	24.0	24.5	25.0	17,150	17,150	16,680	16,666	17,500	7.85	7.85	7.79	7.62	7.85	7.79	7.79
Head Lettuce	AZ	44.1	59.4	54.8	55.0	46.6	17,661	16,713	17,345	18,658	15,546	4.49	3.15	3.55	3.80	3.74	3.75	
	CA	144.0	150.5	141.0	135.0	140.0	42,480	43,645	49,350	42,525	53,200	3.31	3.25	3.92	3.53	4.26	3.65	
	WA	1.3	1.0	0.9	0.9	0.8	273	220	180	189	168	2.35	2.47	2.24	2.35	2.35	2.35	3.25
Leaf Lettuce	AZ	3.2	4.3	5.7	7.30	5.60	1,440	1,441	1,568	1,971	1,512	5.04	3.76	3.08	3.03	3.03	3.59	
	CA	35.0	36.0	42.0	38.00	43.00	7,350	7,560	8,660	8,170	9,460	2.35	2.35	2.31	2.41	2.47	2.38	2.98
Spinach	CA	6.5	9.0	15.2	15.0	17.0	1,040	1,350	2,660	2,400	2,550	1.79	1.68	1.96	1.79	1.68	1.78	1.78
																Average for all crops	3.30	
																Standard Deviation ^c	2.16	

Notes: ^a Source: 1995 data from USDA (1998a, Tables 4-14, 4-15, 4-21, 4-22, 4-33, 4-35, and 4-54), 1996 data from USDA (1999c, Tables 4-14, 4-15, 4-21, 4-22, 4-33, 4-35, and 4-54), 1997 data from USDA (2000a, Tables 4-14, 4-15, 4-21, 4-22, 4-33, 4-35, and 4-54), 1998 and 1999 data from USDA (2001a, Tables 4-14, 4-15, 4-21, 4-22, 4-34, 4-36, and 4-55).

^b Calculated as [1,000 Cwt Produced x 100 lbs/Cwt x 0.4536 kg/lb] / [1,000 Acres Harvested x 4,047 m²/acre] = kg/m².

^c Calculated using the STDEV function of EXCEL.

Table 6.11-2. Commercial Yield of Other Vegetables

Vegetable	State	Area Harvested (1,000 Acres) ^a					Production (1,000 Cwt) ^a					Yield (kg/m ²) ^b					Average Per Crop	
		1995	1996	1997	1998	1999	1995	1996	1997	1998	1999	1995	1996	1997	1998	1999		5-Yr Avg
Carrots – Fresh	AZ	1.9	2.4	2.5	2.5	2.5	523	624	663	625	625	3.09	2.91	2.97	2.80	2.80	2.92	
	CA	55.0	85.7	83.2	86.5	87.0	15,950	25,710	29,998	28,545	25,665	3.25	3.36	4.04	3.70	3.31	3.53	
	WA	1.9	2.5	2.8	3.0	2.6	760	1,050	1,120	1,140	1,040	4.48	4.71	4.48	4.26	4.48	4.48	3.64
Cucumber	CA	5.2	6.0	6.3	6.0	6.5	1,638	1,980	1,985	1,920	2,015	3.53	3.70	3.53	3.59	3.47	3.56	3.56
Onions – Summer	NV	1.9	1.9	1.7	2.1	2.8	874	1,102	918	924	1,568	5.16	6.50	6.05	4.93	6.28	5.78	
	WA	1.0	0.7	0.9	0.85	0.8	400	266	333	255	288	4.48	4.26	4.15	3.36	4.03	4.06	4.92
Bell Peppers	CA	24.0	25.5	21.0	22.0	22.5	6,960	7,650	6,300	6,270	7,425	3.25	3.36	3.36	3.19	3.70	3.37	3.37
Potatoes – Fall	CA	13.0	11.5	10.5	10.3	9.0	5,330	4,600	4,200	3,708	4,005	4.60	4.48	4.48	4.03	4.99	4.52	
	NV	7.6	7.9	6.9	7.0	6.5	2,774	3,160	2,967	2,800	2,860	4.09	4.48	4.82	4.48	4.93	4.56	
	WA	147.0	161.0	152.0	165.0	170.0	80,850	94,990	88,160	93,225	95,200	6.16	6.61	6.50	6.33	6.28	6.38	5.15
																Average for all crops		4.13
																Standard Deviation ^c		0.84

Notes: ^a Source: 1995 data from USDA (1998a, Tables 4-18, 4-26, 4-40, 4-43, and 4-47), 1996 data from USDA (1999c, Tables 4-18, 4-26, 4-40, 4-43, and 4-47), 1997 data from USDA (2000a, Tables 4-18, 4-26, 4-40, 4-43, and 4-47), 1998 and 1999 data from USDA (2001a, Tables 4-18, 4-26, 4-41, 4-44, and 4-48). For all years, onions = summer non-storage.

^b Calculated as [1,000 Cwt Produced x 100 lbs/Cwt x 0.4536 kg/lb] / [1,000 acres Harvested x 4,047 m²/acre] = kg/m².

^c Calculated using the STDEV function of EXCEL.

Table 6.11-3. Commercial Yield of Fruit

Fruits	State	Area Harvested (1,000 Acres) ^a					Production (1,000 Cwt) ^a					Yield (kg/m ²) ^b					Average Per Crop	
		1995	1996	1997	1998	1999	1995	1996	1997	1998	1999	1995	1996	1997	1998	1999		5-Yr Avg
Cantaloupes	AZ	16.0	17.7	17.7	18.5	19.7	3,040	4,071	4,514	4,625	5,319	2.13	2.58	2.86	2.80	3.03	2.68	
	CA	59.3	59.0	62.3	58.0	61.0	11,860	12,980	13,083	12,760	12,810	2.24	2.47	2.35	2.47	2.35	2.38	
Honeydew	AZ	3.6	3.8	4.1	4.2	4.2	576	646	718	840	1,029	1.79	1.91	1.96	2.24	2.75	2.13	
	CA	18.1	20.3	20.5	19.0	20.5	2,896	3,451	3,690	3,610	3,690	1.79	1.91	2.02	2.13	2.02	1.97	
Watermelon	AZ	7.2	7.3	7.2	7.6	7.1	1,800	2,154	2,232	2,280	3,025	2.80	3.31	3.47	3.36	4.78	3.54	
	CA	17.2	17.1	17.0	15.0	14.7	6,364	7,524	7,820	6,750	6,321	4.15	4.93	5.16	5.04	4.82	4.82	2.92 ^c
Strawberries	CA	23.6	25.2	22.6	24.2	24.6	12,980	13,608	13,334	13,552	15,129	6.16	6.05	6.61	6.28	6.89	6.40	
	WA	1.3	1.3	1.4	1.5	1.5	104	105	91	120	120	0.90	0.91	0.73	0.90	0.90	0.86	3.63
Tomatoes	CA	38.0	37.4	34.0	41.0	44.0	10,260	10,472	9,860	9,840	11,440	3.03	3.14	3.25	2.69	2.91	3.00	3.00
Apples ^d																		2.67
Grapes ^d																		1.51
																	Average for all crops	2.75
																	Standard deviation ^e	0.78

Notes: ^a Source for melons, strawberries, and tomatoes: 1995 data from USDA (1998a, Tables 4-17, 4-32, 4-61, 4-73, and 5-70), 1996 data from USDA (1999c, Tables 4-17, 4-32, 4-61, 4-72, and 5-72), 1997 data from USDA (2000a, Tables 4-17, 4-32, 4-61, 4-72, and 5-72), 1998 and 1999 data from USDA (2001a, Tables 4-17, 4-33, 4-62, 4-71, and 5-76).

^b Calculated as $[1,000 \text{ Cwt Produced} \times 100 \text{ lbs/Cwt} \times 0.4536 \text{ kg/lb}] / [1,000 \text{ acres Harvested} / \times 4,047 \text{ m}^2/\text{acre}] = \text{kg/m}^2$.

^c Average of all melons.

^d See Table 6.11-6.

^e Calculated using the STDEV function of EXCEL.

Table 6.11-4. Commercial Yield of Cattle Forage

	State	Annual Yield (tons/acre) ^{a,b}					Annual Yield (wet kg/m ²) ^c					Yield per Cutting (kg/m ²) ^d					5-Yr Avg	Avg Per Crop	
		1995	1996	1997	1998	1999	1995	1996	1997	1998	1999	1995	1996	1997	1998	1999			
Alfalfa	AZ	7.8	8.0	8.2	8.0	7.9	5.25	5.38	5.51	5.38	5.31	1.31	1.34	1.38	1.34	1.33	1.34		
	CA	6.9	7.0	7.2	6.6	6.9	4.64	4.71	4.84	4.44	4.64	1.16	1.18	1.21	1.11	1.16	1.16		
	NV	4.5	4.5	4.2	4.6	4.1	3.03	3.03	2.82	3.09	2.76	0.76	0.76	0.71	0.77	0.69	0.74		
	WA	5.1	4.7	4.8	5.0	4.9	3.43	3.16	3.23	3.36	3.30	0.86	0.79	0.81	0.84	0.82	0.82	1.02	
Corn Silage	AZ	26.0	27.0	25.5	26.5	23.0	5.83	6.05	5.72	5.94	5.16	5.83	6.05	5.72	5.94	5.16	5.74		
	CA	25.0	25.0	26.0	25.0	26.0	5.60	5.60	5.83	5.60	5.83	5.60	5.60	5.83	5.60	5.83	5.69		
	WA	27.0	26.0	28.0	25.0	26.0	6.05	5.83	6.28	5.60	5.83	6.05	5.83	6.28	5.60	5.83	5.92	5.78	
Other Hay	AZ	3.5	3.5	3.7	3.5	4.3	2.35	2.35	2.49	2.35	2.89	2.35	2.35	2.49	2.35	2.89	2.49		
	CA	3.5	2.8	2.8	2.8	2.9	2.35	1.88	1.88	1.88	1.95	2.35	1.88	1.88	1.88	1.95	1.99		
	NV	1.7	1.7	1.8	1.6	1.8	1.14	1.14	1.21	1.08	1.21	1.14	1.14	1.21	1.08	1.21	1.16		
	WA	2.8	2.7	2.6	2.8	2.8	1.88	1.82	1.75	1.88	1.88	1.88	1.82	1.75	1.88	1.88	1.84	1.87	
																Average for all states		2.89	
																Standard deviation ^e		2.54	

- Notes:
- ^a Source: 1995 data from USDA (1998a, Tables 1-41, 6-3, and 6-4), 1996 data from USDA (1999c, Tables 1-41, 6-3, and 6-4), 1997 data from USDA (2000a, Tables 1-41, 6-3, and 6-4), 1998 and 1999 data from USDA (2001a, Tables 1-39, 6-3, and 6-4).
- ^b For alfalfa and other hay, data are the sum of all cuttings per year (USDA 1999b, p. D-3), reported as dry weight equivalent with a conversion factor of 3 tons green weight to 1 ton dry weight (USDA 1999b, pp. A-7 and A-8).
- ^c For alfalfa and other hay, calculated as [dry tons/acre x 3 tons wet/1 ton dry x 907.2 kg/ton] / 4,047 m²/acre = wet kg/m²; For corn silage calculated as [dry tons/acre x 907.2 kg/ton] / 4,047 m²/acre = wet kg/m².
- ^d For alfalfa, calculated as annual yield divided by 4 cuttings per year; for corn silage and other hay calculated as annual yield divided by 1 cutting per year.
- ^e Calculated using the STDEV function of EXCEL.

Table 6.11-5. Commercial Yield of Grain

Grain	State	Yield (bushels/acre) ^{a,b}					Yield (kg/m ²) ^c						Average per Crop
		1995	1996	1997	1998	1999	1995	1996	1997	1998	1999	5-Yr Avg	
Barley	AZ	90.0	105.0	102.0	110.0	114.0	0.48	0.57	0.55	0.59	0.61	0.56	0.44
	CA	70.0	60.0	57.0	60.0	64.0	0.38	0.32	0.31	0.32	0.34	0.34	
	NV	80.0	95.0	100.0	100.0	90.0	0.43	0.51	0.54	0.54	0.48	0.50	
	WA	72.0	62.0	74.0	65.0	59.0	0.39	0.33	0.40	0.35	0.32	0.36	
Corn	AZ	170.0	175.0	165.0	175.0	195.0	1.07	1.10	1.04	1.10	1.22	1.10	1.10
	CA	160.0	160.0	170.0	160.0	170.0	1.00	1.00	1.07	1.00	1.07	1.03	
	WA	190.0	185.0	190.0	190.0	180.0	1.19	1.16	1.19	1.19	1.13	1.17	
Oats	CA	85.0	75.0	80.0	75.0	85.0	0.30	0.27	0.29	0.27	0.30	0.29	0.28
	WA	80.0	80.0	80.0	75.0	75.0	0.29	0.29	0.29	0.27	0.27	0.28	
Winter Wheat	AZ	80.0	95.0	85.0	90.0	105.0	0.54	0.64	0.57	0.60	0.71	0.61	0.54
	CA	61.0	69.0	70.0	60.0	78.0	0.41	0.46	0.47	0.40	0.52	0.45	
	NV	100.0	100.0	100.0	100.0	95.0	0.67	0.67	0.67	0.67	0.64	0.67	
	WA	62.0	70.0	66.0	65.0	58.0	0.42	0.47	0.44	0.44	0.39	0.43	
Average for all crops												0.59	
Standard Deviation ^d												0.36	

Notes: ^a 1995 data from USDA (1998a, Tables 1-8, 1-40, 1-50, and 1-56), 1996 data from USDA (1999c, Tables 1-8, 1-40, 1-51, and 1-57), 1997 data from USDA (2000a, Tables 1-8, 1-39, 1-51 and 1-57), 1998 and 1999 data from USDA (2001a, Tables 1-8, 1-37, 1-49, and 1-55).

^b Approximate net weight of a bushel of barley = 21.8 kg; shelled corn = 25.4 kg; oats = 14.5 kg, and wheat = 27.2 kg (USDA 2001a, p. v through vii);

^c Calculated as bushels/acre x kg/bushel ÷ 4,047 m²/acre.

^d Calculated using the STDEV function of EXCEL.

Table 6.11-6. Commercial Yield of Apples and Grapes

Fruit	State	Yield for Bearing Acreage ^a (apples = lbs/acre, grapes = tons/acre)					Yield (kg/m ²) ^b						Average per Crop
		1995	1996	1997	1998	1999	1995	1996	1997	1998	1999	5-Yr Avg	
Apples	AZ	2,620	25,000	12,200	12,100	8,790	— ^c	2.80	1.37	1.36	0.99	1.63	
	CA	24,300	25,000	25,000	23,200	25,600	2.72	2.80	2.80	2.60	2.87	2.76	
	WA	31,700	33,500	29,400	38,400	29,100	3.55	3.75	3.30	4.30	3.26	3.63	2.67
Grapes	AZ	5.78	5.81	5.81	5.35	5.12	1.30	1.30	1.30	1.20	1.15	1.25	
	CA	8.42	7.16	9.17	7.12	7.02	1.89	1.61	2.06	1.60	1.57	1.74	
	WA	9.59	4.11	8.62	5.69	6.46	2.15	0.92	1.93	1.28	1.45	1.55	1.51

Notes: ^a 1995 data from USDA (1998b, Tables “Apples, Commercial: Bearing Acreage and Yield by State and United States, 1995-97” and “Grapes: Bearing Acreage and Yield by Type, State, and United States, 1995-97”), 1996 data from USDA (1999a, Tables on pages 8 and 40), 1997 data from USDA (2000b, Tables on pages 8 and 40), 1998 data from USDA (2001b, Tables on pages 10 and 44), 1999 data from USDA (2002c, Tables on pages 10 and 46). For all years, grapes = all types.

^b Calculated as apples: lbs/acre x 0.4536 kg/lb ÷ 4,047 m²/acre; grapes: tons/acre x 907.2 kg/ton ÷ 4,047 m²/acre.

^c Value for this year (0.29 kg/m²) was omitted from the analysis because it was extremely low.

Table 6.11-7. Averages and Cumulative Distributions for Yield (kg/m²)

Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	Crop Type	Average ^a	Upper Limit of Interval ^b	Cumulative Probability	
Leafy Vegetables	3.30	1.08	0.00	Fruits	2.75	0.73	0.00	
		1.46	0.05			1.51	0.05	
		1.78	0.20			2.67	0.28	
		2.01	0.35			2.92	0.51	
		2.98	0.50			3.00	0.72	
		3.25	0.65			3.63	0.95	
		3.83	0.80			6.89	1.0	
		7.79	0.95					
Other Vegetables	4.13	7.85	1.00	Grains	0.59	0.27	0.00	
						0.28	0.05	
		2.80	0.00			0.44	0.35	
		3.37	0.05			0.54	0.65	
		3.56	0.28			1.10	0.95	
		3.64	0.51			1.22	1.00	
		4.92	0.72					
		5.15	0.95	Cattle Forage^c		2.14	0.69	0.00
		6.61	1.00			1.02	0.05	
						1.87	0.73	
		5.78	0.95					
			6.28	1.00				

Notes: ^a Mean yield for a crop type from Tables 6.11-1 through 6.11-6, with the exception of the weighted mean calculated for cattle forage. The weighted mean was calculated as (3 x 1.02 [yield for alfalfa] + 1 x 5.78 [yield for corn silage] + 1 x 1.87 [yield for oat hay]) / 5 = 2.14.

^b Limits determined from crop specific yield (see Tables 6.11-1 through 6.11-6).

^c The probabilities for the two intervals between the minimum and maximum crop specific values were weighted 3:1 for the range between alfalfa and oat hay (p = 0.68) versus the range between oat hay and corn silage (p = 0.22).

Table 6.12-1. Maximum Effective Rooting Depths.

Crop	Rooting Depth ^a (m)	Crop	Rooting Depth ^a (m)
Alfalfa hay	1.0	Grapes	1.0
Apples	1.0	Lettuce	0.3
Barley	1.0	Melons	0.8
Bell peppers	0.5	Oats	1.0
Broccoli	0.4	Onions	0.3
Cabbage	0.5	Potatoes	0.4
Carrots	0.5	Spinach	0.3
Cauliflower	0.4	Squash	0.6
Celery	0.3	Strawberries	0.2
Field corn	1.0	Sweet corn	0.8
Cucumbers	0.7	Tomatoes	0.7
		Turf	0.5
		Winter wheat	1.5
		Mean	0.65
		SD ^b	0.33
		CV ^c	0.50

Notes: ^a Source: Allen et al. (1998, Table 22, pp. 163 through 165)

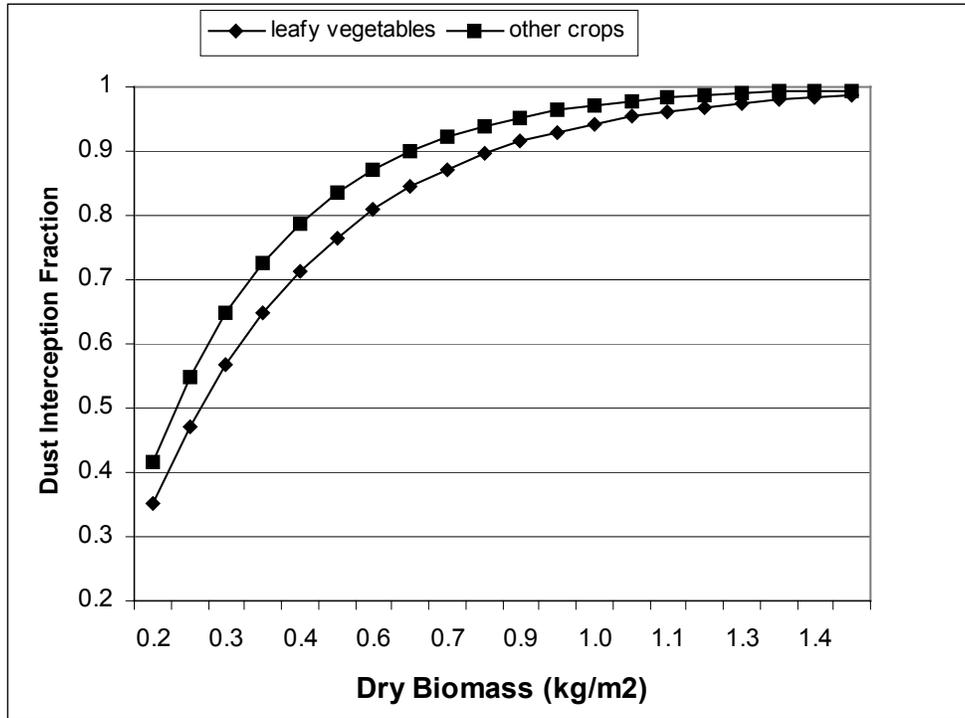
^bStandard deviation calculated using the STDEV function of EXCEL.

^cCoefficient of variation (SD ÷ Average)

Table 6.12-2. Average and Cumulative Distribution for Rooting Depth (Z_r , m)

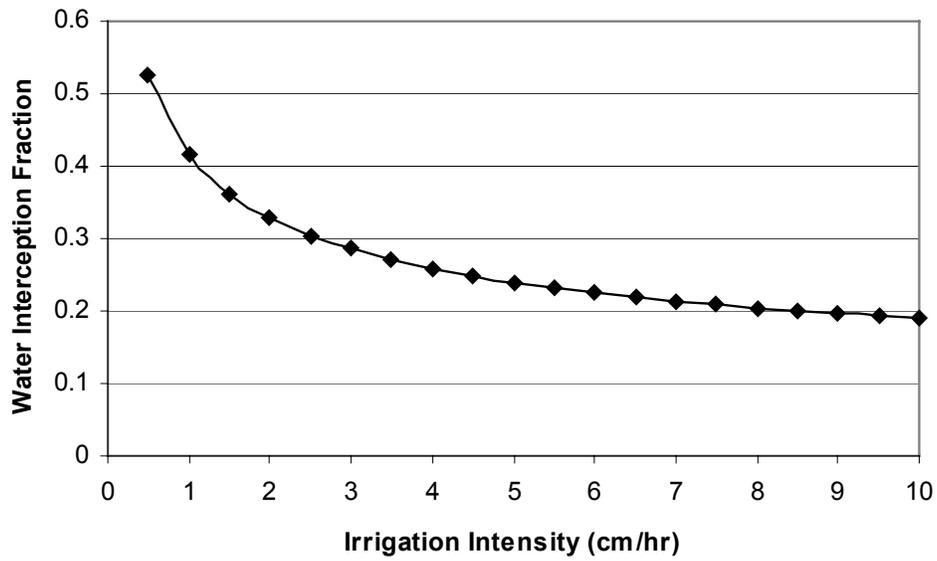
Average ^a	Upper Limit of Interval	Cumulative Probability
0.65	0.15	0.00
	0.20	0.05
	0.30	0.23
	0.50	0.41
	0.70	0.59
	1.00	0.77
	1.50	0.95
	2.00	1.00

Notes: ^aMean Z_r of 23 representative crops and turf calculated from Table 6.12-1.



Note: Calculated as fraction = $1.0 - e^{-aj\text{Dry Biomass}}$, with a = 2.9 for leafy vegetables and 3.6 for other crops.

Figure 6.1-1. Sensitivity of Dust Interception Fraction to Dry Biomass



Note: Calculated as fraction = $2.29 \times \text{Dry Biomass}^{0.695} \times \text{Irrigation Application}^{-0.29} \times \text{Irrigation Intensity}^{-0.341}$, with dry biomass = 0.4 kg/m² and irrigation application = 40 mm.

Figure 6.6-1. Sensitivity of Water Interception Fraction to Irrigation Intensity

7. CONCLUSIONS

This analysis report documents the development of reasonable distributions and averages for twelve agricultural parameters that are representative of environmental conditions expected under current and future climates. This information is summarized in Table 7.1-1 and contained in DTN: MO0306SPA AEIBM.001. The same distributions for current and future climates are recommended for Dry Biomass, Dry to Wet Ratios, Fraction of Overhead Irrigation, Irrigation Intensity, Tillage Depth, Yield, and Rooting Depth. Separate distributions for current and future climates are recommended for Growing Time, Irrigation Rate – Annual Average, Irrigation Application, Irrigation Rate – Daily, and Overwatering Rate. Average values are provided for Irrigation Rate – Annual Average for upper bound monsoon and lower bound future climates (Table 7.1-1).

Fraction of Overhead Irrigation, Irrigation Intensity, Overwatering Rate, Irrigation Rate – Annual Average, Irrigation Application, and Irrigation Rate – Daily are not used in the biosphere volcanic ash exposure scenario, and therefore are only intended for the groundwater exposure scenario. The remaining distributions are intended for both the biosphere groundwater and volcanic ash exposure scenarios.

Uncertainties associated with the recommended parameter distributions are described in Sections 6., 6.1.2, 6.2.2, 6.3.2, 6.4.2, 6.5.2, 6.6.2, 6.7.2, 6.8.2, 6.9.2, 6.10.2, 6.11.2 and 6.12.2. One restriction for subsequent use of the recommended parameter distributions is that they are intended for use in the biosphere model equations presented in Section 6. If the equations used in the completed biosphere model differ from those presented here, use of these distributions must be justified or new parameter values must be developed. The distributions for irrigation parameters (Irrigation Rate – Annual Average, Irrigation Application, Irrigation Rate – Daily, and Overwatering Rate) are restricted for use under the climate conditions described in Tables 4.1-2 and 4.1-5. The averages for Irrigation Rate – Annual Average for upper bound monsoon and lower bound future climates are restricted for use under the climate conditions in Tables 4.1-3 and 4.1-4. The remaining parameter distributions are restricted for use under more general conditions described for current and future climates.

Table 7.1-1. Recommended Distributions and Averages for Agricultural and Environmental Parameters for the Biosphere Model

Parameter - Type of Distribution		
Crop Type	Average^a	Distribution Characteristics^b
Dry Biomass (kg/m²) - Cumulative Distribution		
Leafy Vegetables	0.21	(0.10; 0%), (0.13; 5%), (0.14; 20%), (0.15; 35%), (0.16; 50%), (0.18; 65%), (0.30; 80%), (0.42; 95%), (0.50; 100%)
Other Vegetables	0.43	(0.30; 0%), (0.40; 5%), (0.41; 28%), (0.43; 51%), (0.44; 73%), (0.46; 95%), (0.60; 100%)
Fruits	0.62	(0.10; 0%), (0.56; 5%), (0.60; 35%), (0.65; 65%), (0.68; 95%), (1.30; 100%)
Grains	1.13	(0.50; 0%), (0.61; 5%), (0.74; 35%), (1.20; 65%), (1.97; 95%), (2.20; 100%)
Cattle Forage	0.48	(0.10; 0%), (0.23; 5%), (0.34; 73%), (1.38; 95%), (1.50; 100%)
Dry to Wet Ratio (unitless) – Cumulative Distribution		
Leafy Vegetables	0.070	(0.041; 0%), (0.054; 17%), (0.060; 33%), (0.078; 50%), (0.081; 67%), (0.084; 83%), (0.093; 100%)
Other Vegetables	0.103	(0.035; 0%), (0.063; 17%), (0.078; 33%), (0.080; 50%), (0.103; 67%), (0.122; 83%), (0.240; 100%)
Fruits	0.120	(0.062; 0%), (0.084; 25%), (0.102; 50%), (0.155; 75%), (0.194; 100%)
Grains	0.903	(0.891; 0%), (0.896; 33%), (0.906; 67%), (0.918; 100%)
Cattle Forage	0.220	(0.182; 0%), (0.227; 75%), (0.238; 100%)
Fraction of Overhead Irrigation (unitless) – Normal Distribution		
Leafy Vegetables	0.75	Mean = 0.75, Standard Deviation = 0.1, Minimum = 0.49, Maximum = 1.0
Other Vegetables	0.75	Mean = 0.75, Standard Deviation = 0.1, Minimum = 0.49, Maximum = 1.0
Fruits	0.50	Mean = 0.50, Standard Deviation = 0.1, Minimum = 0.24, Maximum = 1.0
Grains	0.90	Mean = 0.90, Standard Deviation = 0.05, Minimum = 0.77, Maximum = 1.0
Cattle Forage	0.90	Mean = 0.90, Standard Deviation = 0.05, Minimum = 0.77, Maximum = 1.0
Growing Time (days) – Current Climate – Fixed Value		
Leafy Vegetables	75	NA
Other Vegetables	80	NA
Fruits	160	NA
Grains	200	NA
Cattle Forage	75	NA
Growing Time (days) - Future Climate - Fixed Value		
Leafy Vegetables	75	NA
Other Vegetables	100	NA
Fruits	105	NA
Grains	185	NA
Cattle Forage	90	NA
Average Annual Irrigation Rate (m/year)^c – Current Climate – Cumulative Distribution		
All	0.94	(0.33; 0%), (0.40; 5%), (0.66; 23%), (0.83; 41%), (0.92; 59%), (1.33; 77%), (1.94; 95%), (2.29; 100%)

Table 7.1-1. Recommended Distributions and Averages for Agricultural and Environmental Parameters for the Biosphere Model (Continued)

Parameter - Type of Distribution		
Crop Type	Average^a	Distribution Characteristics^b
Average Annual Irrigation Rate (m/year)^c – Future Climate – Cumulative Distribution		
All	0.50	(0.14; 0%), (0.16; 5%), (0.36; 23%), (0.46; 41%), (0.54; 59%), (0.69; 77%), (0.83; 95%), 0.98; 100%)
Average Annual Irrigation Rate (m/year)^d – Current Climate - Normal Distribution		
All	0.94	Mean = 0.94, Standard Error = 0.08, Minimum = 0.73, Maximum = 1.15
Average Annual Irrigation Rate (m/year)^d – Future Climate - Normal Distribution		
All	0.50	Mean = 0.50, Standard Error = 0.04, Minimum = 0.40, Maximum = 0.60
Average Annual Irrigation Rate (m/year) Upper Bound Monsoon Climate		
All	0.52	
Average Annual Irrigation Rate (m/year) Lower Bound Future Climate		
All	0.88	
Irrigation Intensity (cm/hour) – Uniform Distribution^e		
All	4.3	Minimum = 1.0, Maximum = 7.5
Irrigation Application (mm) – Current Climate - Cumulative Distribution		
Leafy Vegetables	14.7	(6.0; 0%), (7.4; 5%), (8.4; 20%), (10.0; 35%), (10.9; 50%), (20.8; 65%), (22.0; 80%), (23.6; 95%), (27.8; 100%)
Other Vegetables	25.4	(8.0; 0%), (9.0; 5%), (18.7; 20%), (19.7; 35%), (21.2; 50%), (32.9; 65%), (34.9; 80%), (41.2; 95%), (48.6; 100%)
Fruits	33.9	(5.0; 0%), (6.0; 5%), (30.2; 28%), (35.5; 51%), (48.4; 72%), (49.2; 95%), (58.1; 100%)
Grains	56.8	(43.0; 0%), (48.7; 5%), (50.1; 35%), (50.3; 65%), (77.9; 95%), (91.9; 100%)
Cattle Forage	57.8	(50.0; 0%), (56.5; 5%), (57.5; 72%), (60.2; 95%), (71.0; 100%)
Irrigation Application (mm) – Future Climate - Cumulative Distribution		
Leafy Vegetables	14.6	(7.0; 0%), (7.8; 5%), (8.0; 20%), (9.0; 35%), (10.1; 50%), (19.3; 65%), (22.0; 80%), (26.1; 95%), (30.8; 100%)
Other Vegetables	25.0	(10.0; 0%), (11.3; 5%), (14.4; 20%), (17.7; 35%), (20.1; 50%), (34.1; 65%), (37.2; 80%), (40.3; 95%), (47.6; 100%)
Fruits	34.2	(6.0; 0%), (7.3; 5%), (31.4; 28%), (34.6; 51%), (43.2; 72%), (54.4; 95%), (64.2; 100%)
Grains	51.3	(28.0; 0%), (32.2; 5%), (46.2; 35%), (59.9; 65%), (66.7; 95%), (78.7; 100%)
Cattle Forage	53.5	(43.0; 0%), (48.3; 5%), (52.5; 73%), (61.9; 95%), (73.0; 100%)
Daily Average Irrigation Rate (mm/day) – Current Climate - Cumulative Distribution		
Leafy Vegetables	5.40	(4.00; 0%), (5.11; 5%), (5.19; 20%), (5.21; 35%), (5.38; 50%), (5.46; 80%), (5.98; 95%), (7.06; 100%)
Other Vegetables	7.55	(5.00; 0%), (6.05; 5%), (6.65; 20%), (6.85; 35%), (7.62; 50%), (8.19; 65%), (8.32; 80%), (9.18; 95%), (10.83; 100%)
Fruits	7.38	(4.00; 0%), (5.38; 5%), (7.00; 28%), (7.56; 51%), (8.35; 72%), (8.60; 95%), (10.15; 100%)
Grains	4.64	(3.00; 0%), (3.44; 5%), (3.58; 35%), (3.86; 65%), (7.67; 95%), (9.05; 100%)
Cattle Forage	6.54	(5.00; 0%), (5.84; 5%), (6.18; 73%), (9.0; 95%), (10.62; 100%)

Table 7.1-1. Recommended Distributions and Averages for Agricultural and Environmental Parameters for the Biosphere Model (Continued)

Parameter - Type of Distribution		
Crop Type	Average^a	Distribution Characteristics^b
Daily Average Irrigation Rate (mm/day) – Future Climate - Cumulative Distribution		
Leafy Vegetables	3.81	(3.00; 0%), (3.34; 5%), (3.51; 20%), (3.86; 50%), (3.92; 65%), (4.02; 80%), (4.18; 95%), (4.93; 100%)
Other Vegetables	3.84	(2.0; 0%), (2.73; 5%), (3.08; 20%), (3.48; 35%), (4.08; 50%), (4.16; 65%), (4.43; 80%), (4.95; 95%), (5.84; 100%)
Fruits	3.90	(2.00; 0%), (2.51; 5%), (3.48; 28%), (4.33; 51%), (4.38; 72%), (4.79; 95%), (5.65; 100%)
Grains	3.36	(1.00; 0%), (1.99; 5%), (3.42; 35%), (3.93; 65%), (4.11; 95%), (4.85; 100%)
Cattle Forage	4.14	(3.00; 0%), (3.64; 5%), (4.01; 73%), (5.03; 95%), (5.94; 100%)
Overwatering Rate (m/year) – Current Climate - Cumulative Distribution		
All	0.079	(0.009; 0%), (0.030; 19%), (0.045; 38%), (0.076; 57%), (0.128; 76%), (0.233; 95%), (0.275; 100%)
Overwatering Rate (m/year) – Future Climate - Cumulative Distribution		
All	0.067	(0.004; 0%), (0.020; 19%), (0.047; 38%), (0.072; 57%), (0.104; 76%), (0.150; 95%), (0.177; 100%)
Tillage Depth (cm) – Uniform Distribution^f		
All	25	Minimum = 5, Maximum = 30
Yield (kg/m²) – Cumulative Distribution		
Leafy Vegetables	3.30	(1.08; 0%), (1.46; 5%), (1.78; 20%), (2.01; 35%), (2.98; 50%), (3.25; 65%), (3.83; 80%), (7.79; 95%), (7.85; 100%)
Other Vegetables	4.13	(2.80; 0%), (3.37; 5%), (3.56; 28%), (3.64; 51%), (4.92; 72%), (5.15; 95%), (6.61; 100%)
Fruits	2.75	(0.73; 0%), (1.51; 5%), (2.67; 28%), (2.92; 51%), (3.00; 72%), (3.63; 95%), (6.89; 100%)
Grains	0.59	(0.27; 0%), (0.28; 5%), (0.44; 35%), (0.54; 65%), (1.10; 95%), (1.22; 100%)
Cattle Forage	2.14	(0.69; 0%), (1.02; 5%), (1.87; 73%), (5.78; 95%), (6.28; 100%)
Rooting Depth (m) – Cumulative Distribution		
All	0.65	(0.15; 0%), (0.20; 5%), (0.30; 23%), (0.50; 41%), (0.70; 59%), (1.00; 77%), (1.50; 95%), (2.00; 100%)

Notes: DTN: MO0306SPAAEIBM.001

^a Averages are calculated per crop type (i.e., Leafy Vegetables) or for 26 representative crops and turf (All) unless otherwise indicated (see notes e and f).

^b Characteristics of the cumulative distribution are the upper bound of each interval and the cumulative probability associated with each interval.

^c A cumulative distribution for IR is recommended for the Biosphere model if yearly variation and a wider range of uncertainty is required.

^d A normal distribution is recommended for IR if values that are representative of the long-term average are required for the Biosphere model.

^e The midpoint of the uniform distribution is presented instead of the average.

^f The most common conventional tillage depth is presented instead of the average.

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8.4 OUTPUT DATA

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APPENDIX A
SELECTION OF REPRESENTATIVE PLANTS

APPENDIX A. SELECTION OF REPRESENTATIVE PLANTS

The first step in development of parameter distributions was selection of plants that are representative of the central tendency and variation within each of the five crop types and home irrigation rates for the current climate and future climate conditions (as represented by conditions in eastern Washington). The parameter values calculated for the representative plants were then used in Section 6 of this report to develop averages and distributions that incorporate variation and uncertainty due to differences among plants within crop types. The following sections summarize information on plants grown in Amargosa Valley and eastern Washington, national food consumption patterns, and other factors considered in selection of representative plants. As described in Section 1, plants selected for current climate conditions are also used for the upper bound monsoon climate, and those selected for future climate are used for both upper and lower bounds.

1. COMMONLY GROWN PLANTS

1.1 AMARGOSA VALLEY

Field surveys and aerial photographs were used to measure acreage of crops grown in Amargosa Valley during 1996 through 1999 (CRWMS M&O 1997b, YMP 1999). Those surveys did not include gardens. Hay accounted for 91 to 93 percent of the total acreage planted per year; most (67 to 97 percent) hay was alfalfa (Table A-1). Pistachios were the next most common crop (4–5 percent of total acreage). Barley and oats were the only grains documented, and garlic and onions were the only vegetables. Fruit trees (listed as “peaches, nectarines, and pomegranates, and so forth” [CRWMS M&O 1997b, Table 3-12]) were also recorded.

The 1997 U.S. Census of Agriculture (USDA 1999b) also lists alfalfa as the most important crop in all of Nye County during 1997 (Table A-2). Other hay was second-most important, and pistachios were third. Tomatoes and numerous types of fruit trees were grown on a few farms. There were 97 farms and 10,221 acres planted in the county in 1997; all crop land was irrigated.

Thirteen residents of Amargosa Valley (representing nine households) actively involved in agriculture filled out questionnaires and were interviewed in 1997 to determine, among other things, the garden and commercial crops they grew and the reasons for growing them (Horak and Carns 1997). Although the results of this focus-group study may not be representative of all agricultural practices in the valley, the study provides a valid list of crops commonly grown there (Horak and Carns 1997, Tables 1 and 2 on pp. 26 and 27, respectively). Alfalfa was the most common cattle feed grown, and oats and other hays were also mentioned. Grains grown by those interviewed were barley, oats, red wheat, and corn (Horak and Carns 1997, Table 1 and p. 15). A large variety of vegetables were listed, including commercial production of garlic, onions, and pumpkins, and garden production of potatoes, carrots, tomatoes, squash, lettuce, broccoli, cabbage, and many others. Fruit trees (type not specified), grapes, and melons were grown commercially and for personal consumption. Three participants also had pistachio trees.

A guide for planting vegetables in Nye County lists 50 vegetables and fruits that can be grown there (Mills et al. n.d.). Although this list is not comprehensive, it likely includes the easiest to grow and most commonly grown garden plants in the area.

Warm and cool season grasses can be grown in the Mojave Desert. Bermudagrass is a commonly used, drought adapted turfgrass in southern Nevada (Morris and Johnson 1991, p. 1) and tall fescue is the recommended cool season grass for this region (Morris and Johnson 1986, p. 3).

1.2 EASTERN WASHINGTON

Agriculture is an important industry in eastern Washington. There were about 280,000 acres of farmland in Spokane County and 800,000 in Whitman County (where Rosalia and St. John are located) in 1997 (Table A-3). Only about four percent and one percent of the agricultural land in each county, respectively, was irrigated (USDA 1999d). The most important crop was winter wheat, comprising 46 percent of the total acreage planted in the two counties. Other common crops were barley (19 percent of total acreage), dry peas (10 percent), spring wheat (9 percent), lentils (8 percent), alfalfa (4 percent), and grass seed crops (3 percent). Numerous fruits and vegetables were grown on a smaller scale, especially in Spokane County. The only crops commonly irrigated were some vegetables (e.g., dry beans, sweet corn, pumpkins, tomatoes, peppers) and orchards. About 14 percent of acreage planted in alfalfa was irrigated (Table A-3).

The types of garden crops that can be grown in eastern Washington is quite varied and includes many of the same crops suggested for Nye County (Antonelli et al. 1998; Washington State University Cooperative Extension 2002).

Cool season grasses recommended for eastern Washington include tall fescue and Kentucky bluegrass. Most warm season grasses are not recommended for that region (Stahnke et al. 2001, p. 6).

2. FOOD CONSUMPTION

A U.S. Department of Agriculture report (Putnam and Allshouse 1999) on U.S. food consumption patterns was examined to identify plants commonly eaten (Table A-4). Consumption estimates were derived from measurements of national food production (minus non-consumptive uses such as exports, farm use, industrial use) divided by population size; therefore, they are estimates of the upper bounds of national rates of consumption of commercially produced foods. However, because the same methods were used for all products within a food type, they are valid for general comparisons of nationwide consumption patterns within food types (Putnam and Allshouse 1999, pp. 2 through 4). Crops not grown in southern Nevada or eastern Washington (e.g., bananas, citrus, rice) were omitted from this analysis (Table A-4).

Per capita consumption of head lettuce during 1997 was more than twice that of other leafy vegetables. Consumption of potatoes far exceeded consumption of other vegetables, including other root vegetables, corn, and other vegetables. Melons were consumed more than other fruits, followed by tomatoes, apples, and grapes. Wheat consumption was much greater than corn products and other grains (Table A-4).

Food consumption information was examined only to identify commonly eaten plants in the U.S., not to predict food consumption patterns of the population in the town of Amargosa Valley. Food consumption patterns used in the biosphere model were developed from a survey of people

in Amargosa Valley (DOE 1997, DTN MO0010SPANYE00.001). There is only limited information from that survey that can be used to identify commonly eaten, locally grown plants in Amargosa Valley because people surveyed were asked how often they ate any of a group of plants, but were not asked to identify specific plants. The only exception was a question asked toward the end of the survey requesting respondents to list “any other locally-produced food, such as tomatoes, or anything I did not already mention” (DOE 1997, p. B-10). Previously mentioned fruits and vegetables included leafy vegetables (“such as cabbage, asparagus, lettuce, spinach, broccoli, or herbs”), root vegetables (“such as potatoes, garlic, beets, turnips, carrots, or onions”), grains, and fruits (“such as grapes, raisins, berries, plums, melons, or peaches”) (DOE 1997, pp. B-3 through B-6). Therefore, responses to the question are not valid for identifying commonly eaten locally produced leafy vegetables, root vegetables, or fruits. The most common responses to the question by Nye County residents were squash, tomatoes, peppers, cucumbers, zucchini, corn, and radishes (DTN MO0010SPANYE00.001).

3. REPRESENTATIVE CROP VALUE PARAMETERS

Of the parameters required for each crop type, irrigation rate probably is the most important contributor to variation in BDCFs because it appears in the numerator for calculations of soil concentrations (which is used in pathways for root uptake, external exposure, and inhalation exposure) and water-to-plant deposition rates. Irrigation rates among garden and agricultural crops for a specified location are influenced primarily by planting date and growing season, because those two parameters control how long and during what time of year plants must be irrigated. To evaluate variation in irrigation rate among plants within a crop type, growing seasons for commonly grown and consumed plants were plotted (Figures A-1 and A-2). Data on growing season are discussed in Appendix D, and presented in Tables D-1 and D-2. Plant growth form also was considered in selection of representative crops to ensure that the range in biomass and dry:wet ratios within crop types was represented by crops selected.

Lettuce and most other commonly consumed leafy vegetables are small annuals that are planted in the spring. In southern Nevada, many leafy vegetables can also be grown in the fall (Figure A-1), but the growing season for celery is too long for spring and fall production in eastern Washington (Figure A-2). Asparagus is the only perennial leafy vegetable and has a very different growth form from other plants in this category.

Most root and other vegetables are planted in mid to late spring and have only one growing season per year. The exceptions are onions (two seasons in southern Nevada) and carrots (two seasons in both areas). Growth form varies substantially within this group.

Fruits are a very diverse group. Melons and tomatoes are late spring or summer annuals. Other commonly consumed fruits are perennials, including orchard fruits (e.g., apples), vining grapes, and prostrate strawberries.

Wheat and barley are grown during winter in Nye County, but barley often is grown as a spring crop in Washington. Feed corn and oats are spring-summer crops in both locations.

Alfalfa hay is a perennial plant, and the common annual hays in Nye County (e.g., oats) generally are spring crops. Corn silage is planted in the spring.

4. PLANT SELECTION

Based on the above information, three to seven plants were selected per crop type. The representative crops selected are those likely to be grown in the two regions of interest; commonly eaten in the U.S.; and representative of the range of variation in the crop type, but without having extreme values. Because the same crops can be grown in both climates considered, the same representative crops were selected for both conditions. However, different grasses were selected to represent home irrigation rates.

Leafy vegetables—Seven of the eight commonly consumed (Table A-4) and locally grown (Mills et al. n.d.; Antonelli et al. 1998) leafy vegetables were selected: broccoli, cabbage, cauliflower, celery, head lettuce, leaf lettuce, and spinach. Asparagus was not selected because its growth form is not typical of leafy vegetables, its growing season length is extreme compared to other leafy vegetables, and it is not frequently consumed.

Other vegetables—Seven other vegetables were selected: bell peppers, carrots, cucumbers, onions, potatoes, squash, and sweet corn. Six of these are the most commonly eaten other vegetables (Table A-4). The seventh, squash, was chosen instead of other commonly eaten vegetables (garlic and snap beans) because it was commonly mentioned in the food consumption survey for Amargosa Valley (DTN MO0010SPANYE00.001).

Fruits—Five fruits were selected: melons, tomatoes, apples, grapes, and strawberries. Peaches, plums, and pears, were not selected because they are similar to apples. Pistachios and other nuts were not selected because another tree (apples) was selected that has higher water use requirements (Allen et al. 1998, Tables 11, pp. 104 through 108 and 12, pp. 110 through 114).

Grains—Wheat and barley were selected because they are the two most commonly grown grains in eastern Washington and were also grown in Nye County. Oats and feed corn were also selected because they are grown in both locations, although in small amounts. This selection includes both winter and spring/summer grains (Figures A-1 and A-2).

Cattle forage—Alfalfa was selected because it is the dominant crop in Amargosa Valley (Tables A-1 and A-2) and is the most common feed crop in eastern Washington (Table A-3). Oats and corn silage were also selected to include spring/summer hay and silage.

Home irrigation—The recommended warm season grass, bermudagrass, was selected as representative for calculation of home irrigation rates in southern Nevada (Morris and Johnson 1986, 1991). The cool season grass, tall fescue, was selected for eastern Washington, because warm season grasses generally are not grown there (Stahnke et al. 2001).

Table A-1. Acres Planted in Amargosa Valley^a

Crop	Year			
	1996 ^b	1997 ^b	1998 ^c	1999 ^c
Alfalfa Hay	1,747	1,822	1,278	1,360
Other Hay	51	68	634	313
Barley	17	32	34	
Oats	45			
Pistachios	92	80	98	98
Fruit Trees	2	8	18	16
Grapes	8	10	10	11
Garlic	5	5	0.3	0.3
Onions	5			

Notes: ^aCommercial agricultural production during spring in Radiological Monitoring Program Grid cells 408, 409, 508, and 509.

^bSource: CRWMS M&O 1997b (Tables 3-12 and 3-13).

^cSource: YMP 1999 (Tables 10 and 11).

Table A-2. Crops Grown in Nye County, 1997^a

Crop	Number of Farms	Acres
Harvested Cropland	97	10,221
Irrigated Cropland	97	10,221
Alfalfa Hay	51	5,703
Small Grain Hay	8	178
Tame Hay	8	379
Wild Hay	15	2,820
Vegetables, Total	5	9
Tomatoes	4	4
Orchards, Total	22	254
Apples	4	11
Apricots	3	3
Cherries	3	1
Grapes	7	16
Peaches	8	16
Pears	3	5
Pomegranates	3	D ^b
Pecans	3	D ^b
Pistachios	9	181

Notes: ^a Source: USDA 1999b, Chapter 2, Tables 13, 28, 29, 30, and 31.

^b D = Data not disclosed.

Table A-3. Crops grown in Spokane and Whitman Counties, Washington, 1997^{a, b}

Selected Crops	Spokane County ^c			Whitman County		
	Number of Farms	Acres	Irrigated Acres	Number of Farms	Acres	Irrigated Acres
Total farms	1,133	280,969	10,044	852	801,501	4,805
Feed corn	3	D	D(1)	4	101	D(1)
Spring wheat	145	21,485	520	358	78,603	D(1)
Winter wheat	303	93,839	882	747	399,495	D(2)
Barley	246	43,927	837	566	160,110	268
Canola	8	1,584		8	1,498	
Oats	51	2,435	D(2)	12	203	
Dry edible beans				10	1,283	1,283
Dry edible peas	81	19,596		276	84,356	D(1)
Lentils	80	25,373		155	57,544	
Field/grass seed	82	22,657	D(2)	45	4,251	D(2)
Alfalfa hay	633	35,493	4,606	134	6,644	1,438
Small grain hay	110	3,495	138	42	D	D(2)
Tame hay	184	8,390	538	102	2,981	D(1)
Wild hay	109	4,183		47	1,552	
Corn Silage	4	128	128			
Vegetables—Total	37	449	408	33	5,792	
Carrots	6	34	D(3)			
Green peas	4	D	D(3)	31	5,589	
Lettuce	3	1	1			
Sweet peppers	3	7	7			
Pumpkins	17	139	119			
Squash	10	58	D(6)			
Sweet corn	15	152	150			
Tomatoes	11	5	5			
Orchards – Total	48	367	192	9	25	19
Apples	44	227	-	9	19	-
Apricots	14	11	-			-
Cherries	29	50	-	4	D	-

Table A-3. Crops grown in Spokane and Whitman Counties, Washington, 1997^{a, b} (continued)

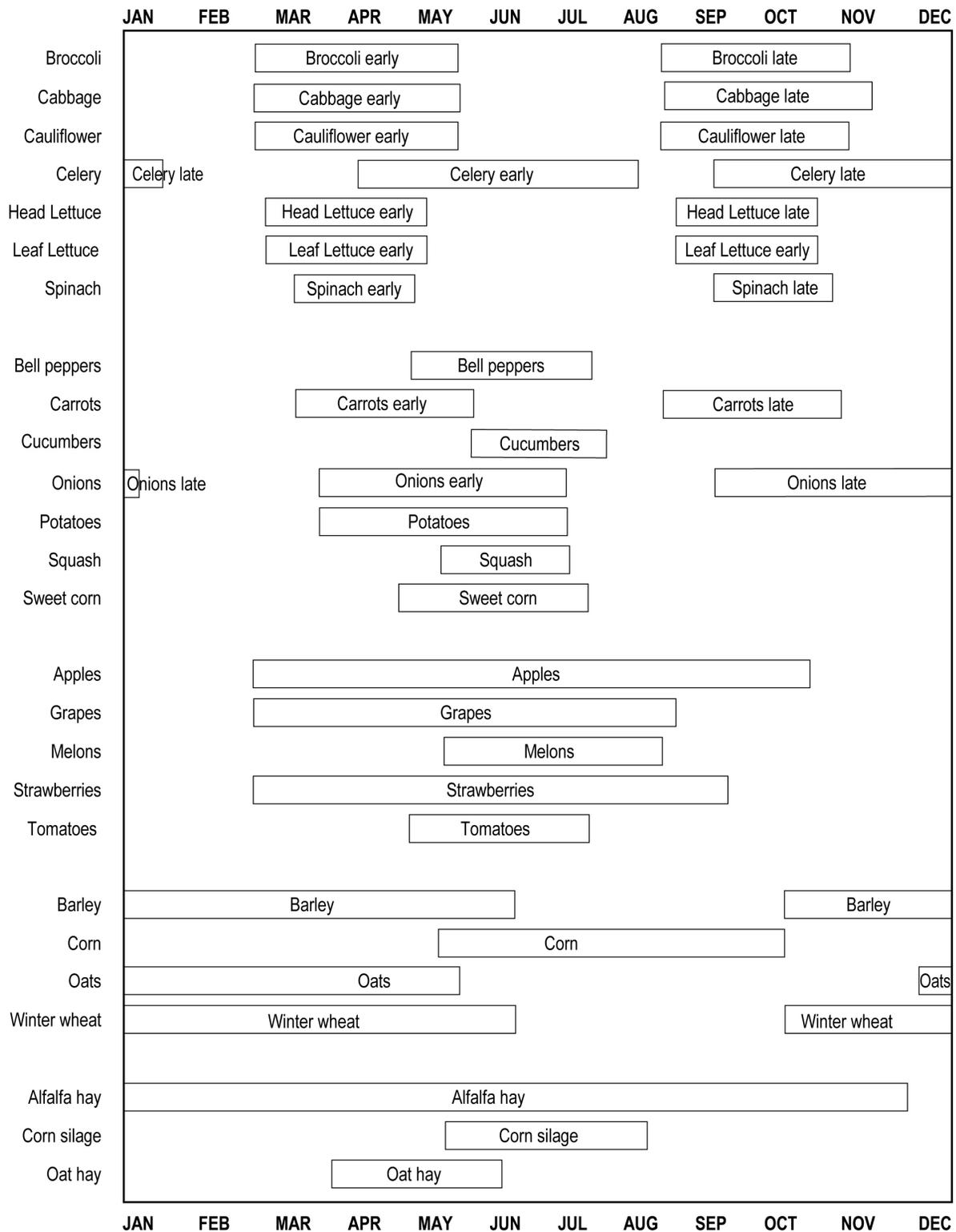
Selected Crops	Spokane County ^c			Whitman County		
	N farms	Acres	Irrigated Acres	N farms	Acres	Irrigated Acres
Peaches	17	42	-			
Pears	16	24	-	4	2	-
Nursery Crops	69	378	-	14	980	-

Notes: ^a Source: USDA 1999d, Tables 13, 26, 27, 28, 29, 30, 31, and 33.
^b Blanks indicate not grown or irrigated, dash indicates not reported, D indicates data withheld to avoid reporting for individual farms (number in parentheses is the number of farms irrigating a crop).
^c Other crops listed for Spokane County include feed corn, snap beans, cucumbers and pickles, garlic, herbs, dry onions, green peas, potatoes, grapes, plums, blackberries, raspberries, strawberries, and floriculture and nursery products.

Table A-4. Per-Capita Food Consumption^{a, b}

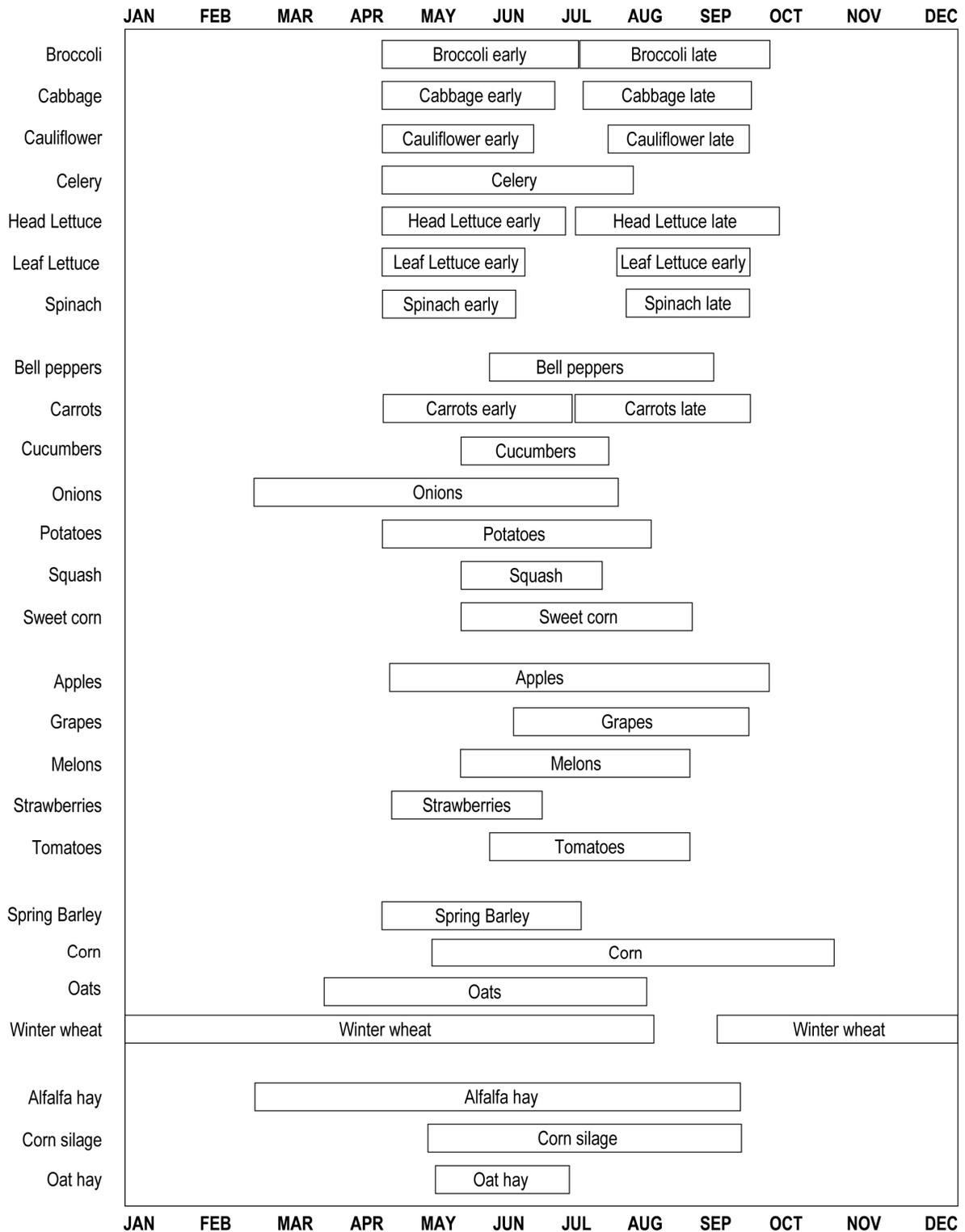
Crop Type Crop ^c	Consumption (pounds) ^d	Crop Type Crop ^c	Consumption (pounds) ^d
Leafy Vegetables		Fruits and Nuts	
Lettuce-Head	24.3	Melons	30.4
Cabbage	10.2	Tomatoes	18.9
Lettuce-Leaf	6.1	Apples	18.5
Celery	6.0	Grapes	8.0
Broccoli	5.2	Peaches	5.7
Cauliflower	1.6	Strawberries	4.2
Asparagus	0.7	Pears	3.5
Spinach	0.6	Plums & Prunes	1.5
Other Vegetables		Tree Nuts	2.2
Potatoes	47.9	Grains	
Onions	17.9	Wheat Flour	149.7
Carrots	12.5	Corn Products	23.1
Sweet Corn	8.1	Oat Products	6.5
Bell Peppers	7.2	Barley Products	0.7
Cucumbers	6.3		
Garlic	2.1		
Snap Beans	1.4		

Notes: ^a Source: Putnam and Allshouse 1999, 1997 data from Tables 2, 16, 17, 27, 32, and 34.
^b Only crops with >0.5 pounds consumed are listed.
^c Crops not likely to be grown in southern Nevada or eastern Washington are not listed, including citrus, avocados, bananas, mangoes, pineapples, papayas, rice.
^d Consumption of fresh fruits and vegetables, and total consumption of grains, based on farm weight.



00139DR_GrowSeason_NyeCoNVrev1.ai

Figure A-1. Growing season lengths for representative crops under current climate conditions



00139DR_GrowSea_IntermediateGlacialClimate.ai

Figure A-2. Growing season lengths for representative crops under future climate conditions

APPENDIX B
**JUSTIFICATION OF METHODS USED FOR CALCULATING IRRIGATION
PARAMETERS**

APPENDIX B. JUSTIFICATION OF METHODS USED FOR CALCULATING IRRIGATION PARAMETERS

1. BACKGROUND INFORMATION

Plant water use—Photosynthesis is the process by which light energy is used to drive the synthesis of organic compounds in plants. The photosynthetic process requires atmospheric carbon dioxide (CO₂). To gain CO₂ for photosynthesis, plants must lose water to the atmosphere. Carbon dioxide diffuses through small pores in the leaf surface (stomata) to intercellular spaces of the leaf, and to the photosynthetic cells (Figure B-1). Concurrently, water moves in the opposite direction, from wet cell membranes inside the leaf through open stomata to the atmosphere, a process called transpiration (Figure B-1). Because water and CO₂ share the same diffusional pathway through the stomata, there is an inevitable cost of water for CO₂ gain.

Water moves from the soil, through the plant, to the atmosphere down an increasingly negative water potential gradient (Figure B-2). Water potential is a thermodynamic parameter that describes the energy status of water in the soil-plant-atmosphere system (Brady and Weil 1999, pp. 178 and 179). The soil acts as a water reservoir with texture determining the water holding capacity. Soils with high clay and silt content hold water more tightly than sandy soils. Water enters the plant through the roots and moves through a column of high tensile water in specialized cells called xylem, and into the atmosphere through open stomata. Water flow through the soil-plant-atmosphere system represents important processes in the overall hydrologic cycle.

When soil moisture is limiting, plants can reduce water loss through stomatal closure. However, stomatal closure also results in reducing the supply of CO₂, which ultimately reduces plant productivity. In arid regions, approximately 400 to 700 units of water are lost for every unit of dry matter produced by a plant (Brady and Weil 1999, p. 227 through 228). This is because the diffusion gradient for water from inside the leaf to the atmosphere is orders of magnitude steeper than that for CO₂ diffusion into the leaf. Water is required for photosynthesis and other metabolic processes; however, 95 - 99 percent of the water that passes through a plant is lost through transpiration (Nobel 1983a, p. 506). Thus, transpiration is an accurate estimate of water uptake by plant roots (Nobel 1983a, p. 506). Water is also lost from the soil and other surfaces (i.e., plant litter), through the process of direct evaporation. Direct evaporation from the soil generally occurs in the upper 0.15 to 0.20 m of the soil profile (Figure B-3). Evapotranspiration (*ET*) is the combined water loss through plant transpiration and direct evaporation.

Plant water availability depends on soil texture, soil water potential, soil hydraulic conductivity, rooting depth, and species specific ability to extract moisture from the soil. When the rate of water absorption through the roots equals or exceeds *ET*, internal plant water balance is maintained, and carbon gain is not affected. If *ET* exceeds water absorption for a period of time, internal water deficits occur and plants wilt. Short-term water deficits can occur under periods of high air temperatures and low humidity. However, if soil moisture is available, plants can recover. As soil moisture is depleted, it becomes more difficult for plants to extract water, resulting in lower plant water potentials and reduced carbon gain. Without additional water,

plants will permanently wilt. Therefore, in agricultural situations, irrigation water must be applied to a crop in time to prevent water stress from occurring if reduction in crop yield is to be avoided.

Water balance of a cropped field—To prevent crop water stress, water entering a plot of vegetated land must equal that leaving. Water enters the system through precipitation, irrigation, surface and subsurface flow in, and capillary rise from the water table (Allen et al. 1998, p. 12) (Figure B-3). Water leaves the system through ET , runoff, subsurface flow out, and percolation below the root zone (Figure B-3).

Fluxes such as subsurface flow on or off a vegetated plot of land, or capillary rise from a water table are difficult to measure and are usually ignored. Thus, methods for assessing the appropriate amount of irrigation water required to avoid crop water stress rely on estimates of crop evapotranspiration (ET_c), precipitation, and the storage capacity of the soil within the crop rooting zone.

Commonly, ET of a grass or alfalfa reference surface (ET_o) is calculated and used with a crop specific coefficient (K_c) to estimate ET_c (Doorenbos and Pruitt 1977, p. 37; Allen et al. 1998, p. 89; Jensen et al. 1990, p.114). Climatic influences on ET are incorporated into ET_o and crop specific influences on ET are reflected in K_c values. The Food and Agriculture Organization of the United Nations (FAO) first published a procedure using the $K_c ET_o$ approach for calculating ET_c (Doorenbos and Pruitt 1977). Four alternative methods for calculating ET_o were suggested. Since this publication, advances in research and understanding of crop water requirements revealed the need to revise and update the calculation procedures (Allen et al. 1998, pp. 15 through 18). Improvements were identified and incorporated in the FAO Irrigation and Drainage Paper 56, Crop Evapotranspiration (Allen et al. 1998, pp. 15 through 18). The methods for calculating crop water requirements and irrigation supply requirements presented in Allen et al. (1998) and Doorenbos and Pruitt (1977) were used in this analysis report.

2. JUSTIFICATION FOR USE OF FAO METHODS

There is a long history of the study of ET that dates back to the late 1800s (Jensen et al. 1990, p. 4). One of the advancements in estimating ET occurred when Penman developed an equation to estimate evaporation from a free water surface using energy balance concepts (Allen et al. 1998, pp. 18 and 19). This free water surface was originally proposed as a reference surface. However, differences in aerodynamics, water vapor diffusion, and radiation characteristics between open water and a vegetated surface made relating ET to free water evaporation difficult (Allen et al. 1998, p. 23). The approach was later modified by Penman to apply to leaf surfaces, and then by Monteith to apply to whole plant canopies (Equation B-1). Net radiation balance, ambient temperature, vapor pressure deficit, conductance at the soil or canopy surface, and leaf or canopy conductance characterize the rate of water loss from a vegetated surface (Allen et al. 1998, Equation 3, p. 19):

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)} \quad (\text{Eq. B-1})$$

where

- ET = evapotranspiration (mm day⁻¹),
- R_n = net radiation energy (MJ m⁻² day⁻¹),
- G = soil heat flux (MJ m⁻² day⁻¹),
- ρ = density of air (kg m⁻³),
- c_p = specific heat of air (MJ kg⁻¹ °C⁻¹),
- $e_s - e_a$ = vapor pressure deficit (kPa),
- Δ = slope of saturation vapour pressure curve (kPa °C⁻¹),
- λ = latent heat of vaporization (MJ kg⁻¹),
- γ = psychrometric constant (kPa °C⁻¹),
- r_s and r_a = (bulk) surface and aerodynamic resistances (s m⁻¹).

A variety of modifications to the Penman-Monteith equation have been developed to provide ease of calculation, or to provide methods for ET calculation when the data required for the Penman-Monteith are not available. Several of these methods for calculating ET_o can provide reasonable predictions of ET for specific environmental circumstances. Several methods for estimating ET_o have been evaluated in various comparative studies (see Jensen et al. 1990, pp. 164 through 265; Martin et al. 1991; and Ventura et al. 1999 for examples). In a comprehensive evaluation of 20 different methods for estimating ET_o , Jensen et al. (1990, pp. 164 through 265) compared calculated ET_o values to measured ET in 11 variable climate locations. Published evaluations of six commonly used methods are described below to show that the selected FAO methods lessen the uncertainties in irrigation parameters compared to the alternatives.

2.1 Thornthwaite Formula.

The Thornthwaite formula, based on air temperature, is one of the simplest approaches for calculating potential ET (Martin et al. 1991):

$$PE = 1.6 \frac{(10T)^a}{I} \quad (\text{Eq. B-2})$$

where

- PE = potential evapotranspiration (mm),

T = mean monthly temperature (°C),

I = heat index, constant for a site, function of long term mean temperatures,

a = an empirical derived value that is function of I .

However, it has limited applicability and its recommended use is restricted to climates similar to that of the east-central region of the United States (Martin et al. 1991; Jensen et al. 1990, pp. 225 through 235). Jensen et al. (1990, pp. 225 through 235) showed that the Thornthwaite formula consistently underestimated ET at arid locations and was one of the poorest methods in estimating ET_o when compared to measured ET . Therefore, the Thornthwaite formula was considered inadequate for this analysis.

2.2 Blaney-Criddle

The Blaney-Criddle method, also based on air temperature, was modified in Doorenbos and Pruitt (1977, p. 3) to develop a grass reference method (Equation B-3). Jensen et al. (1990, p. 235) showed that this method tended to overestimate ET_o by 15 to 25 percent in humid climates, but provided good estimates in arid climates when compared to measured data. Martin et al. (1991, p. 333) suggested that the modified Blaney-Criddle (Equation B-3) should only be considered an approximate method for determining ET_o for irrigation scheduling, and that other methods were preferable if appropriate atmospheric data were available.

$$ET_o = k_1 + k_2(pT/100) \quad (\text{Eq. B-3})$$

where

ET_o = daily ET for a grass reference crop,

T = average air temperature,

p = percent of annual sunlight,

k_1 and k_2 = adjustment coefficients for the FAO method.

2.3 Jensen-Haise

The Jensen-Haise equation is an energy balance approach used to predict ET_o for an alfalfa reference surface (Martin et al. 1991, Equation 2, p. 334; Jensen et al. 1990, p. 166):

$$ET_o = C_T(T - T_x)R_s / 1486 \quad (\text{Eq. B-4})$$

where

$C_T = 1/(C_1 + C_2C_H)$,

$C_1 = 68 - 3.6(\text{elevation in feet})/1,000$,

$C_2 = 13, \text{ }^\circ\text{F}$ (a constant),

$$C_H = 50/(e_2 - e_1), \text{ mbars,}$$

$$T_x = 27.5 - 0.25(e_2 - e_1) - \text{elevation}/1,000,$$

e_2 = saturated vapor pressure (mbars) at the mean maximum air temperature for the hottest month,

e_1 = Saturated vapor pressure (mbars) at the mean minimum air temperature for the hottest month,

R_s = Incoming solar radiation, langleys/day,

T = Average monthly air temperature, °F.

This equation uses air temperature, incoming solar radiation, and air humidity to calculate ET_o . Elevation and latitude are used to correct for local conditions. It is more reliable for arid climates than Blaney-Criddle because of the inclusion of solar radiation and adjustments for local conditions (Martin et al.1991). It was less reliable in semiarid to subhumid climates where it tended to underestimate ET_o when compared to measured data (Jensen et al. 1990, p. 235).

The Jensen-Haise equation was used in the Analysis Model Report ANL-MGR-MD-000001, *Input Parameter Values for External and Inhalation Radiation Exposure Analysis* (CRWMS M&O 2000b, pp. 48 through 50) to calculate ET_o to determine irrigation rates for turf under current climate conditions. However, use of a grass as opposed to the alfalfa reference surface used in Jensen-Haise was preferred in the current analysis because published K_c values for a grass reference were available for all of the representative crops. Additionally, because the Jensen-Haise method tended to underestimate ET_o in semi-arid and sub-humid climates, it would likely underestimate ET_o for the glacial transition climate (future climate analog) required for this analysis.

2.4 Priestley-Taylor

The Priestley-Taylor method is a simplification of the Penman-Montieth equation with the absence of an advection term for sensible heat energy (Jensen et al. 1990, Equation 6.35, p. 100):

$$ET_o = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (\text{Eq. B-5})$$

where

α = constant ranging from 1.08 to 1.34 depending on the crop and location,

Δ = slope of the saturation vapor pressure-temperature curve,

γ = psychrometric constant,

R_n = net radiation,

G = soil heat flux.

The equation was developed to predict ET_o for a grass reference under humid conditions with a wet grass surface (Jensen et al. 1990, p. 100). Hatfield and Allen (1996) compared the results of the Priestley-Taylor method and the Penman-Montieth equation (Equation B-1) with measured

ET under arid conditions. They found the Penman-Monteith model tracked actual *ET* for cotton, grain sorghum, and grass forage better and more consistently throughout the growing season than the Priestley-Taylor method. When compared to measured *ET*, the Priestley-Taylor method produced reasonably good estimates in humid locations; however, it substantially underestimated seasonal *ET* in arid climates (Jensen et al. 1990, p. 235) making it inappropriate for this analysis.

2.5 FAO Corrected Penman

The FAO corrected Penman equation was modified from the original Penman by Doorenbos and Pruitt (1977) to estimate ET_o for a grass reference surface (Equation B-6). A more sensitive wind function, an adjustment factor for local weather conditions (c), and an assumption that soil heat flux (G) equals 0 for daily time frames were added to the original Penman:

$$ET_o = c \left[\frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} 2.7 W_f (e_z^o - e_z) \right] \quad (\text{Eq. B-6})$$

where

c = adjustment factor to compensate for local climate conditions,

Δ = slope of the saturation vapor pressure-temperature curve,

γ = psychrometric constant,

R_n = net radiation,

G = soil heat flux,

W_f = temperature related weighting factor,

$e_z^o - e_z$ = difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air.

The Penman-Monteith and FAO corrected Penman equations (Equations B-1 and B-6) were fairly well correlated with measured *ET* data in 10 of 11 sites studied by Jensen et al. (1990, p. 234). However, the FAO corrected Penman equation consistently overestimated ET_o under both humid and arid conditions (Jensen et al. 1990, p. 234; Allen et al 1998, p. 17).

The variable results of these and other validation studies prompted the FAO to elicit scientists and specialists to establish recommendations for an ET_o formula that was generally applicable under a wide variety of conditions without the need for extensive local calibrations (see Allen et al. 1998, pp. v, 17, and 18). The consultations and recommendations resulted in revised methodologies that are published by the FAO in Allen et al. (1998). The FAO Penman-Monteith method is currently recommended as the standard for calculating ET_o (Allen et al. 1998). Based on this recommendation and the results of studies by Jensen et al. (1990), Martin et al. (1991), and Hatfield and Allen (1996), it was determined that the FAO methodologies in Allen et al. (1998) would reduce the uncertainties in irrigation parameters compared to other methods, and produce valid, reasonable parameter values.

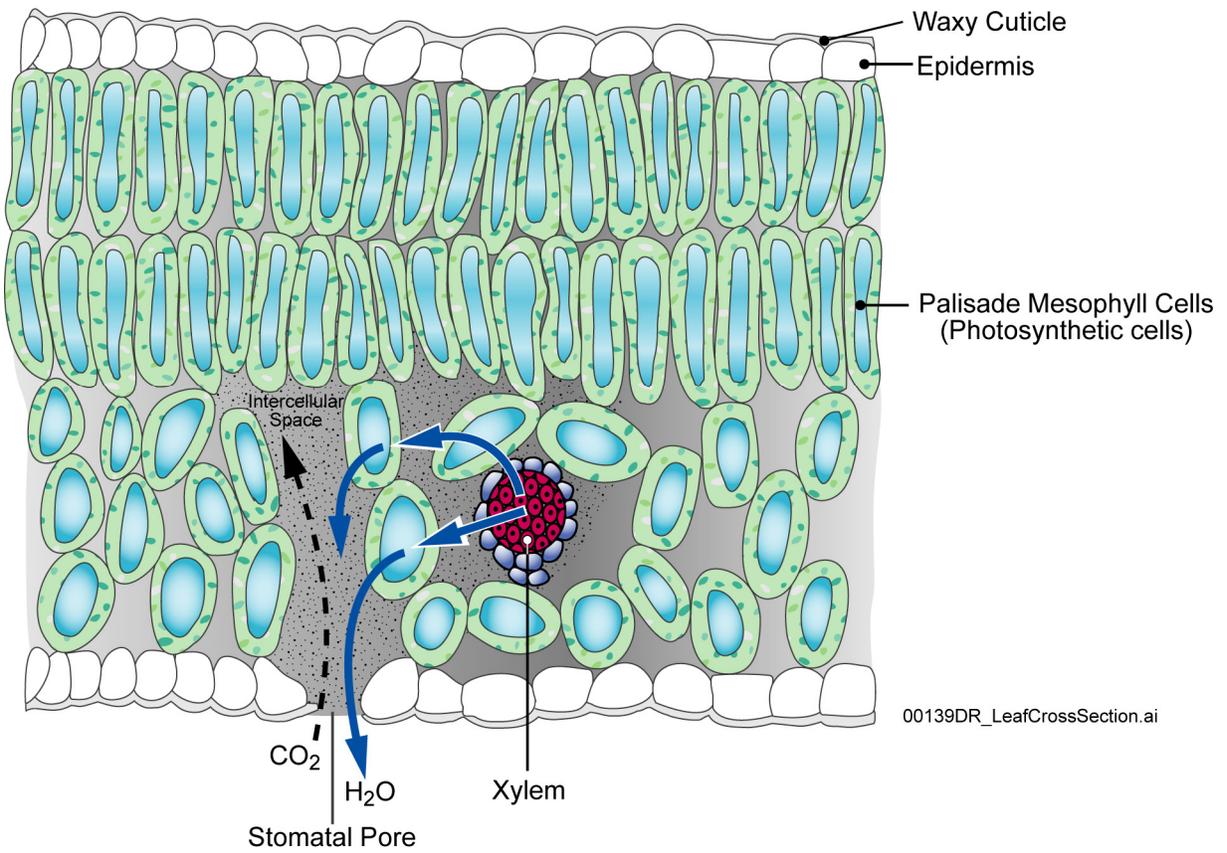


Figure B-1. Leaf cross section showing diffusional pathway for carbon dioxide (CO_2) and water (H_2O)

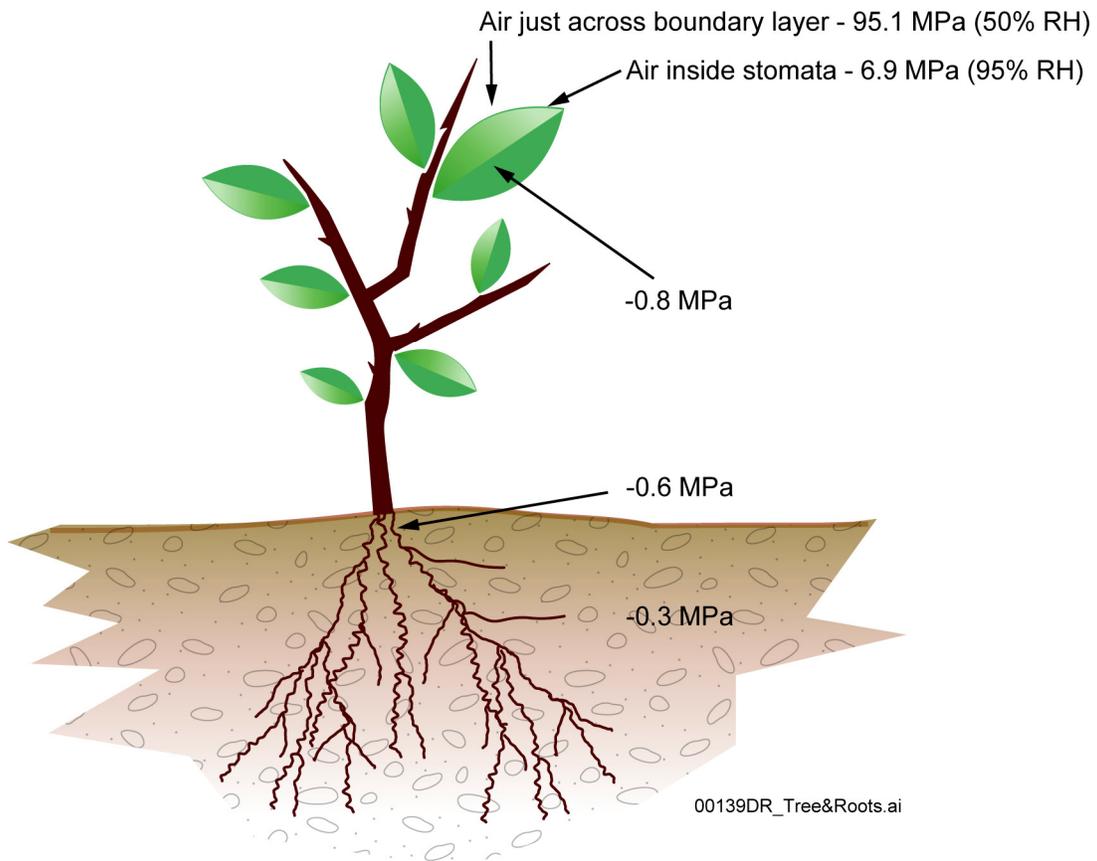


Figure B-2. Water potential (MPa) in various components of the soil-plant-atmosphere system. Water moves through the system along a gradient of increasingly negative water potentials.

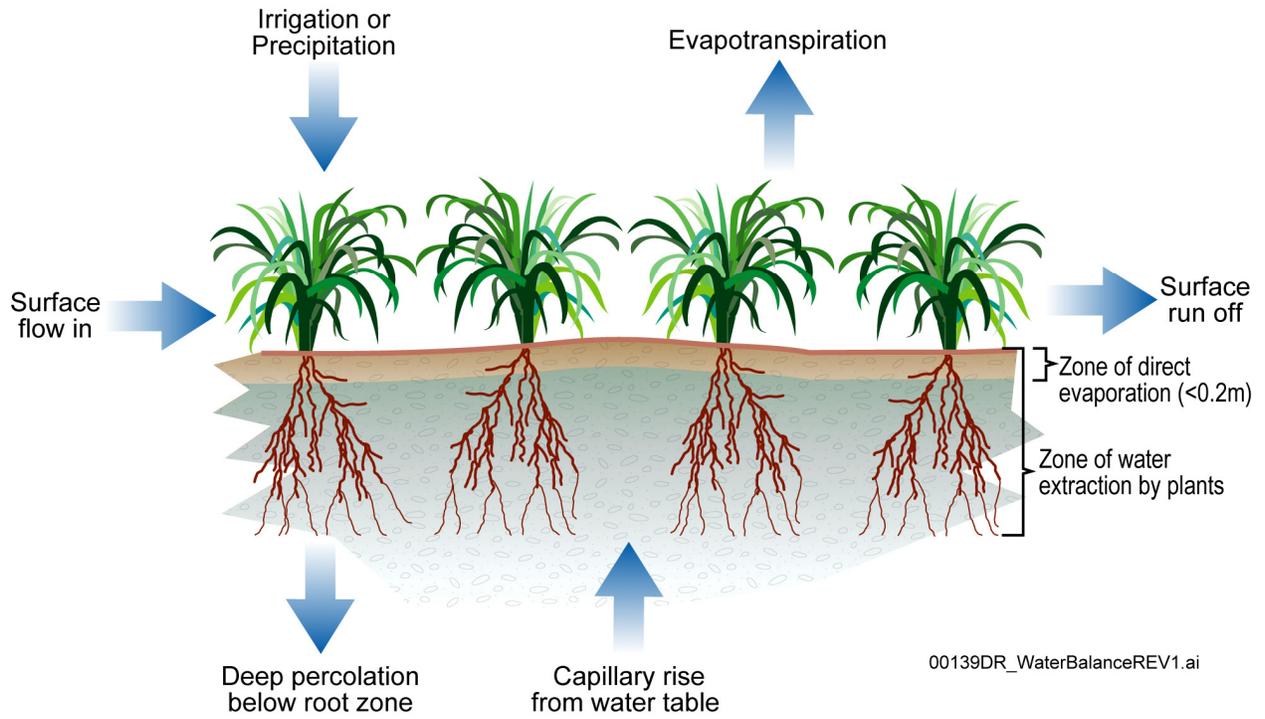


Figure B-3. Water balance of a cropped field

APPENDIX C
METHODS FOR CALCULATING REFERENCE EVAPOTRANSPIRATION

APPENDIX C. METHODS FOR CALCULATING REFERENCE EVAPOTRANSPIRATION

1. INTRODUCTION

Reference evapotranspiration (ET_o) was calculated for a grass reference surface and represents the effects of climate on crop ET . The reference surface as defined by Allen et al. (1998, p. 15) is a “hypothetical grass reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23”. It is considered to be of uniform height, actively growing, completely shading the ground, with an adequate water supply.

Meteorological factors that drive evapotranspiration include solar radiation, air temperature, air humidity, and wind speed. Climatological and physical parameters required to derive monthly mean ET_o were either measured directly or derived from standard meteorological data. Weather data inputs are described in Section 4.1.5 (Tables 4.1-2, 4.1-3, 4.1-4, and 4.1-5). Monthly mean ET_o was calculated for current, upper bound monsoon, lower bound future, and future climate conditions. Altitude and latitude of the YMP meteorological monitoring Site 9 were used in calculations for all climate conditions.

The FAO Penman-Monteith equation was used to calculate ET_o (Allen et al. 1998, Equation 6, p. 24):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (\text{Eq. C-1})$$

where

ET_o = reference evapotranspiration (mm day^{-1}),

R_n = net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$),

G = soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$),

T = mean daily air temperature at 2 m height ($^{\circ}\text{C}$),

u_2 = wind speed at 2 m height (m s^{-1}),

e_s = saturation vapor pressure (kPa),

e_a = actual vapour pressure (kPa),

$e_s - e_a$ = saturation vapour pressure deficit (kPa),

Δ = slope vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$),

γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

Justification for use of this equation is in Appendix B. The step-by-step methods to calculate ET_o are described and example calculations are provided below.

2. CALCULATIONS

Several calculations related to humidity and radiation parameters are required to generate the variables used in Equation C-1.

2.1 Humidity

Atmospheric humidity is an important driver of transpiration from plant leaves. The air in the intercellular spaces of a leaf (Appendix B, Figure B-1) is nearly saturated with water vapor. As the air outside the leaf dries, the leaf to air water vapour gradient increases, increasing the rate of water loss through the stomata (Appendix B, Figure B-2). With increasing evaporative demands the plant will begin to close stomata to prevent water loss. However, stomatal closure also results in reduced concentrations of CO₂ for use in photosynthesis (see Appendix B for additional background). Similarly, when atmospheric humidity is high, the leaf-to-air water vapour gradient decreases. This results in lower evaporative demand, allowing stomates to remain open without high rates of water loss.

Three atmospheric parameters were generated from meteorological data and used directly in the calculation of ET_o . These include the slope of the saturation vapour pressure curve (Δ), the psychrometric constant (γ), and the vapor pressure deficit ($e_s - e_a$).

2.1.1 Slope of Saturation Vapour Pressure Curve (Δ)

Δ is the slope of the relationship between the saturation vapour pressure of the air and air temperature. Vapour pressure is the component of total atmospheric pressure exerted by the motion of water vapour molecules. Saturation vapour pressure is the vapour pressure the air would have if it were saturated with water vapour molecules at a given temperature. As temperature increases, the storage capacity of the air increases, which results in higher saturation vapour pressure. Δ is calculated from mean monthly air temperature (°C) according to the following equation (Allen et al. 1998, Equation 13, p. 37):

$$\Delta = 4098 \left[\frac{0.6108 \exp\left(\frac{17.22T}{T + 237.3}\right)}{(T + 237.3)^2} \right] \quad (\text{Eq. C-2})$$

where

$\exp(x)$ = 2.7183 (base of natural logarithm) raised to the power (x),

T = mean monthly air temperature (°C).

Example:

For January current climate conditions, $T = 7.1$ °C (see Table 4.1-2).

$$\Delta = 4098 \left[\frac{0.6108 \exp\left(\frac{17.22 \times 7.10}{7.10 + 237.3}\right)}{(7.10 + 237.3)^2} \right] = 4098 \left[\frac{0.6108 \times 1.6491}{59,731.36} \right] = 0.069 \text{ kPa } ^\circ\text{C}^{-1} \quad (\text{Eq. C-2})$$

Monthly mean Δ values for current, upper bound monsoon, lower bound future, and future climate conditions are in Tables C-1, C-2, C-3, and C-4 respectively.

2.1.2 Psychrometric Constant (γ)

The psychrometric constant represents a balance between the heat required to evaporate water into an air stream from the wick of a wet bulb thermometer (wet wick with thermometer beneath it) and the air's potential to absorb the water and carry it away. The constant is dependent on atmospheric pressure, latent heat of vaporization (energy required for evaporation), the specific heat of air at a constant pressure (quantity of energy required to raise the temperature of a given amount of air by one degree at constant pressure), and the ratio of molecular weight of water vapour to dry air. Values for γ at different altitudes are provided in Allen et al. (1998, Table 2.2, p. 214). The weather station altitude of 838 m for the Yucca Mountain meteorological monitoring Site 9 (data for current climatic conditions) corresponds to a table value for γ of 0.061 kPa $^\circ\text{C}^{-1}$. This value was used in the calculations of ET_o for current, upper bound monsoon, lower bound future, and future climates.

2.1.3 Vapour Pressure Deficit ($e_s - e_a$)

The vapour pressure deficit ($e_s - e_a$) is the difference between the saturation vapor pressure (e_s) and the actual vapor pressure (e_a) of the air. Essentially, it is the amount of water vapor that the air could still hold before becoming saturated and represents the evaporative power of the air. The air becomes dryer as the vapor pressure deficit increases.

Mean e_s is calculated from mean monthly maximum and minimum air temperatures (see Tables 4.1-2, 4.1-3, 4.1-4, and 4.1-5 for temperature data). The relationship of e_s to temperature is given by the following (Allen et al. 1998, Equations 11 and 12, p. 36):

$$e^o(T) = 0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right] \quad (\text{Eq. C-3})$$

where

$e^o(T)$ = saturation vapour pressure at temperature T (kPa),

T = air temperature ($^\circ\text{C}$),

$\exp(x)$ = 2.7183 (base of natural logarithm) raised to the power (x),

and

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \quad (\text{Eq. C-4})$$

Example: For January current climate conditions, $T_{max} = 13.50$ °C and $T_{min} = 1.30$ °C (Table 4.1-2).

$$e^o(T_{max}) = 0.6108 \exp\left[\frac{17.27(13.5)}{13.5 + 237.3}\right] = 0.6108 \exp 0.929 = 1.55 \text{ kPa} \quad (\text{Eq. C-3})$$

$$e^o(T_{min}) = 0.6108 \exp\left[\frac{17.27(1.30)}{1.30 + 237.3}\right] = 0.6108 \exp 0.094 = 0.67 \text{ kPa} \quad (\text{Eq. C-3})$$

$$e_s = \frac{1.548 + 0.6711}{2} = 1.1093 \text{ kPa} \quad (\text{Eq. C-4})$$

Monthly $e^o(T_{max})$, $e^o(T_{min})$, and e_s for current, upper bound monsoon, lower bound future, and future climate conditions are in Tables C-1, C-2, C-3, and C-4 respectively.

Actual vapour pressure (e_a) can be calculated from relative humidity (RH), the dewpoint temperature (T_{dew}), or psychrometric data. No air humidity data were available for the upper bound monsoon climate and so T_{dew} was calculated from T_{min} using equation C-5 (see below). Monthly mean T_{dew} was available from the Delta, Utah weather station (lower bound future climate analog). Monthly mean T_{dew} was used in equation C-6 to calculate e_a for the upper bound monsoon and lower bound future climates (see below). Monthly mean maximum and minimum RH values were available for both current and future climates. However, examination of RH values for the current climate indicated that these values were not representative of the expected conditions of the reference area for which ET_o was calculated (See Allen et al. 1998, Annex 6, pp. 257 through 264). Under reference area conditions, RH_{max} is expected to approach 90 - 100 percent. For the current climate, mean RH_{max} ranged from a low of 23.7 percent in July to a high of 61.9 percent in January (Sections 4.1.3.1, Table 4.1-2). Use of such low RH values would result in overestimation of ET_o , which would translate into overestimation of crop irrigation requirements. Allen et al. (1998, p. 36 and Annex 6, pp. 257 through 262) recommended use of T_{dew} calculated from daily minimum temperature rather than using unreliable or unrepresentative RH values, or when no humidity data is available. Therefore, instead of using RH_{max} to calculate e_a for the current climate and in the absence of humidity data for the upper bound monsoon climate, T_{dew} was estimated from T_{min} (Allen et al. 1998, Equation 6-6, p. 261):

$$T_{dew} = T_{min} - K_o \quad (\text{Eq. C-5})$$

Where $K_o = 0$ °C for January, 1 °C for February, 3 °C for March through October, 1 °C for November, and 0 °C for December for current climate, and $K_o = 1$ °C for all months for upper bound monsoon climate. Different values for K_o were used for current climate because the extreme aridity could cause the minimum temperature to be significantly greater than the dewpoint temperature in spring through fall months. Smaller differences between minimum

temperature and dewpoint were expected during the same time period for the moister monsoon climate. The monsoon climate has warmer (more evaporative) winter seasons than current climate making the 1 °C adjustment appropriate for December and January. These adjustments increased values of T_{dew} to reflect the higher humidity anticipated under reference conditions. The adjusted T_{dew} was used in the following equation to calculate e_a for the current and upper bound monsoon climates (Allen et al. 1998, Equation 14, p. 37):

$$e_a = e^o(T_{dew}) = 0.6108 \exp\left[\frac{17.27T_{dew}}{T_{dew} + 237.3}\right] \quad (\text{Eq. C-6})$$

Example: For January current climate $T_{min} = 1.3$ °C (Section 4.1.5.1, Table 4.1-2) and $T_{dew} = 1.3$ °C (Equation C-5).

$$e_a = 0.6108 \exp\left[\frac{17.27 \times 1.3}{1.3 + 237.3}\right] = 0.6108 \exp(0.0941) = 0.671 \text{ kPa} \quad (\text{Eq. C-6})$$

Because RH_{max} from the future climate data set approached 90 percent for most months (Section 4.1.5.4, Table 4.1-5) no correction was needed. Therefore, RH_{min} , RH_{max} , T_{min} , and T_{max} were used to calculate e_a (Allen et al. 1998, Equation 17, p. 38):

$$e_a = \frac{e^o(T_{min}) \frac{RH_{max}}{100} + e^o(T_{max}) \frac{RH_{min}}{100}}{2} \quad (\text{Eq. C-7})$$

Example: For January future climate $RH_{min} = 79$ percent and $RH_{max} = 86$ percent (Section 4.1.5.4, Table 4.1-5), $e^o(T_{min}) = 0.384$ and $e^o(T_{max}) = 0.641$ (from Table C-4).

$$e_a = \frac{0.384(.86) + 0.641(.79)}{2} = \frac{0.330 + 0.506}{2} = 0.418 \text{ kPa} \quad (\text{Eq. C-7})$$

Monthly e_a values for current, upper bound monsoon, lower bound future, and future climates are in Tables C-1, C-2, C-3, and C-4 respectively.

Using mean e_s and e_a calculated for January current climate conditions, the vapor pressure deficit is:

$$(e_s - e_a) = 1.1093 - 0.671 = 0.438 \text{ kPa} \quad (\text{Eq. C-8})$$

Monthly $(e_s - e_a)$ values for current, upper bound monsoon, lower bound future, and future climates are in Tables C-1, C-2, C-3, and C-4 respectively.

2.2 Radiation

Net radiant energy is one of the main factors controlling the energy balance of a vegetated soil surface. Heat energy for ET is principally supplied by solar radiation, which can reach the plant canopy as direct sunlight, or sunlight scattered by molecules and particles in the atmosphere.

Both direct and scattered sunlight can be reflected by surroundings to the plant canopy. Net radiation (R_n) represents the balance between energy absorbed, reflected, and emitted by the earth's surface and is used directly in the calculation of ET_o . Extraterrestrial radiation (R_a), solar radiation (R_s), relative sunshine duration (n/N), clear sky radiation (R_{so}), net shortwave radiation (R_{ns}), and net longwave radiation (R_{nl}) are required either directly or indirectly in calculating R_n .

2.2.1 Extraterrestrial Radiation (R_a)

Extraterrestrial radiation is the solar radiation received at the top of the earth's atmosphere on a horizontal surface. It is a function of latitude, date, and time of day. Allen et al. (1998) provide R_a values for the 15th day of each month for different latitudes (Annex 2, Table 2.6, p. 219). These values provide an estimate of R_a that deviates from the monthly average by less than 1 percent. Because the latitude will not change among climate conditions, latitude for the weather station representing current climate was used and R_a was the same for all climate conditions.

Example: Weather station latitude for the current climate was $36^\circ 40' 38''$ (Table 4.1-2). From Table 2.6 (Allen et al., 1998, p. 219), R_a for January at the station latitude is $17.5 \text{ MJ m}^{-2} \text{ day}^{-1}$.

Monthly R_a averages are in Tables C-5, C-6, C7, and C8.

2.2.2 Solar Radiation (R_s)

Solar radiation (R_s) was measured at the YMP meteorological monitoring Site 9 for the current climate (Section 4.1.5, Table 4.1-2). However, it was not measured at the Nogales, Delta, or Spokane weather stations, (analogues for upper bound monsoon, lower bound future, and future climates), and was therefore calculated according to Allen et al. (1998, Equation 35, p. 50). This equation uses the Angstrom formula to relate R_s to relative sunshine duration and R_a :

$$R_s = \left(a_s + b_s \frac{n}{N} \right) R_a \quad (\text{Eq. C-9})$$

where

n/N = relative sunshine duration (percent of possible sunshine),

a_s = fraction of extraterrestrial radiation reaching the earth on overcast days ($n = 0$),

$a_s + b_s$ = fraction of extraterrestrial radiation reaching the earth on clear days ($n = N$),

R_a = extraterrestrial radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

The Angstrom values a_s and b_s vary with atmospheric conditions such as dust and humidity, and with solar declination. However, no site specific calibration for these variables were available. Therefore the values of $a_s = 0.25$ and $b_s = 0.50$ recommended by Allen et al. (1998, p. 50) were used in the calculations of R_s for upper bound monsoon, lower bound future, and future climates. Values for percent of possible sunshine (n/N) from Tables 4.1-3, 4.1-4, and 4.1-5 were converted to decimal values for calculations of R_s .

Example: January R_a for future climate = 17.5 (from Table C-8), and $n/N = 0.28$ (converted from percent to decimal for calculation, Table 4.1-5).

$$R_s = (0.25 + 0.50 (0.28)) \times 17.5 = 6.8 \text{ MJ m}^{-2} \text{ day}^{-1} \quad (\text{Eq. C-9})$$

Monthly R_s values for current and future climates are in Tables C-5, C-6, C-7, and C-8, .

2.2.3 Clear Sky Radiation (R_{so})

Clear sky radiation (R_{so}) is the radiation that would hit a flat surface under cloudless conditions (Allen et al. 1998, Equation 37, p. 51):

$$R_{so} = (0.75 + 2 \times 10^{-5} Z) R_a \quad (\text{Eq. C-10})$$

where

Z = station elevation above sea level (m, note that this is the same for all climates).

Example: Station elevation for the current climate = 838 m and R_a for January = 17.5 (from Table C-5).

$$R_{so} = (0.75 + 2 \times 10^{-5} \times 838) 17.5 = 13.4 \text{ MJ m}^{-2} \text{ day}^{-1} \quad (\text{Eq. C-10})$$

Clear sky radiation is required to calculate net longwave radiation (R_{nl}) which is used directly in the calculation of R_n . Mean monthly R_{so} values are in Tables C-5, C-6, C-7, and C-8.

2.2.4 Net Solar (shortwave) Radiation (R_{ns})

Net solar radiation incorporates albedo (shortwave radiation reflected from the canopy of the grass reference crop) into incoming solar radiation and is used directly in the calculation of R_n (Allen et al. 1998, Equation 38, p. 51):

$$R_{ns} = (1 - \alpha) R_s \quad (\text{Eq. C-11})$$

where:

α = albedo of grass reference crop = 0.23 (Allen et al. 1998, p. 51).

Example: For January current climate $R_s = 9.5 \text{ MJ m}^{-2} \text{ day}^{-1}$ (From Table C-5).

$$R_{ns} = (1 - 0.23) 9.5 = 7.3 \text{ MJ m}^{-2} \text{ day}^{-1} \quad (\text{Eq. C-11})$$

Mean monthly R_{ns} values are in Tables C-5, C-6, C-7, and C-8.

2.2.5 Net Longwave Radiation (R_{nl})

Net loss of radiant energy (R_{nl}) occurs primarily through thermal or longwave radiation. The Stefan-Boltzmann law predicts that black body radiation emission (radiation emitted by a perfect radiator) is proportional to surface temperature raised to the fourth power (Nobel 1983b, p. 347). Plants are virtually black body absorbers and emitters to longwave radiation. However, radiant energy is also absorbed and emitted by water vapor, carbon dioxide, ozone and clouds which affects the outgoing energy flux. Because of this, the Stefan-Boltzmann law is corrected for humidity and cloudiness in the calculation of net outgoing longwave radiation (R_{nl} , Allen et al. 1998, Equation 39, p. 52):

$$R_{nl} = \sigma \left[\frac{T_{max, K^4} + T_{min, K^4}}{2} \right] \left(0.34 - 0.14 \sqrt{e_a} \right) \left[1.35 \frac{R_s}{R_{so}} - 0.35 \right] \quad (\text{Eq. C-12})$$

where

σ = Stefan-Boltzmann constant ($4.903 \times 10^{-9} \text{ MJ K}^{-4} \text{ m}^{-2} \text{ day}^{-1}$),

$T_{max, K}$ = maximum absolute temperature during the 24-hour period ($K = ^\circ\text{C} + 273.16$),

$T_{min, K}$ = minimum absolute temperature during the 24-hour period ($K = ^\circ\text{C} + 273.16$),

e_a = actual vapour pressure (kPa),

R_s/R_{so} = relative shortwave radiation (limited to ≤ 1.0),

R_s = measured (current climate) or calculated (future climate) solar radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$),

R_{so} = calculated clear-sky radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$).

Example: For January current climate $T_{max} = 13.5 \text{ }^\circ\text{C}$ and $T_{min} = 1.3 \text{ }^\circ\text{C}$ (Section 4.1.5, Table 4.1-2), $e_a = 0.671$ (Table C-1), $R_s = 9.5 \text{ MJ m}^{-2} \text{ day}^{-1}$, $R_{so} = 13.4 \text{ MJ m}^{-2} \text{ day}^{-1}$ (Table C-5).

Allen et al. (1998) provides values for $\sigma T_{max, K^4}$ based on air temperatures ($^\circ\text{C}$) (Table 2.8 p. 221). For $T_{max} = 13.5 \text{ }^\circ\text{C}$ the value for $\sigma T_{max, K^4} = 33.11$. For $T_{min} = 1.30 \text{ }^\circ\text{C}$ the value for $\sigma T_{min, K^4} = 27.90$.

$$\begin{aligned} R_{nl} &= \left[\frac{33.11 + 27.90}{2} \right] \left(0.34 - 0.14 \sqrt{0.671} \right) \left[1.35 \left(\frac{9.5}{13.4} \right) - 0.35 \right] \quad (\text{Eq. C-12}) \\ &= 30.46 \times 0.225 \times 0.606 = 4.2 \text{ MJ m}^{-2} \text{ day}^{-1} \end{aligned}$$

Mean monthly R_{nl} values are in Tables C-5, C-6, C-7, and C-8.

2.2.6 Net Radiation (R_n)

Net Radiation is the balance between net shortwave radiation (both incoming and reflected) and net loss of longwave radiation (Allen et al. 1998, Equation 40, p. 53):

$$R_n = R_{ns} - R_{nl} \quad (\text{Eq. C-13})$$

Example: For January current climate $R_{ns} = 7.3$ and $R_{nl} = 4.2$ (from Table C-5).

$$R_n = 7.3 - 4.2 = 3.2 \text{ MJ m}^{-2} \text{ day}^{-1} \quad (\text{Eq. C-13})$$

Mean monthly R_n values are in Tables C-5, C-6, C-7, and C-8.

2.3 Soil Heat Flux

Soil heat flux (G) can be derived for monthly periods assuming a constant soil heat capacity of $2.1 \text{ MJ m}^3 \text{ }^\circ\text{C}^{-1}$ and that, over long time periods, soil temperature at a depth of 2 m changes approximately with average air temperature (Allen et al. 1998, Equation 43, p. 54)

$$G_{\text{month},i} = 0.07(T_{\text{month},i+1} - T_{\text{month},i-1}) \quad (\text{Eq. C-14})$$

Example: For January current climate, $T_{\text{month},i+1} = 9.6 \text{ }^\circ\text{C}$ and $T_{\text{month},i-1} = 6.9 \text{ }^\circ\text{C}$ (Table 4.1-2).

$$G_{\text{january}} = 0.07(9.6 - 6.9) = 0.19 \quad (\text{Eq. C-14})$$

Monthly values for G are in Tables C-5, C-6, C-7 and C-8, respectively.

2.4 Wind Speed (u_2)

Wind speed (u_2) data were collected at the weather stations for current, upper bound monsoon, and future climates. Wind speed for lower bound future climate was taken from Milford, Utah, the closest weather station to Delta, Utah (lower bound future climate analog). Standard anemometer height in agrometeorology is 2 m above the ground surface (Allen et al. 1998, p. 55). Anemometer height at the weather stations used in this analysis was 10 m. Because wind speed increases with height above the soil surface, a logarithmic wind profile function is required to adjust wind speeds placed at heights other than the standard 2 m. Therefore, the following correction was made for wind speed (Allen et al. 1998, Equation 47, p. 56):

$$u_2 = u_z \frac{4.87}{\ln(67.8z - 5.24)} \quad (\text{Eq. C-15})$$

where

u_z = wind speed measured at z m above ground surface (m s^{-1}),

z = height of measurement above ground surface (m).

Example: For January future climate, $u_{10} = 3.9 \text{ m s}^{-1}$ (Table 4.1-5).

$$u_2 = 3.9 \frac{4.87}{\ln(67.8 * 10 - 5.24)} = 2.9 \text{ m s}^{-1} \quad (\text{Eq. C-15})$$

Mean monthly values for u_2 are in Tables C-5, C-6, C-7, and C-8.

2.5 Reference Evapotranspiration

Using the humidity, radiation, soil heat flux, and wind speed values generated in this Appendix for January current climate, mean monthly ET_o for January can be calculated using Equation C-1.

Example: For January current climate conditions,

$$\Delta = 0.069$$

$$Rn = 3.2$$

$$G = 0.19$$

$$\gamma = 0.061$$

$$T = 7.1$$

$$u_2 = 2.9$$

$$(e_s - e_a) = 0.438$$

$$ET_o = \frac{0.408 * 0.069(3.2 - 0.19) + 0.061 \frac{900}{7.1 + 273} 2.9(0.438)}{0.069 + 0.061(1 + 0.34 * 2.9)} = 1.73 \text{ mm/day} \quad (\text{Eq. C-1})$$

Mean monthly ET_o for current, upper bound monsoon, lower bound future, and future climates are in Table C-9.

Table C-1. Atmospheric Parameters for Current Climate Conditions

Month	T _{dew} (°C)	e ^o _{Tmax} (kPa)	e ^o _{Tmin} (kPa)	e _s (kPa)	Δ (kPa °C ⁻¹)	e _a (kPa)	e _s - e _a (kPa)
January	1.3	1.547	0.671	1.109	0.069	0.671	0.438
February	2.1	1.889	0.763	1.326	0.080	0.711	0.615
March	3.1	2.564	0.942	1.753	0.101	0.763	0.990
April	5.1	3.093	1.080	2.087	0.120	0.878	1.208
May	10.1	4.268	1.508	2.888	0.161	1.236	1.651
June	15.4	5.717	2.116	3.917	0.212	1.750	2.167
July	18.5	7.067	2.564	4.816	0.254	2.13	2.686
August	17.9	6.954	2.472	4.713	0.248	2.051	2.662
September	13.7	5.231	1.901	3.566	0.192	1.568	1.998
October	7.0	3.361	1.228	2.295	0.127	1.002	1.293
November	2.6	2.103	0.791	1.447	0.085	0.737	0.710
December	0.8	1.588	0.647	1.118	0.068	0.647	0.470

Notes: T_{dew} = dewpoint temperature (Equation C-5).
e^o_{Tmax} = saturation vapor pressure at the maximum monthly air temperature (Equation C-3).
e^o_{Tmin} = saturation vapor pressure at the minimum monthly air temperature (Equation C-3).
e_s = saturation vapor pressure (Equation C-4).
Δ = the slope of the saturation vapor pressure curve (Equation C-2).
e_a = actual vapor pressure (Equation C-6).
e_s - e_a = vapor pressure deficit (Equation C-8).

Table C-2. Atmospheric Parameters for Upper Bound Monsoon Climate Conditions

Month	T _{dew} (°C)	e ^o _{Tmax} (kPa)	e ^o _{Tmin} (kPa)	e _s (kPa)	Δ (kPa °C ⁻¹)	e _a (kPa)	e _s - e _a (kPa)
January	-3.7	2.028	0.500	1.264	0.071	0.464	0.800
February	-2.2	2.267	0.559	1.413	0.078	0.519	0.894
March	0.1	2.617	0.662	1.640	0.090	0.616	1.024
April	2.6	3.307	0.788	2.047	0.108	0.734	1.313
May	6.3	4.270	1.025	2.648	0.135	0.957	1.691
June	11.4	5.745	1.439	3.592	0.178	1.347	2.245
July	16.5	5.486	2.000	3.743	0.199	1.877	1.866
August	16.2	5.157	1.958	3.558	0.192	1.838	1.720
September	12.2	4.845	1.514	3.180	0.168	1.418	1.762
October	5.4	3.743	0.961	2.352	0.124	0.896	1.456
November	-0.7	2.644	0.626	1.635	0.088	0.582	1.053
December	-3.4	2.071	0.512	1.292	0.072	0.476	0.816

Notes: T_{dew} = dewpoint temperature (Equation C-5).
e^o_{Tmax} = saturation vapor pressure at the maximum monthly air temperature (Equation C-3).
e^o_{Tmin} = saturation vapor pressure at the minimum monthly air temperature (Equation C-3).
e_s = saturation vapor pressure (Equation C-4).
Δ = the slope of the saturation vapor pressure curve (Equation C-2).
e_a = actual vapor pressure (Equation C-6).
e_s - e_a = vapor pressure deficit (Equation C-8).

Table C-3. Atmospheric Parameters for Lower Bound Future Climate Conditions

Month	$e^{\circ}_{T_{max}}$ (kPa)	$e^{\circ}_{T_{min}}$ (kPa)	e_s (kPa)	Δ (kPa °C ⁻¹)	e_a (kPa)	$e_s - e_a$ (kPa)
January	0.807	0.286	0.546	0.036	0.326	0.221
February	0.979	0.355	0.667	0.044	0.371	0.296
March	1.372	0.478	0.925	0.058	0.404	0.521
April	2.035	0.689	1.362	0.081	0.541	0.822
May	2.867	0.942	1.904	0.108	0.662	1.242
June	3.980	1.228	2.604	0.140	0.689	1.915
July	5.452	1.705	3.579	0.186	1.057	2.522
August	5.125	1.587	3.356	0.175	0.907	2.449
Sept	3.854	1.097	2.476	0.132	0.746	1.730
October	2.338	0.717	1.528	0.088	0.587	0.941
November	1.274	0.421	0.848	0.053	0.458	0.390
December	0.907	0.326	0.616	0.041	0.371	0.245

Notes: $e^{\circ}_{T_{max}}$ = saturation vapor pressure at the maximum monthly air temperature (Equation C-3).
 $e^{\circ}_{T_{min}}$ = saturation vapor pressure at the maximum monthly air temperature (Equation C-3).
 e_s = saturation vapor pressure (Equation C-4).
 Δ = the slope of the saturation vapor pressure curve (Equation C-2).
 e_a = actual vapor pressure (Equation C-6).
 $e_s - e_a$ = vapor pressure deficit (Equation C-8).

Table C-4. Atmospheric Parameters for Future Climate Conditions

Month	$e^{\circ}_{T_{max}}$ (kPa)	$e^{\circ}_{T_{min}}$ (kPa)	e_s (kPa)	Δ (kPa °C ⁻¹)	e_a (kPa)	$e_s - e_a$ (kPa)
January	0.641	0.384	0.512	0.037	0.418	0.094
February	0.859	0.476	0.667	0.047	0.498	0.169
March	1.127	0.554	0.840	0.056	0.529	0.312
April	1.587	0.681	1.134	0.072	0.611	0.523
May	2.167	0.903	1.535	0.093	0.781	0.754
June	2.934	1.192	2.063	0.120	0.975	1.088
July	3.867	1.444	2.655	0.148	1.011	1.645
August	3.793	1.439	2.616	0.146	0.984	1.632
Sept	2.680	1.049	1.864	0.109	0.828	1.036
October	1.681	0.717	1.199	0.075	0.695	0.504
November	0.886	0.536	0.711	0.050	0.570	0.141
December	0.657	0.399	0.528	0.038	0.448	0.080

Notes: $e^{\circ}_{T_{max}}$ = saturation vapor pressure at the maximum monthly air temperature (Equation C-3).
 $e^{\circ}_{T_{min}}$ = saturation vapor pressure at the maximum monthly air temperature (Equation C-3).
 e_s = saturation vapor pressure (Equation C-4).
 Δ = the slope of the saturation vapor pressure curve (Equation C-2).
 e_a = actual vapor pressure (Equation C-7).
 $e_s - e_a$ = vapor pressure deficit (Equation C-8).

Table C-5. Radiation parameters, Soil Heat Flux, and Wind Speed for Current Climate Conditions

Month	R_a (MJ m ⁻² day ⁻¹)	R_s (MJ m ⁻² day ⁻¹)	R_{so} (MJ m ⁻² day ⁻¹)	R_{ns} (MJ m ⁻² day ⁻¹)	R_{nl} (MJ m ⁻² day ⁻¹)	R_n (MJ m ⁻² day ⁻¹)	G (MJ m ⁻² day ⁻¹)	u_2 (m s ⁻¹)
January	17.5	9.5	13.4	7.3	4.2	3.2	0.19	2.8
February	22.6	13.9	17.3	10.7	5.1	5.6	0.46	3.1
March	29.0	19.4	22.2	14.9	6.0	8.9	0.50	3.3
April	35.7	24.6	27.4	18.9	6.2	12.7	0.60	3.6
May	40.0	27.5	30.7	21.2	5.9	15.3	0.75	3.5
June	41.7	29.9	32.0	23.0	5.6	17.4	0.62	3.5
July	40.8	29.4	31.3	22.6	5.2	17.4	0.22	3.4
August	37.4	27.0	28.7	20.8	5.3	15.4	-0.39	3.5
Sept	31.5	22.6	24.2	17.4	5.9	11.5	-0.90	3.3
October	24.6	17.4	18.9	13.4	6.3	7.1	-1.04	3.1
November	18.7	11.9	14.3	9.2	5.4	3.7	-0.76	3.1
December	16.1	9.6	12.3	7.4	4.8	2.5	-0.25	3.0

Notes: R_a = extraterrestrial radiation (from Allen et al., Annex 2, Table 2.6, p. 219).
 R_s = solar radiation (from Table 4.1-2).
 R_{so} = clear sky radiation (Equation C-10).
 R_{ns} = net solar radiation (Equation C-11).
 R_{nl} = net longwave radiation (Equation C-12).
 R_n = net radiation (Equation C-13).
G = solar heat flux (Equation C-14).
 u_2 = wind speed (from Table 4.1-2) corrected for height according to Equation C-15.

Table C-6. Radiation parameters, Soil Heat Flux, and Wind Speed for Upper Bound Monsoon Climate Conditions

Month	R_a (MJ m ⁻² day ⁻¹)	n/N	R_s (MJ m ⁻² day ⁻¹)	R_{so} (MJ m ⁻² day ⁻¹)	R_{ns} (MJ m ⁻² day ⁻¹)	R_{nl} (MJ m ⁻² day ⁻¹)	R_n (MJ m ⁻² day ⁻¹)	G (MJ m ⁻² day ⁻¹)	u_2 (m s ⁻¹)
January	17.5	0.80	11.4	13.4	8.8	6.0	2.8	0.09	1.5
February	22.6	0.82	14.9	17.3	11.5	6.1	5.4	0.28	2.2
March	29.0	0.86	19.7	22.2	15.2	6.3	8.9	0.38	2.2
April	35.7	0.92	25.3	27.4	19.5	6.7	12.8	0.51	2.2
May	40.0	0.93	28.6	30.7	22.0	6.6	15.4	0.65	2.3
June	41.7	0.93	29.8	32.0	23.0	6.2	16.7	0.51	2.2
July	40.8	0.78	26.1	31.3	20.1	4.5	15.6	0.10	1.7
August	37.4	0.80	24.3	28.7	18.7	4.7	14.1	-0.23	1.5
Sept	31.5	0.87	21.6	24.2	16.6	5.6	11.0	-0.58	1.7
October	24.6	0.88	17.0	18.9	13.1	6.3	6.8	-0.81	1.8
November	18.7	0.85	12.6	14.3	9.7	6.3	3.4	-0.65	1.4
December	16.1	0.79	10.4	12.3	8.0	5.9	2.1	-0.26	1.7

Notes: R_a = extraterrestrial radiation (from Allen et al., Annex 2, Table 2.6, p. 219).
n/N = percent of possible sunshine converted to decimal value (from Table 4.1-3)
 R_s = solar radiation (from Equation C-9).
 R_{so} = clear sky radiation (Equation C-10).
 R_{ns} = net solar radiation (Equation C-11).
 R_{nl} = net longwave radiation (Equation C-12).
 R_n = net radiation (Equation C-13).
G = solar heat flux (Equation C-14).
 u_2 = wind speed (from Table 4.1-3) corrected for height according to Equation C-15.

Table C-7. Radiation Parameters, Soil Heat Flux, and Wind Speed for Lower Bound Future Climate Conditions

Month	R_a (MJ m ⁻² day ⁻¹)	n/N	R_s (MJ m ⁻² day ⁻¹)	R_{so} (MJ m ⁻² day ⁻¹)	R_{ns} (MJ m ⁻² day ⁻¹)	R_{nl} (MJ m ⁻² day ⁻¹)	R_n (MJ m ⁻² day ⁻¹)	G (MJ m ⁻² day ⁻¹)	u_2 (m s ⁻¹)
January	17.5	0.58	9.45	13.4	7.3	4.1	3.2	0.08	3.6
February	22.6	0.64	12.88	17.3	9.9	4.5	5.4	0.51	3.5
March	29.0	0.63	16.39	22.2	12.6	4.7	7.9	0.70	3.8
April	35.7	0.69	21.24	27.4	16.4	5.2	11.1	0.74	3.8
May	40.0	0.73	24.6	30.7	18.9	5.6	13.3	0.68	4.1
June	41.7	0.82	27.52	32.0	21.2	6.6	14.6	0.70	4.1
July	40.8	0.77	25.91	31.3	19.9	5.9	14.1	0.29	4.0
August	37.4	0.79	24.12	28.7	18.6	6.2	12.4	-0.45	3.7
Sept	31.5	0.80	20.48	24.2	15.8	6.2	9.6	-0.88	3.3
October	24.6	0.76	15.50	18.9	11.9	5.7	6.2	-1.09	3.5
November	18.7	0.62	10.47	14.3	8.1	4.5	3.6	-0.88	3.1
December	16.1	0.60	8.86	12.3	6.8	4.2	2.6	-0.41	3.3

Notes: R_a = extraterrestrial radiation (from Allen et al., Annex 2, Table 2.6, p. 219).
n/N = percent of possible sunshine converted to decimal value (from Table 4.1-4).
 R_s = solar radiation (from Equation C-9).
 R_{so} = clear sky radiation (Equation C-10).
 R_{ns} = net solar radiation (Equation C-11).
 R_{nl} = net longwave radiation (Equation C-12).
 R_n = net radiation (Equation C-13).
G = solar heat flux (Equation C-14).
 u_2 = wind speed (from Table 4.1-4), with corrections for measurement height using Equation C-15.

Table C-8. Radiation Parameters, Soil Heat Flux, and Wind Speed for Future Climate Conditions

Month	R_a (MJ m ⁻² day ⁻¹)	n/N	R_s (MJ m ⁻² day ⁻¹)	R_{so} (MJ m ⁻² day ⁻¹)	R_{ns} (MJ m ⁻² day ⁻¹)	R_{nl} (MJ m ⁻² day ⁻¹)	R_n (MJ m ⁻² day ⁻¹)	G (MJ m ⁻² day ⁻¹)	u_2 (m s ⁻¹)
January	17.5	0.28	6.8	13.4	5.3	2.2	3.1	0.21	2.9
February	22.6	0.41	10.3	17.3	7.9	3.0	4.9	0.45	3.1
March	29.0	0.55	15.2	22.2	11.7	4.0	7.8	0.49	3.2
April	35.7	0.61	19.8	27.4	15.3	4.4	10.8	0.59	3.4
May	40.0	0.65	23.0	30.7	17.7	4.7	13.0	0.63	3.1
June	41.7	0.67	24.4	32.0	18.8	4.8	14.0	0.58	3.1
July	40.8	0.80	26.5	31.3	20.4	5.8	14.6	0.25	2.8
August	37.4	0.78	23.9	28.7	18.4	5.7	12.7	-0.39	2.8
Sept	31.5	0.72	19.2	24.2	14.8	5.2	9.6	-0.82	2.8
October	24.6	0.55	12.9	18.9	9.9	4.0	6.0	-0.93	2.8
November	18.7	0.29	7.4	14.3	5.7	2.3	3.4	-0.76	2.9
December	16.1	0.23	5.9	12.3	4.5	1.9	2.6	-0.31	2.9

Notes: R_a = extraterrestrial radiation (from Allen et al., Annex 2, Table 2.6, p. 219).
 n/N = percent of possible sunshine (from Table 4.1-5).
 R_s = solar radiation (from Equation C-9).
 R_{so} = clear sky radiation (Equation C-10).
 R_{ns} = net solar radiation (Equation C-11).
 R_{nl} = net longwave radiation (Equation C-12).
 R_n = net radiation (Equation C-13).
G = solar heat flux (Equation C-14).
 u_2 = wind speed (from Table 4.1-5), with corrections for measurement height using Equation C-15.

Table C-9. Mean Monthly Reference Evapotranspiration for Current , Upper Bound Monsoon, Lower Bound Future, and Future Climate Conditions

Month	Current Climate ET _o ^a (mm day ⁻¹)	Upper Bound Monsoon Climate ET _o ^a (mm day ⁻¹)	Lower Bound Future Climate ET _o ^a (mm day ⁻¹)	Future Climate ET _o ^a (mm day ⁻¹)
January	1.73	1.92	1.21	0.62
February	2.63	2.96	1.67	1.10
March	4.22	3.82	2.85	1.99
April	5.54	5.10	4.30	3.18
May	6.89	6.32	6.01	4.21
June	8.21	7.36	7.96	5.31
July	8.93	6.25	8.82	6.51
August	8.62	5.64	8.26	6.15
September	6.79	5.08	6.27	4.44
October	4.64	3.99	4.05	2.50
November	2.75	2.45	1.90	0.97
December	1.85	2.00	1.25	0.58

Notes: ^a Mean reference evapotranspiration (ET_o) calculated according to Equation C-1. Climate data used in the calculations are from Section 4, Tables 4.1-2 through 4.1-5.

APPENDIX D
METHODS FOR DERIVING CROP
COEFFICIENTS AND CROP EVAPOTRANSPIRATION

APPENDIX D. METHODS FOR DERIVING CROP COEFFICIENTS AND CROP EVAPOTRANSPIRATION

1. INTRODUCTION

The single crop coefficient (K_c) approach described by Allen et al. (1998, pp. 103 through 134) was used to calculate crop evapotranspiration (ET_c) which is required for calculation of the irrigation parameters. This method uses a grass reference evapotranspiration (ET_o , Appendix C) and crop specific coefficients to calculate ET_c (Allen et al. 1998, Equation 58, p. 103):

$$ET_c = ET_o * K_c \quad (\text{Eq. D-1})$$

ET_o incorporates the effects of local climatic conditions on ET_c , and K_c integrates the effects of four primary crop characteristics that differ from the reference grass (crop height, albedo, canopy resistance, and evaporation from soil). Changes in crop characteristics (i.e., leaf area, stomatal conductance, phenological stages) over the growing season also affect K_c , and so growth stage information is used in deriving crop specific values. Locally determined values for K_c were not available for this analysis so values published in Allen et al. 1998 (Table 12, pp. 110 through 114) were used for the 26 representative crops and turf. Relative humidity and wind speed were used to correct the published K_c values to correspond with local conditions according to Allen et al. (1998, pp. 121 through 127). Methods and example calculations are provided below.

2. METHODS

Crop coefficients were derived for the 26 representative crops and turf grass by: 1) using the growth stage lengths and K_c values from Allen et al. (1998, Table 11, pp. 104 through 108, and Table 12, pp. 110 through 114), 2) developing season lengths from appropriate local or regional data sources to correct growth stage lengths, and 3) correcting K_c values under non-standard climatic conditions. Once K_c values were corrected, average monthly values were calculated to correspond with average monthly ET_o .

2.1 GROWING SEASON LENGTHS

2.1.1 Current Climate

The season lengths developed in this section apply to both current climate and upper bound monsoon climate states.

Fruits and vegetables - As described and justified in Section 4.1.4, information from the University of Nevada and University of Arizona Cooperative Extensions were used to determine planting dates (Mills et al. no date) and season lengths (Call 1999) for most representative fruits and vegetables. Planting dates and season lengths for each crop were calculated as the midpoint of ranges (Table D-1). Harvest date was calculated by adding the number of days in the season to the selected planting date (Table D-1). Except for sweet corn, two planting seasons were

included for all vegetables that Mills et al. (no date) show can be planted in spring and fall in southern Nye County. Mills et al. show that sweet corn can be planted from mid-April through mid-May and from mid through late June. Because the season length of sweet corn is 63 to 100 days (Table D-1), an April-May crop could not be harvested before the second crop is planted in June.

Apples and strawberries— As described in Section 4.1.4, information from Allen et al. (1998, Table 11, p. 107) was used to determine the onset of growth and season lengths for apples and strawberries. Allen et al. (1998, Table 11, p. 107) lists a planting time of March and a total growing season of 240 days for orchard fruit trees in California. This is corroborated by Caprile et al. (2001) with reference to irrigating apples from April through September in the San Joaquin Valley, California. In the category of “Grapes and Berries”, a planting time of March and growing season of 205 days is suggested (Allen et al. 1998, Table 11, p. 107). Based on this information, March 1 was selected for onset of growth for both apples and strawberries (Table D-1). A growing season length of 240 days and harvest date of October 27 were selected for apples. A growing season length of 205 days and harvest date of September 22 were selected for strawberries (Table D-1).

Grapes—As described in Section 4.1.4, information from the founder of the Pahrump Valley Vineyards was used for initiation of growth and season length for grapes. Grapes in Amargosa Valley bloom in late March to early April and are harvested late August to early September (LeStrange 1997a). This is corroborated by the planting period (March) and growing season length (205 days) suggested by Allen et al. (1998, Table 11, p. 107,) for grapes grown in California. Based on this information, a growth initiation date of March 1 and a harvest date of August 31 were selected for grapes (Table D-1).

Barley, winter wheat, oat hay, and alfalfa—As described in Section 4.1.4, information from a local farmer was used to determine planting and harvest dates for barley, winter wheat, oat hay, and alfalfa. According to this source, one crop of winter wheat, barley, and oats can be produced per year in Amargosa Valley (LeStrange 1997b). Winter wheat and barley are planted in October and harvested in June, and oats are planted in March or April and harvested in June (LeStrange 1997b). According to Allen et al. (1998, Table 11, p. 106), cereal oats in desert climates are planted in December and have a growing season of 160 days. Based on this information, a planting date of October 16 (mid-month) and a harvest date of June 16 (mid-month) were chosen for winter wheat and barley. A planting date of March 31 (mid-point between March 1 and April 30) and harvest date of June 14 (mid-month) were chosen for oat hay (Table D-1). A planting date of December 16 (mid-month) and a harvest date of May 25 were selected for oats (Table D-1).

In Amargosa Valley, approximately six to seven alfalfa cuttings can occur per year with the first cutting around mid to late April and the last cutting mid to late November (LeStrange 1997b). Irrigation generally begins in early February and ends in December when alfalfa goes dormant (LeStrange 1997b). Allen et al. (1998) suggested a planting month of January with a 60-day growing period for the first cutting of alfalfa in California. Given this, the suggested six cuttings per year with dormancy beginning in December (LeStrange 1997b) can be achieved with initial growth starting January 1, the first cutting 60 days later on March 2, and the second through sixth cuttings occurring 55 days apart. Based on this information, January 1 was chosen for

growth initiation, with cuttings on March 2, April 26, June 20, August 14, October 8, and December 2 (Table D-1). The average time between cuttings is 56 days.

Feed corn and corn silage – As described in Section 4.1.4, information from *Nevada Agricultural Statistics 2000-2001* (USDA 2002b, pp.16 and 17) was used to determine planting and harvest dates for feed corn and corn silage. According to this source, corn is planted during May and June, silage is harvested in August through October, and feed corn is harvested in October and November. Because this source describes growing seasons for all of Nevada, the first months listed for planting and harvest were chosen for this analysis. May 16 (mid-month) was selected as the planting date for corn silage and feed corn (Table D-1). August 17 (mid-month) and October 17 (mid-month) were selected as harvest dates for corn silage and feed corn, respectively (Table D-1).

2.1.2 Future Climate

The season lengths developed in this section apply to both lower bound future and future climate states.

As described and justified in Section 4.1.4, information from the Washington State University Cooperative Extension and Washington Agricultural Statistics Service were used to determine planting dates (Washington State University Cooperative Extension, 2002; Painter et al. 1995; Washington Agricultural Statistics Service 1999) and season lengths (Antonelli et al. 1998; Painter et al. 1995; Washington Agricultural Statistics Service 1999) for most representative fruits, vegetables, and field crops. Planting date and season length for early season and single season crops were calculated as the midpoint of ranges, and harvest date was calculated by adding the number of days in the season to the selected planting date (Table D-2). Two seasons were included for all vegetables having a season length less than the number of days between first harvest and October 1, the expected date that temperatures become too cold for vegetable growth in eastern Washington (Antonelli 1998, Figure 3, p. 4). For example, a second season for celery was not included because the time between the first harvest (August 11) and October 1 is less than the 110-day season length for celery. An exception to this method was made for broccoli, because the early and late seasons overlapped by only five days. To accommodate, the late-season length was moved back by six days, which is within the range of season length for this crop (Table D-2).

As described and justified in Section 4.1.4, information from *Intermountain Alfalfa Management* (Orloff and Marble 1997, pp. 106 through 107; Schmierer et al. 1997, pp. 9 through 18) was used to determine dates for growth initiation, the last harvest, and cutting schedules for alfalfa. For conditions similar to those in eastern Washington, three- to four-cut schedules are common for alfalfa (Orloff and Marble 1997, pp. 106 through 107) with a three-cut schedule recommended if at least one cutting is used for beef cattle or horses. A three-cut schedule was chosen for this analysis. Initiation of spring growth or planting is recommended when temperatures are -3°C to -4°C (Schmierer et al. 1997, pp. 9 through 18, Allen et al. 1998, Table 11, p. 107). The last harvest of the growing season should occur four to six weeks before the first killing frost (Schmierer et al. 1997, pp. 9 through 18). Using mean monthly temperature data for Spokane (Table 4.1-5) this corresponds approximately to a growing period of March 1 (mean minimum temperatures -1.33°C) through September 28 (assuming first killing frost occurs the first week

in November). Allen et al. (1998, Table 11, p. 107) recommended 75 days for the first cutting cycle in Idaho (similar climate to Spokane, but drier). The recommended interval between the first and second cuttings, or second and third cuttings, was 30-50 days in Schmierer et al. (1997, pp. 9 through 18). Based on this information, March 1 and September 28 were chosen for growth initiation and the last cutting date, respectively (Table D-2). Using a three-cut schedule with the initial cut after 75 days of growth, the remaining intervals between the second and third cuts are 68 days (Table D-2). A three-cut schedule was chosen with the first cutting on May 15 (75 days from growth initiation), the second cutting on July 22 (68 days), and the third cutting on September 28 (Table D-2).

2.2 Growth Stage Lengths

Allen et al. (1998, pp. 103 through 108) divided crop development into four growth stages (initial, development, mid-season, and late season) that are related to leaf area index (ground area covered by crop canopy) and developmental stages. The initial stage begins at the planting date and ends when the crop has reached approximately 10 percent ground cover. The development stage runs from 10 percent cover to effective full cover, which, for many crops, occurs when flowering is initiated. The mid-season stage begins when the crop has reached effective full cover and ends at the start of maturity. The late season stage runs from maturity to harvest or senescence. The stages are crop specific and the lengths are affected by local climatic factors.

Growth stages and total growing season lengths from Allen et al. (1998, Table 11, pp. 104 through 108) were selected for current and future climates based on regional information. Growth stage information selected for current climate was also used for upper bound monsoon climate. Growth stage information selected for future climate was used for both lower and upper bounds. For the current climate, growth stages for California, California Desert, Semi Arid, or Arid Region were selected depending upon availability (Table D-3). When both California Desert and Arid Region were options, the region with planting dates and season lengths most similar to those identified for the local conditions were selected (see Table D-1). For the future climate, growth stage lengths for the California Desert, Mediterranean, Idaho, 35 – 45° L, high latitudes or Europe were selected depending on which more accurately reflected data for Spokane conditions (Table D-4).

Growing season lengths developed for each crop for all climates (Tables D-1 and D-2) were used to adjust growth stage lengths from Allen et al. (1998, Table 11, pp. 104 through 108) to local conditions. This was done by determining the ratio of the published stage length to the total growing time. This ratio was multiplied by the length of the growing season determined for local conditions and rounded to the nearest whole day. Occasionally, rounding resulted in stage lengths that were either a day too long or too short to sum to the total growing season length. If the sum of the days of stage lengths did not equal the total number of days in the growing season, the stage length days were adjusted to sum to the growing season length. Adjusted stages for current climate were also used for upper bound monsoon, and those for future climate were used for both lower and upper bounds.

Example: For the current climate early lettuce crop the published growth stage lengths and total growing time were (Allen et al. 1998, Table 11, pp. 104 through 108):

Initial stage = 25 days

Development stage = 35 days

Mid-season stage = 30 days

Late stage = 10 days

Total = 100 days

The season length for the early lettuce crop for current climate conditions was 60 days (from Table D-1). The adjusted stage lengths were:

Initial stage = $25/100 \times 60 = 15$ days

Development stage = $34/100 \times 60 = 21$ days

Mid-season stage = $30/100 \times 60 = 18$ days

Late stage = $10/100 \times 60 = 6$ days

Published and adjusted crop growth stage lengths are in Tables D-3 and D-4, respectively.

3. K_C CORRECTIONS

Allen et al. (1998, Table 12, pp. 110 through 114) published K_c values for initial ($K_{c \text{ ini}}$), mid-season ($K_{c \text{ mid}}$), and end of the late season ($K_{c \text{ end}}$) growth stages for several crops. The values were developed for non-stressed, well-managed crops in subhumid climates (minimum relative humidity, $[RH_{\min}] \approx 45$ percent, wind speed $[u_2] \approx 2$ m/s). When RH_{\min} and u_2 (2 m above the surface) were different from the assumptions, the following recommended corrections for $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ were used (Allen et al. 1998, Equations 62 and 65, pp. 121 and 125, respectively):

$$K_{c \text{ mid}} = K_{c \text{ mid (Tab)}} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (\text{Eq. D-2})$$

$$K_{c \text{ end}} = K_{c \text{ end (Tab)}} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)] \left(\frac{h}{3}\right)^{0.3} \quad (\text{Eq. D-3})$$

where

$K_{c \text{ mid (Tab)}}$ or $K_{c \text{ end (Tab)}}$ = $K_{c \text{ mid}}$ value (Equation D-2) or $K_{c \text{ end}}$ value (Equation D-3) from Table 12 (Allen et al. 1998, pp. 110 through 114),

RH_{\min} = mean minimum RH (%) during the mid-season (Equation D-2) or late season (Equation D-3) growth stages,

u_2 = mean daily wind speed (m s^{-1}) at 2 m during the mid-season (Equation D-2) or late season (Equation D-3) growth stages,

h = mean plant height (m) during the mid-season (Equation D-2) or late season (Equation D-3) growth stages.

The following limitations to RH , u_2 , and h apply to Equations D-2 and D-3:

$$20 \text{ percent} \leq RH_{min} \leq 80 \text{ percent},$$

$$1 \text{ m s}^{-1} \leq u_2 \leq 6 \text{ m s}^{-1}, \text{ and}$$

$$0.1 \text{ m} \leq h \leq 10 \text{ m}.$$

Additionally, Equation D-3 is only applied when $K_{c \text{ end}}$ values from Table 12 (Allen et al. 1998, pp. 110 through 114) exceed 0.45. This is because a $K_{c \text{ end}}$ value of 0.45 or less indicates that the crop is allowed to senesce and dry in the field. In this case, RH_{min} and u_2 have little effect on $K_{c \text{ end}}$ and no adjustment is necessary. Because the K_c adjustments are based on site specific relative humidity and wind speed, adjustments were required for all climate states considered for Annual Average Irrigation Rate calculations.

For the current climate mean daily u_2 was greater than 2 m s^{-1} and less than 6 m s^{-1} for all months (Appendix C Table C-5). RH_{min} was less than 45 percent for all months and less than 20 percent March through October (Section 4.15, Table 4.1-2). To meet the requirements for Equations D-2 and D-3 for March through October and still adjust approximately for local conditions, 20 percent was substituted for the recorded RH_{min} . Adjustments for $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ were required for all crops except grapes, oats, oat hay, feed corn, barley, and winter wheat which had $K_{c \text{ end}}$ values less than 0.45 (Allen et al. 1998, Table 12, pp. 110 through 114).

Minimum relative humidity was not available for the upper bound monsoon or lower bound future climates. To estimate RH_{min} the following equation was used from Allen et al. (1998, p. 35, Equation 10):

$$RH = 100 \frac{e_a}{e^o(T)} \quad (\text{Eq. D-4})$$

where

$$T = T_{max}$$

Estimated RH_{min} values for upper bound monsoon and lower bound future climates are in Table D-5.

For the upper bound monsoon climate, mean daily u_2 was greater than 2 m s^{-1} February through June and less than 6 m s^{-1} for all months (Table C-6). RH_{min} was less than 45 percent and greater than 20 percent for all months (Table D-5). Therefore, the requirements of Equations D-2 and D-3 were met for all months. Adjustments for $K_{c \text{ mid}}$ and $K_{c \text{ end}}$ were required for all crops except grapes, oat hay, oat feed, feed corn, barley, and winter wheat which had $K_{c \text{ end}}$ values less than 0.45 (Allen et al. 1998, Table 12, pp. 110 through 114).

For the lower bound future climate, mean daily u_2 was greater than 2 m s^{-1} and less than 6 m s^{-1} for all months (Section 4.1.5, Table 4.1-4, and Appendix C Table C-7). RH_{min} was less than 45

percent for all months and less than 20 percent June through September (Table D-5). To meet the requirements for Equations D-2 and D-3 for June through September and still adjust approximately for local conditions, 20 percent was substituted for the recorded RH_{min} . Adjustments for $K_{c\ mid}$ and $K_{c\ end}$ were required for all crops except grapes, oats, oat hay, feed corn, barley, and winter wheat which had $K_{c\ end}$ values less than 0.45 (Allen et al. 1998, Table 12, pp. 110 through 114).

For the future climate, mean daily u_2 was greater than $2\ m\ s^{-1}$ and less than $6\ m\ s^{-1}$ for all months (Table C-8). RH_{min} was less than 45 percent May through September and was 20 percent or greater for all months (Section 4.1.5, Table 4.1-5). Therefore, the requirements of Equations D-2 and D-3 were met for all months. Adjustments for $K_{c\ mid}$ and $K_{c\ end}$ were required for all crops except grapes, oat hay, oat feed, feed corn, barley, and winter wheat which had $K_{c\ end}$ values less than 0.45 (Allen et al. 1998, Table 12, pp. 110 through 114).

The adjustments to $K_{c\ mid}$ and $K_{c\ end}$ required mean plant height during the mid- and late season growing stages. Because the mid-season stage begins at effective full cover, it was reasonable to assume that plants had reached their maximum height at this time. No local data exists for crop heights so the maximum crop heights published in Allen et al. (1998, Table 12, pp. 110 through 114) were used in the calculations, with the exception of wine grapes (see Tables D-6 through D-9). Those heights are listed in Tables D-6 through D-9.

Example: The $K_{c\ mid}$ calculation for early leaf lettuce (current climate) requires the following:

$K_{c\ mid} = 1.0$ (Allen et al. 1998, Table 12, p. 110),

Stage length = 18 days (Table D-3),

Stage month(s) = April = 18 days (Table D-1),

$RH_{min} = 13.7\%$ (Table 4.1-2, required adjustment = 20%),

$u_2 = 3.6\ m\ s^{-1}$ (Table C-5),

$h = 0.3\ m$ (Allen et al. 1998, Table 12, p. 110, and Table D-5).

$$K_{c\ mid} = 1.0 + [0.04(3.6 - 2) - 0.004(20 - 45)] \left(\frac{0.3}{3} \right)^{0.3} = 1.1 \quad (\text{Eq. D-2})$$

The following inputs are required for $K_{c\ end}$. The late stage growing period occurs in April and May. Values for both months must be considered.

$K_{c\ end} = 0.95$ (Allen et al. 1998, Table 12, p. 110),

Stage length = 6 days (Table D-3),

Stage month(s) = April = 1 day; May = 5 days (Table D-1),

$RH_{min} = \text{April} = 13.7\%$; May = 14.2% (Table 4.1-2, required adjustment = 20%),

$u_2 = \text{April} = 3.6\ m\ s^{-1}$; May = $3.5\ m\ s^{-1}$ (Table C-5),

$h = 0.3\ m$ (Allen et al. 1998, Table 12, pg. 110, and Table D-6).

Mean $RH_{min} = 20$ percent

$$Mean u_2 = \left(\frac{1}{6} \times 3.6\right) + \left(\frac{5}{6} \times 3.5\right) = 3.5 \text{ m s}^{-1}$$

$$K_{c\text{end}} = 0.95 + [0.04(3.5 - 2) - 0.004(20 - 45)] \left(\frac{0.3}{3}\right)^{0.3} = 1.06 \quad (\text{Eq. D-3})$$

Adjusted K_c values and maximum crop heights are in Tables D-6 through D-9.

4. AVERAGE MONTHLY K_c VALUES

For K_c values for different growth stages to correspond with mean monthly ET_o , it was necessary to calculate mean monthly K_c for each crop. This was done by first identifying the months in which the four growth stages occurred using planting dates in Tables D-1 and D-2 and growth stage lengths in Tables D-3 and D-4. Months with overlapping growth stages were noted and the number of days in the month for each growth stage was recorded. K_c curves were constructed according to Allen et al. (1998, Figure 36, p. 132) to aide in determination of mean monthly values (Figure D-1). If the development or late stages were split across a month, the following equation was used to calculate K_c for the day of the growth stage that ended the month:

$$K_{ci} = K_{c\text{prev}} + \left[\frac{i - \sum(L_{\text{prev}})}{L_{\text{stage}}} \right] (K_{c\text{next}} - K_{c\text{prev}}) \quad (\text{Eq. D-5})$$

where

i = day within the growing season,

K_{ci} = K_c crop coefficient on day i ,

$K_{c\text{prev}}$ = K_c for the previous growth stage,

L_{stage} = length of stage under consideration (days),

$\sum(L_{\text{prev}})$ = sum of the lengths of all previous stages (days).

Example: The crop coefficient curve for lettuce (current climate) is shown in Figure D-1. The following inputs were required to calculate the monthly K_c values.

Planting date = March 6 (Julian Day 65, Table D-1)

	Initial	Dev	Mid	Late	End	Total
Stage length	15	21	18	6		60
Stage ends (J-day)	80	101	119	125		
K_c	0.7		1.08		1.03	
March (days)	15	10				25
April (days)		11	18	1		30
May (days)				5		5

K_{ci} (Equation D-5) was required for March 31 (Julian Day 90) because the development stage overlapped March and April, and for April 30 (Julian Day 120) because the late stage overlapped April and May.

$$K_{c(90)} = 0.70 + \left[\frac{(90 - 65) - 15}{21} \right] (1.08 - 0.70) = 0.88 \quad (\text{Eq. D-5})$$

$$K_{c(120)} = 1.08 + \left[\frac{(120 - 65) - (15 + 21 + 18)}{6} \right] (1.03 - 1.08) = 1.07 \quad (\text{Eq. D-5})$$

The mean $K_{c \text{ month}}$ values were calculated by multiplying the number of days in the growth stage by the corresponding K_c to get a weighted average:

$$K_{c \text{ March}} = \frac{15}{25} 0.70 + \frac{10}{25} \left(\frac{0.70 + 0.88}{2} \right) = 0.74$$

$$K_{c \text{ April}} = \frac{11}{30} \left(\frac{0.88 + 1.08}{2} \right) + \frac{18}{30} 1.08 + \frac{1}{30} \left(\frac{1.08 + 1.07}{2} \right) = 1.05$$

$$K_{c \text{ May}} = \frac{5}{5} \left(\frac{1.07 + 1.03}{2} \right) = 1.05$$

Mean monthly K_c values are in Tables D-10, D-11, D-12, and D-13.

5. CALCULATION OF CROP EVAPOTRANSPIRATION

Mean daily ET_o for each month (Appendix C, Table C-9) and K_c (Tables D-10 through D-13) were used in Equation D-1 to generate mean monthly crop evapotranspiration (ET_c) for the 26 crops and turf grass for all climates (Tables D-10 through D-13). Mean daily ET_c values for each month were multiplied by the number of growing days per month to get total mean monthly ET_c (Tables D-10 through D-13). These monthly values were used to generate seasonal irrigation requirements (Appendix E) which were used to calculate Annual Average Irrigation Rate (IR), Daily Average Irrigation Rate (IRD_j), Irrigation Application (IA_j), and Overwatering Rate (OW) (see Section 6 and Appendix E).

Example: Monthly mean ET_o , monthly mean K_c , and number of growing season days in each month were required for calculating mean daily and monthly ET_c . $ET_{c \text{ daily}}$ is K_c multiplied by ET_o (Equation D-1). $ET_{c \text{ monthly}}$ is $ET_{c \text{ daily}}$ multiplied by the number of days in the month.

	March	April	May
K_c	0.74	1.05	1.05
ET_o	4.22	5.54	6.89
Days	25	30	5
$ET_{c \text{ daily}} = K_c * ET_o$	$0.74 * 4.22 = 3.12$	$1.05 * 5.54 = 5.82$	$1.05 * 6.89 = 7.23$
$ET_{c \text{ monthly}} = ET_{c \text{ daily}} * \text{Days}$	$3.12 * 25 = 78.0$	$5.82 * 30 = 174.60$	$7.23 * 5 = 36.15$

It should be noted that the values presented in the Appendix tables are rounded. Calculations were done using more precise values from the original data sources, resulting in small differences between the examples and the data reported in the tables in some cases.

Table D-1. Growing Season – Current and Upper Bound Monsoon Climates

Crop	Start of Season ^a				Season Length (days) ^b				
	Start	End	Mid ^c	Julian ^d	Min	Max	Mid	Harvest ^e	Julian
Broccoli early	09-Feb	20-Mar	1-Mar	60	60	100	80	20-May	140
Broccoli late	01-Aug	20-Sep	26-Aug	238	60	100	80	14-Nov	318
Cabbage early	09-Feb	20-Mar	1-Mar	60	70	100	85	25-May	145
Cabbage late	01-Aug	20-Sep	26-Aug	238	70	100	85	19-Nov	323
Cauliflower early	09-Feb	20-Mar	1-Mar	60	70	90	80	20-May	140
Cauliflower late	01-Aug	20-Sep	26-Aug	238	70	90	80	14-Nov	318
Celery early	01-Apr	20-Apr	11-Apr	101	125	125	125	14-Aug	226
Celery late	01-Sep	30-Sep	16-Sep	259	125	125	125	19-Jan	19
Head lettuce early	09-Feb	31-Mar	6-Mar	65	40	80	60	5-May	125
Head lettuce late	10-Aug	20-Sep	31-Aug	243	40	80	60	30-Oct	303
Leaf lettuce early	09-Feb	31-Mar	6-Mar	65	40	80	60	5-May	125
Leaf lettuce late	10-Aug	20-Sep	31-Aug	243	40	80	60	30-Oct	303
Spinach early	09-Feb	20-Apr	16-Mar	75	40	60	50	5-May	125
Spinach late	01-Sep	30-Sep	16-Sep	259	40	60	50	5-Nov	309
Bell peppers	10-Apr	31-May	6-May	126	70	85	78	23-Jul	204
Carrots early	09-Feb	20-Apr	16-Mar	75	70	80	75	30-May	150
Carrots late	01-Aug	20-Sep	26-Aug	238	70	80	75	9-Nov	313
Cucumbers	01-Apr	31-Jul	1-Jun	152	50	70	60	31-Jul	212
Onions early	01-Mar	20-Apr	26-Mar	85	100	120	110	14-Jul	195
Onions late	01-Sep	30-Sep	16-Sep	259	100	120	110	4-Jan	4
Potatoes	01-Mar	20-Apr	26-Mar	85	100	120	110	14-Jul	195
Squash	10-Apr	20-Jun	16-May	136	50	65	58	13-Jul	194
Sweet corn	10-Apr	20-May	30-Apr	120	63	100	82	21-Jul	202
Apples			1-Mar	60			240	27-Oct	300
Grapes			1-Mar	60			183	31-Aug	243
Melons	10-Apr	20-Jun	16-May	136	70	130	100	24-Aug	236
Strawberries			1-Mar	60			205	22-Sept	265
Tomatoes	10-Apr	31-May	6-May	126	55	105	80	25-Jul	206
Barley	01-Oct	31-Oct	16-Oct	289	213	272	243	16-Jun	167
Feed Corn	01-May	30-May	16-May	136			154	17-Oct	290
Oats	01-Dec	31-Dec	16-Dec	350			160	25-May	145
Winter wheat	01-Oct	31-Oct	16-Oct	289	213	272	243	16-Jun	167

Table D-1. Growing Season – Current and Upper Bound Monsoon Climates (continued)

	Start of Season ^a				Season Length (days) ^b				
	Start	End	Mid ^c	Julian ^d	Min	Max	Mid	Harvest ^e	Julian
Alfalfa hay			Jan 1	1			335	2-Dec	336
Corn silage	01-May	30-May	16-May	136			93	17-Aug	229
Oat hay	01-Mar	30-Apr	31-Mar	90	75	75	75	14-Jun	165

Notes: ^a Sources: Mills et al. (n.d.), except corn and corn silage (USDA 2002b, pp. 16 and 17) apples and strawberries (Allen et al. 1998, Table 11, pp.104-108), grapes, barley, oats, winter wheat, alfalfa, and oat hay (LeStrange 1997a and 1997b, DTN: MO0210SPAGRO06.029).

^b Sources: Call (1999, Table 10.10 for celery, spinach, and carrots and crop-specific information on pages 71–125 of Chapter 10 for others), except corn and corn silage (USDA 2002b, pp. 16 and 17) apples and strawberries (Allen et al. 1998, Table 11, pp.104-108) grapes, barley, oats, winter wheat, alfalfa, and oat hay (LeStrange 1997a and 1997b, DTN: MO0210SPAGRO06.029) (see Section 4.1.4).

^c Midpoint of start of season.

^d Julian date of midpoint of season start.

^e Calculated as midpoint of start of season plus median season length, except apples, grapes, strawberries, winter wheat, barley, grain corn, oats, winter wheat, corn silage and oat hay.

Table D-2. Growing Season – Upper and Lower Bound Future Climates

	Start of Season ^a				Season Length (days) ^b				
	Start	End	Mid ^c	Julian ^d	Min	Max	Mid	Harvest ^e	Julian
Broccoli early	15-Apr	01-May	23-Apr	113	65	100	83	15-Jul	196
Broccoli late			16-Jul	197	65	100	83	7-Oct	280
Cabbage early	15-Apr	01-May	23-Apr	113	60	90	75	7-Jul	188
Cabbage late			18-Jul	199			75	1-Oct	274
Cauliflower early	15-Apr	01-May	23-Apr	113	50	75	63	25-Jun	176
Cauliflower late			30-Jul	211	50	75	63	1-Oct	274
Celery	15-Apr	01-May	23-Apr	113	100	120	110	11-Aug	223
Head lettuce early	15-Apr	01-May	23-Apr	113	75	80	78	10-Jul	191
Head lettuce late			15-Jul	196	75	80	78	1-Oct	274
Leaf lettuce early	15-Apr	01-May	23-Apr	113	55	60	58	20-Jun	171
Leaf lettuce late			4-Aug	196	55	60	58	11-Sep	254
Spinach early	15-Apr	01-May	23-Apr	113	50	60	55	17-Jun	168
Spinach late			7-Aug	219	50	60	55	1-Oct	274
Bell peppers	01-Jun	15-Jun	8-Jun	159	90	110	100	16-Sep	259
Carrots early	15-Apr	01-May	23-Apr	113	70	90	80	12-Jul	193
Carrots late			13-Jul	194	70	90	80	1-Oct	274
Cucumbers	15-May	01-Jun	24-May	144	60	75	68	31-Jul	212
Onions	01-Mar	01-Mar	1-Mar	60	130	180	155	3-Aug	215
Potatoes	15-Apr	01-May	23-Apr	113	90	140	115	16-Aug	228
Squash	15-May	01-Jun	24-May	144	60	70	65	28-Jul	209
Sweet corn	15-May	01-Jun	24-May	144	70	140	105	6-Sep	249
Apples	05-Apr	10-May	22-Apr	112			166	5-Oct	278
Grapes	25-May	10-Jul	17-Jun	168			105	30-Sep	273
Melons	15-May	01-Jun	24-May	144	90	115	103	4-Sep	247
Strawberries	10-Apr	15-May	27-Apr	117			64	30-Jun	181
Tomatoes	01-Jun	15-Jun	8-Jun	159	65	110	88	4-Sep	247
Spring barley	01-Apr	30-Apr	16-Apr	106			91	16-Jul	197
Feed Corn	15-Apr	5-Jun	11-May	131			178	5-Nov	309
Oats	5-Mar	20-Apr	28-Mar	87			141	16-Aug	228
Winter wheat	01-Sep	30-Sep	16-Sep	259			334	16-Aug	228

Table D-2. Growing Season – Upper and Lower Bound Future Climates (continued)

	Start of Season ^a				Season Length (days) ^b				
	Start	End	Mid ^c	Julian ^d	Min	Max	Mid	Harvest ^e	Julian
Alfalfa hay			1-Mar	60			211	28-Sept	271
Corn silage	15 Apr	5 Jun	11 May	131			137	25-Sep	268
Oat hay			15-May	135			57	11-Jul	192

Notes: ^aSources: Early season and single season annual vegetables and fruits–Washington State University Cooperative Extension (2002, p. 2, with celery assigned the same dates as other leafy vegetables); late season annual vegetables–calculated as October 1 (which is about expected date of first killing frost [Antonelli 1998, Figure 3]) minus median season length; winter wheat–Painter et al. (1995, Table A1); spring barley–Painter et al. (1995, Table A4); apples, grapes, strawberries, grain corn, oats, corn silage, and oat hay–Washington Agricultural Statistics Service (1999, with oat hay = other hay); alfalfa – Schmierer et al. (1997, pp. 9 - 18), Orloff and Marble (1997, pp. 106 – 107).
^bSources: Antonelli et al. (1998, Table 2), except apples, grapes, strawberries, wheat, barley, and oat hay, which were calculated as days from midpoint of season start to harvest^e.
^cMidpoint of start of season.
^dJulian date of midpoint of season start.
^eCalculated as midpoint of season start plus median season length, except winter wheat–Painter et al. (1995, Table A1); spring barley–Painter et al. 1995 (Table A4); apples, grapes, strawberries, grain corn, oats, corn silage, and oat hay–Washington Agricultural Statistics Service (1999, midpoint of most active harvest dates, with oat hay = other hay).

Table D-3. Length (days) of Four Crop Growth Stages and Total Growing Season for Current and Upper Bound Monsoon Climate Conditions.

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Leaf Lettuce early						
Stage Length ^b	25	35	30	10	100	Arid Region
Adjusted Stage Length ^c	15	21	18	6	60	
Leaf Lettuce late						
Stage Length	25	35	30	10	100	Arid Region
Adjusted Stage Length	15	21	18	6	60	
Head Lettuce early						
Stage Length	25	35	30	10	100	Arid Region
Adjusted Stage Length	15	21	18	6	60	
Head Lettuce late						
Stage Length	25	35	30	10	100	Arid Region
Adjusted Stage Length	15	21	18	6	60	
Cabbage early						
Stage Length	40	60	50	15	165	California Desert
Adjusted Stage Length	20	31	26	8	85	
Cabbage late						
Stage Length	40	60	50	15	165	California Desert
Adjusted Stage Length	20	31	26	8	85	
Celery early						
Stage Length	30	55	105	20	210	Semi Arid
Adjusted Stage Length	18	33	62	12	125	
Celery late						
Stage Length	25	40	95	20	180	Semi Arid
Adjusted Stage Length	17	28	66	14	125	
Broccoli early						
Stage Length	35	45	40	15	135	California Desert
Adjusted Stage Length	21	26	24	9	80	
Broccoli late						
Stage Length	35	45	40	15	135	California Desert
Adjusted Stage Length	21	26	24	9	80	
Cauliflower early						
Stage Length	35	50	40	15	140	California Desert
Adjusted Stage Length	20	29	23	8	80	
Cauliflower late						
Stage Length	35	50	40	15	140	California Desert
Adjusted Stage Length	20	29	23	8	80	

Table D-3. Length (days) of Four Crop Growth Stages and Total Growing Season for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Spinach early						
Stage Length	20	30	40	10	100	Arid Region
Adjusted Stage Length	10	15	20	5	50	
Spinach late						
Stage Length	20	30	40	10	100	Arid Region
Adjusted Stage Length	10	15	20	5	50	
Potatoes						
Stage Length	30	35	50	25	140	California Desert
Adjusted Stage Length	24	27	39	20	110	
Onions early						
Stage Length	20	35	110	45	210	Arid Region; CA
Adjusted Stage Length	10	18	58	24	110	
Onions late						
Stage Length	20	35	110	45	210	Arid Region; CA
Adjusted Stage Length	10	18	58	24	110	
Carrots early						
Stage Length	30	50	90	30	200	California Desert
Adjusted Stage Length	11	19	34	11	75	
Carrots late						
Stage Length	30	50	90	30	200	California Desert
Adjusted Stage Length	11	19	34	11	75	
Sweet corn						
Stage Length	20	40	70	10	140	California Desert
Adjusted Stage Length	12	23	41	6	82	
Bell peppers						
Stage Length	30	40	110	30	210	Arid Region
Adjusted Stage Length	11	15	41	11	78	
Cucumbers						
Stage Length	20	30	40	15	105	Arid Region
Adjusted Stage Length	11	17	23	9	60	
Zucchini Squash						
Stage Length	25	35	25	15	100	Arid Region
Adjusted Stage Length	15	20	14	9	58	
Melons						
Stage Length	15	40	65	15	135	California Desert
Adjusted Stage Length	11	30	48	11	100	

Table D-3. Length (days) of Four Crop Growth Stages and Total Growing Season for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Tomatoes						
Stage Length	35	40	50	30	155	California
Adjusted Stage Length	18	21	26	15	80	
Apples						
Stage Length	30	50	130	30	240	California
Adjusted Stage Length	30	50	130	30	240	
Wine Grapes						
Stage Length	20	50	75	60	205	California
Adjusted Stage Length	18	45	67	53	183	
Strawberries						
Stage Length	20	50	75	60	205	California
Adjusted Stage Length	20	50	75	60	205	
Winter Wheat						
Stage Length	20	60	70	30	180	California
Adjusted Stage Length	27	81	94	41	243	
Barley						
Stage Length	20	50	60	30	160	California Desert
Adjusted Stage Length	30	76	91	46	243	
Corn-feed						
Stage Length	25	40	45	30	140	Arid Region
Adjusted Stage Length	27	44	50	33	154	
Oats						
Stage Length	20	50	60	30	160	California
Adjusted Stage Length	20	50	60	30	160	
Alfalfa hay (1st cutting)						
Stage Length	10	20	20	10	60	California
Adjusted Stage Length	10	20	20	10	60	
Alfalfa hay (2nd cutting)						
Stage Length	5	10	10	5	30	California
Adjusted Stage Length	9	18	18	10	55	
Alfalfa hay (3rd cutting)						
Stage Length	5	10	10	5	30	California
Adjusted Stage Length	9	18	18	10	55	
Alfalfa hay (4th cutting)						
Stage Length	5	10	10	5	30	California
Adjusted Stage Length	9	18	18	10	55	

Table D-3. Length (days) of Four Crop Growth Stages and Total Growing Season for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Alfalfa hay (5th cutting)						
Stage Length	5	10	10	5	30	California
Adjusted Stage Length	9	18	18	10	55	
Alfalfa hay (6th cutting)						
Stage Length	5	10	10	5	30	California
Adjusted Stage Length	9	18	18	10	55	
Corn silage						
Stage Length	25	40	45	30	140	Arid Region
Adjusted Stage Length	17	26	30	20	93	
Oat hay						
Stage Length	20	50	60	30	160	California Desert
Adjusted Stage Length	9	24	28	14	75	

Notes: Initial = initial crop growth stage, Dev = development stage, Mid = mid-season stage, and Late = late season stage.

^a Geographic region from which growth stage and season lengths were determined (Source: Allen et al. 1998, Table 11, pp. 104 -108).

^b Source: Allen et al. 1998, Table 11, pp. 104 - 108.

^c Stage lengths adjusted from Allen et al. (1998) according to Appendix D, Section 2.2.

Table D-4. Length (days) of Crop Growth Stages and Total Growing Season for Lower and Upper Bound Future Climate Conditions.

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Leaf Lettuce early						
Stage Length ^b	20	30	15	10	75	Mediterranean
Adjusted Stage Length ^c	15	23	12	8	58	
Leaf Lettuce late						
Stage Length	20	30	15	10	75	Mediterranean
Adjusted Stage Length	15	23	12	8	58	
Head Lettuce early						
Stage Length	20	30	15	10	75	Mediterranean
Adjusted Stage Length	21	31	16	10	78	
Head Lettuce late						
Stage Length	20	30	15	10	75	Mediterranean
Adjusted Stage Length	21	31	16	10	78	
Cabbage early						
Stage Length	40	60	50	15	165	California Desert
Adjusted Stage Length	18	27	23	7	75	
Cabbage late						
Stage Length	40	60	50	15	165	California Desert
Adjusted Stage Length	18	27	23	7	75	
Celery						
Stage Length	25	40	45	15	125	Mediterranean
Adjusted Stage Length	22	35	40	13	110	
Broccoli early						
Stage Length	35	45	40	15	135	California Desert
Adjusted Stage Length	21	28	25	9	83	
Broccoli late						
Stage Length	35	45	40	15	135	California Desert
Adjusted Stage Length	21	28	25	9	83	
Cauliflower early						
Stage Length	35	50	40	15	140	California Desert
Adjusted Stage Length	16	22	18	7	63	
Cauliflower late						
Stage Length	35	50	40	15	140	California Desert
Adjusted Stage Length	16	22	18	7	63	
Spinach early						
Stage Length	20	20	20	5	65	Mediterranean
Adjusted Stage Length	17	17	17	4	55	

Table D-4. Length (days) of Crop Growth Stages and Total Growing Season for Lower and Upper Bound Future Climate Conditions (continued)

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Spinach late						
Stage Length	20	20	20	5	65	Mediterranean
Adjusted Stage Length	17	17	17	4	55	
Potatoes						
Stage Length	45	30	70	20	165	Idaho
Adjusted Stage Length	31	21	49	14	115	
Onions						
Stage Length	15	25	70	40	150	Mediterranean
Adjusted Stage Length	16	26	72	41	155	
Carrots early						
Stage Length	30	40	60	20	150	Mediterranean
Adjusted Stage Length	16	21	32	11	80	
Carrots late						
Stage Length	30	40	60	20	150	Mediterranean
Adjusted Stage Length	16	21	32	11	80	
Sweet corn						
Stage Length	20	25	25	10	80	Mediterranean
Adjusted Stage Length	26	33	33	13	105	
Bell peppers						
Stage Length	30	35	40	20	125	Europe and Med.
Adjusted Stage Length	24	28	32	16	100	
Cucumbers						
Stage Length	20	30	40	15	105	Arid Region
Adjusted Stage Length	13	19	26	10	68	
Squash						
Stage Length	20	30	25	15	90	Med; Europe
Adjusted Stage Length	14	22	18	11	65	
Melons						
Stage Length	25	35	40	20	120	Mediterranean
Adjusted Stage Length	22	30	34	17	103	
Tomatoes						
Stage Length	30	40	45	30	145	Mediterranean
Adjusted Stage Length	18	24	28	18	88	
Apples						
Stage Length	20	70	90	30	210	High Latitudes
Adjusted Stage Length	16	55	71	24	166	

Table D-4. Length (days) of Crop Growth Stages and Total Growing Season for Lower and Upper Bound Future Climate Conditions (continued)

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Wine Grapes						
Stage Length	20	50	90	20	180	High Latitudes
Adjusted Stage Length	12	30	52	11	105	
Strawberries						
Stage Length	20	50	90	20	180	High Latitudes
Adjusted Stage Length	7	18	32	7	64	
Winter wheat						
Stage Length	30	140	40	30	240	Mediterranean
Adjusted Stage Length	42	195	55	42	334	
Barley						
Stage Length	20	25	60	30	135	35-45 °L
Adjusted Stage Length	14	17	40	20	91	
Feed corn						
Stage Length	30	40	50	50	170	Idaho
Adjusted Stage Length	32	42	52	52	178	
Oats						
Stage Length	20	25	60	30	135	35-45 °L
Adjusted Stage Length	21	26	63	31	141	
Alfalfa hay (1st cutting)						
Stage Length	10	30	25	10	75	Idaho
Adjusted Stage Length	10	30	25	10	75	
Alfalfa hay (2nd cutting)						
Stage Length	5	20	10	10	45	Idaho
Adjusted Stage Length	8	30	15	15	68	
Alfalfa hay (3rd cutting)						
Stage Length	5	20	10	10	45	Idaho
Adjusted Stage Length	8	30	15	15	68	
Corn silage						
Stage Length	30	40	50	50	170	Idaho
Adjusted Stage Length	24	32	40	41	137	

Table D-4. Length (days) of Crop Growth Stages and Total Growing Season for Lower and Upper Bound Future Climate Conditions (continued)

Crop	Initial	Dev	Mid	Late	Season Length	Region ^a
Oat hay						
Stage Length	20	25	60	30	135	35-45 °L
Adjusted Stage Length	9	10	26	12	57	

Notes: Initial = initial crop growth stage, Dev = development stage, Mid = mid-season stage, and Late = late season stage.

^aGeographic region from which growth stage and season lengths were determined (Source: Allen et al. 1998, Table 11, pp. 104 -108).

^bSource: Allen et al. 1998, Table 11, pp 104 - 108.

^cStage lengths adjusted from Allen et al. (1998) according to Appendix D, Section 2.2.

Table D-5. Estimated Minimum Relative Humidity for Upper Bound Monsoon and Lower Bound Future Climates.

Month	Upper Bound Monsoon Climate	Lower Bound Future Climate
	RH _{min} (%) ^a	RH _{min} (%) ^a
January	22.9	40.4
February	22.9	37.9
March	23.5	29.4
April	22.2	26.6
May	22.4	23.1
June	23.4	17.1
July	34.2	19.4
August	35.6	17.7
September	29.3	19.4
October	23.9	25.1
November	22.0	35.9
December	23.0	40.9

Notes: ^a Minimum Relative humidity was calculated from maximum temperatures in Tables 4.1-3 (upper bound monsoon) and 4.1-4 (lower bound future) and Allen et al. (1998, Eq. 10, p. 35).

Table D-6. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Current Climate Conditions

Crop	$K_{c \text{ ini}}^a$	$K_{c \text{ mid}}^b$	$K_{c \text{ end}}^c$	Maximum Crop Height (m)^d
Leaf Lettuce early	0.70	1.08	1.03	0.3
Leaf Lettuce late	0.70	1.07	1.02	0.3
Head Lettuce early	0.70	1.08	1.03	0.3
Head Lettuce late	0.70	1.07	1.02	0.3
Cabbage early	0.70	1.14	1.04	0.4
Cabbage late	0.70	1.12	1.02	0.4
Celery early	0.70	1.15	1.10	0.6
Celery late	0.70	1.12	1.04	0.6
Broccoli early	0.70	1.13	1.03	0.3
Broccoli late	0.70	1.12	1.01	0.3
Cauliflower early	0.70	1.14	1.04	0.4
Cauliflower late	0.70	1.13	1.02	0.4
Spinach early	0.70	1.08	1.03	0.3
Spinach late	0.70	1.07	1.01	0.3
Potatoes	0.50	1.25	0.85	0.6
Onions early	0.70	1.14	0.84	0.4
Onions late	0.70	1.12	0.80	0.4
Carrots early	0.70	1.13	1.03	0.3
Carrots late	0.70	1.12	1.02	0.3
Sweet corn	0.30	1.28	1.18	1.5
Bell peppers	0.60	1.15	1.00	0.7
Cucumbers	0.60	1.08	0.83	0.3
Squash	0.50	1.03	0.83	0.3
Melons	0.50	1.15	0.84	0.4
Tomatoes ^e	0.60	1.25	0.90	0.6
Apples	0.60	1.12	0.91	4.0
Wine Grapes	0.30	0.83	0.45	1.5
Strawberries	0.40	0.92	0.82	0.2
Winter wheat	0.70	1.25	0.25	1.0
Barley	0.30	1.25	0.25	1.0
Feed Corn ^f	0.30	1.34	0.35	2.0
Oats	0.30	1.26	0.25	1.0
Alfalfa hay (1 st cutting)	0.40	1.27	1.23	0.7
Alfalfa hay (2 nd cutting)	0.40	1.31	1.26	0.7
Alfalfa hay (3 rd cutting)	0.40	1.26	1.25	0.7

Table D-6. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Current Climate Conditions (continued)

Crop	$K_{c\ ini}^a$	$K_{c\ mid}^b$	$K_{c\ end}^c$	Maximum Crop Height (m)^d
Alfalfa hay (4 th cutting)	0.40	1.30	1.25	0.7
Alfalfa hay (5 th cutting)	0.40	1.30	1.24	0.7
Alfalfa hay (6 th cutting)	0.40	1.28	1.22	0.7
Oat hay	0.30	1.27	0.25	1.0
Corn silage ^g	0.30	1.34	0.74	2.0

Notes: ^a K_c values for the initial growth stage. Source: Allen et al. 1998, Table 12, pp. 110 - 114.

^b K_c values for the mid-season growth stage adjusted from Allen et al. (1998, Equation 62, p. 121) according to Equation D-2.

^c K_c values for the end of the late season growth stage adjusted from Allen et al. (1998, Equation 65, p. 125) according to Equation D-3.

^dSource: Allen et al. 1998, Table 12, pp. 110 through 114.

^eMidpoint of the range for $K_{c\ end}$ (0.8) was used.

^f $K_{c\ end}$ for dry harvest was used.

^g $K_{c\ end}$ for wet harvest was used.

Table D-7. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Upper Bound Monsoon Climate Conditions

Crop	$K_{c \text{ ini}}^a$	$K_{c \text{ mid}}^b$	$K_{c \text{ end}}^c$	Maximum Crop Height (m)^d
Leaf Lettuce early	0.70	1.05	1.00	0.3
Leaf Lettuce late	0.70	1.04	0.99	0.3
Head Lettuce early	0.70	1.05	1.00	0.3
Head Lettuce late	0.70	1.04	0.99	0.3
Cabbage early	0.70	1.11	1.01	0.4
Cabbage late	0.70	1.09	0.99	0.4
Celery early	0.70	1.09	1.01	0.6
Celery late	0.70	1.09	1.04	0.6
Broccoli early	0.70	1.10	1.00	0.3
Broccoli late	0.70	1.09	0.98	0.3
Cauliflower early	0.70	1.05	1.01	0.4
Cauliflower late	0.70	1.09	0.99	0.4
Spinach early	0.70	1.05	1.00	0.3
Spinach late	0.70	1.04	0.98	0.3
Potatoes	0.50	1.21	0.78	0.6
Onions early	0.70	1.10	0.78	0.4
Onions late	0.70	1.09	0.79	0.4
Carrots early	0.70	1.10	1.00	0.3
Carrots late	0.70	1.09	0.99	0.3
Sweet corn	0.30	1.21	1.08	1.5
Bell peppers	0.60	1.10	0.92	0.7
Cucumbers	0.60	1.02	0.77	0.3
Squash	0.50	0.99	0.77	0.3
Melons	0.50	1.07	0.76	0.4
Tomatoes ^e	0.60	1.19	0.82	0.6
Apples	0.60	1.01	0.83	4.0
Wine Grapes	0.30	0.77	0.45	1.5
Strawberries	0.40	0.88	0.76	0.2
Winter wheat	0.70	1.22	0.25	1.0
Barley	0.30	1.22	0.25	1.0
Feed Corn ^f	0.30	1.23	0.35	2.0
Oats	0.30	1.22	0.25	1.0
Alfalfa hay (1 st cutting)	0.40	1.26	1.21	0.7
Alfalfa hay (2 nd cutting)	0.40	1.26	1.21	0.7
Alfalfa hay (3 rd cutting)	0.40	1.26	1.18	0.7

Table D-7. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Upper Bound Monsoon Climate Conditions (continued)

Crop	$K_{c\ ini}^a$	$K_{c\ mid}^b$	$K_{c\ end}^c$	Maximum Crop Height (m)^d
Alfalfa hay (4 th cutting)	0.40	1.22	1.16	0.7
Alfalfa hay (5 th cutting)	0.40	1.23	1.20	0.7
Alfalfa hay (6 th cutting)	0.40	1.24	1.20	0.7
Oat hay	0.30	1.22	0.25	1.0
Corn silage ^g	0.30	1.24	0.62	2.0

Notes: ^a K_c values for the initial growth stage. Source: Allen et al. 1998, Table 12, pp. 110 - 114.

^b K_c values for the mid-season growth stage adjusted from Allen et al. (1998, Equation 62, p. 121) according to Equation D-2.

^c K_c values for the end of the late season growth stage adjusted from Allen et al. (1998, Equation 65, p. 125) according to Equation D-3.

^dSource: Allen et al. 1998, Table 12, pp. 110 through 114.

^eMidpoint of the range for $K_{c\ end}$ (0.8) was used.

^f $K_{c\ end}$ for dry harvest was used.

^g $K_{c\ end}$ for wet harvest was used.

Table D-8. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Lower Bound Future Climate Conditions.

Crop	$K_{c \text{ ini}}^a$	$K_{c \text{ mid}}^b$	$K_{c \text{ end}}^c$	Maximum Crop Height (m) ^d
Leaf Lettuce early	0.70	1.09	1.04	0.3
Leaf Lettuce late	0.70	1.08	1.03	0.3
Head Lettuce early	0.70	1.09	1.04	0.3
Head Lettuce late	0.70	1.08	1.03	0.3
Cabbage early	0.70	1.15	1.05	0.4
Cabbage late	0.70	1.13	1.03	0.4
Spinach early	0.70	1.09	1.04	0.3
Spinach late	0.70	1.08	1.02	0.3
Celery	0.70	1.16	1.10	0.6
Broccoli early	0.70	1.14	1.04	0.3
Broccoli late	0.70	1.13	1.02	0.3
Cauliflower early	0.70	1.15	1.05	0.4
Cauliflower late	0.70	1.13	1.03	0.4
Potatoes	0.50	1.26	0.85	0.6
Onions	0.70	1.14	0.85	0.4
Carrots early	0.70	1.14	1.04	0.3
Carrots late	0.70	1.13	1.03	0.3
Sweet Corn	0.30	1.29	1.18	1.5
Bell peppers	0.60	1.16	1.00	0.7
Cucumbers	0.60	1.09	0.84	0.3
Squash	0.50	1.04	0.84	0.3
Melons	0.50	1.14	0.84	0.4
Tomatoes ^e	0.60	1.26	0.90	0.6
Alfalfa hay (1st cutting)	0.40	1.30	1.26	0.7
Alfalfa hay (2nd cutting)	0.40	1.32	1.27	0.7
Alfalfa hay (3rd cutting)	0.40	1.30	1.25	0.7
Apples	0.45	1.14	0.86	4.0
Wine Grapes	0.30	0.84	0.45	1.75
Strawberries	0.40	0.93	0.83	0.2
Winter wheat	0.40	1.28	0.25	1.0
Barley	0.30	1.28	0.25	1.0
Oats	0.30	1.28	0.25	1.0

Table D-8. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Lower Bound Future Climate Conditions (continued)

Crop	$K_{c\ ini}^a$	$K_{c\ mid}^b$	$K_{c\ end}^c$	Maximum Crop Height (m)^d
Feed Corn ^f	0.30	1.35	0.35	2.0
Corn silage ^g	0.30	1.36	0.74	2.0
Oat hay	0.30	1.28	0.25	1.0

- Notes: ^a K_c values for the initial growth stage. Source: Allen et al. 1998, Table 12, pp. 110 through 114.
- ^b K_c values for the mid-season growth stage adjusted from Allen et al. (1998, Equation 62, p. 121) according to Equation D-2.
- ^c K_c values for the end of the late season growth stage adjusted from Allen et al. (1998, Equation 65, p. 125) according to Equation D-3.
- ^dSource: Allen et al. 1998, Table 12, pp. 110 through 114.
- ^eMidpoint of the range for $K_{c\ end}$ was used.
- ^f $K_{c\ end}$ for dry harvest was used.
- ^g $K_{c\ end}$ for wet harvest was used.

Table D-9. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Future Climate Conditions.

Crop	K_c ini^a	K_c mid^b	K_c end^c	Maximum Crop Height (m)^d
Leaf Lettuce early	0.70	1.04	0.99	0.3
Leaf Lettuce late	0.70	1.05	0.99	0.3
Head Lettuce early	0.70	1.04	1.00	0.3
Head Lettuce late	0.70	1.04	0.99	0.3
Cabbage early	0.70	1.09	1.00	0.4
Cabbage late	0.70	1.09	0.99	0.4
Spinach early	0.70	1.04	0.99	0.3
Spinach late	0.70	1.04	0.98	0.3
Celery	0.70	1.11	1.06	0.6
Broccoli early	0.70	1.09	1.00	0.3
Broccoli late	0.70	1.09	0.96	0.3
Cauliflower early	0.70	1.09	0.99	0.4
Cauliflower late	0.70	1.09	0.99	0.4
Potatoes	0.50	1.21	0.81	0.6
Onions	0.70	1.09	0.80	0.4
Carrots early	0.70	1.09	1.00	0.3
Carrots late	0.70	1.09	0.99	0.3
Sweet Corn	0.30	1.24	1.13	1.5
Bell peppers	0.60	1.11	0.95	0.7
Cucumbers	0.60	1.05	0.80	0.3
Squash	0.50	1.00	0.80	0.3
Melons	0.50	1.10	0.80	0.4
Tomatoes ^e	0.60	1.21	0.86	0.6
Alfalfa hay (1 st cutting)	0.40	1.24	1.19	0.7
Alfalfa hay (2nd cutting)	0.40	1.26	1.21	0.7
Alfalfa hay (3rd cutting)	0.40	1.25	1.20	0.7
Apples	0.45	1.05	0.77	4.0
Wine Grapes	0.30	0.78	0.45	1.75
Strawberries	0.40	0.89	0.80	0.2
Winter wheat	0.40	1.20	0.25	1.0
Barley	0.30	1.20	0.25	1.0
Oats	0.30	1.21	0.25	1.0

Table D-9. Adjusted Crop Coefficients (K_c) and Maximum Crop Height for Early and Late Season Crops for Future Climate Conditions (continued)

Crop	$K_{c\ ini}^a$	$K_{c\ mid}^b$	$K_{c\ end}^c$	MaximumCrop Height (m) ^d
Feed Corn ^f	0.30	1.28	0.35	2.0
Corn silage ^g	0.30	1.29	0.67	2.0
Oat hay	0.30	1.21	0.25	1.0

- Notes: ^a K_c values for the initial growth stage. Source: Allen et al. 1998, Table 12, pp. 110 through 114.
^b K_c values for the mid-season growth stage adjusted from Allen et al. (1998, Equation 62, p. 121) according to Equation D-2.
^c K_c values for the end of the late season growth stage adjusted from Allen et al. (1998, Equation 65, p. 125) according to Equation D-3.
^dSource: Allen et al. 1998, Table 12, pp. 110 through 114.
^eMidpoint of the range for $K_{c\ end}$ was used.
^f $K_{c\ end}$ for dry harvest was used.
^g $K_{c\ end}$ for wet harvest was used.

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions

Crop	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Leaf Lettuce early - K_c^a			0.74	1.05	1.05							
ET_o (mm/day) ^b			4.22	5.54	6.89							
ET_c (mm/day) ^c			3.10	5.79	7.25							
Monthly ET_c (mm/month) ^d			77.62	173.60	36.27							
Leaf Lettuce late - K_c									0.77	1.06		
ET_o (mm/day)									6.79	4.64		
ET_c (mm/day)									5.21	4.90		
ET_c (mm/month)									156.17	147.00		
Head Lettuce early - K_c			0.74	1.05	1.05							
ET_o (mm/day)			4.22	5.54	6.89							
ET_c (mm/day)			3.10	5.79	7.25							
Monthly ET_c (mm/month)			77.62	173.60	36.27							
Head Lettuce late - K_c									0.77	1.06		
ET_o (mm/day)									6.79	4.64		
ET_c (mm/day)									5.21	4.90		
ET_c (mm/month)									156.17	147.00		
Cabbage early - K_c			0.72	1.03	1.12							
ET_o (mm/day)			4.22	5.54	6.89							
ET_c (mm/day)			3.05	5.73	7.74							
ET_c (mm/month)			91.52	171.81	193.42							
Cabbage late - K_c								0.70	0.75	1.07	1.10	
ET_o (mm/day)								8.62	6.79	4.64	2.75	
ET_c (mm/day)								6.03	5.10	4.96	3.04	
ET_c (mm/month)								30.17	153.12	153.66	57.69	

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Celery early - K_c				0.70	0.92	1.15	1.15	1.13				
ET_o (mm/day)				5.54	6.89	8.21	8.93	8.62				
ET_c (mm/day)				3.88	6.37	9.42	10.25	9.72				
ET_c (mm/month)				73.67	197.50	282.74	317.72	136.03				
Celery late - K_c	1.09								0.70	0.89	1.12	1.12
ET_o (mm/day)	1.73								6.79	4.64	2.75	1.85
ET_c (mm/day)	1.89								4.79	4.13	3.08	2.07
ET_c (mm/month)	35.87								66.57	127.99	92.51	64.20
Broccoli early - K_c			0.72	1.05	1.11							
ET_o (mm/day)			4.22	5.54	6.89							
ET_c (mm/day)			3.05	5.82	7.64							
ET_c (mm/month)			91.37	174.64	152.86							
Broccoli late - K_c								0.70	0.75	1.08	1.09	
ET_o (mm/day)								8.62	6.79	4.64	2.75	
ET_c (mm/day)								6.03	5.11	5.02	2.99	
ET_c (mm/month)								30.17	153.40	155.73	41.87	
Cauliflower early - K_c			0.73	1.05	1.12							
ET_o (mm/day)			4.22	5.54	6.89							
ET_c (mm/day)			3.06	5.84	7.69							
ET_c (mm/month)			91.84	175.07	153.87							
Cauliflower late - K_c								0.70	0.76	1.08	1.09	
ET_o (mm/day)								8.62	6.79	4.64	2.75	
ET_c (mm/day)								6.03	5.14	5.03	3.01	
ET_c (mm/month)								30.17	154.28	156.05	42.10	

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions (continued)

Spinach early - K_c			0.72	1.04	1.06							
ET_o (mm/day)			4.22	5.53	6.89							
ET_c (mm/day)			3.04	5.76	7.28							
ET_c (mm/month)			45.61	172.67	36.41							
Spinach late - K_c									0.71	1.02	1.04	
ET_o (mm/day)									6.79	4.64	2.75	
ET_c (mm/day)									4.85	4.75	2.87	
ET_c (mm/month)									67.92	147.19	14.36	
Potatoes - K_c			0.50	0.56	1.13	1.24	0.94					
ET_o (mm/day)			4.22	5.53	6.89	8.21	8.93					
ET_c (mm/day)			2.11	3.08	7.82	10.16	8.39					
ET_c (mm/month)			10.54	92.34	242.48	304.69	117.39					
Onions early - K_c			0.70	0.93	1.14	1.12	0.92					
ET_o (mm/day)			4.22	5.53	6.89	8.21	8.93					
ET_c (mm/day)			2.95	5.17	7.85	9.17	8.25					
ET_c (mm/month)			14.76	155.06	243.20	275.13	115.55					
Onions late - K_c	0.83								0.71	1.04	1.12	1.04
ET_o (mm/day)	1.73								6.79	4.64	2.75	1.85
ET_c (mm/day)	1.44								4.85	4.86	3.08	1.91
ET_c (mm/month)	5.76								67.84	150.55	92.54	59.35
Carrots early - K_c			0.71	1.05	1.11							
ET_o (mm/day)			4.22	5.54	6.89							
ET_c (mm/day)			3.00	5.79	7.67							
ET_c (mm/month)			45.04	173.75	230.14							

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions (continued)

Carrots late - K_c							0.70	0.90	1.12	1.06	
ET_o (mm/day)							8.62	6.79	4.64	2.75	
ET_c (mm/day)							6.03	6.14	5.20	2.92	
ET_c (mm/month)							30.17	184.23	161.34	26.25	
Sweet Corn - K_c				0.55	1.27	1.27					
ET_o (mm/day)				6.89	8.21	8.93					
ET_c (mm/day)				6.04	7.96	8.82					
ET_c (mm/month)				186.31	238.80	185.22					
Bell Peppers - K_c				0.74	1.15	1.12					
ET_o (mm/day)				6.89	8.21	8.93					
ET_c (mm/day)				5.13	9.46	9.97					
ET_c (mm/month)				128.33	283.89	229.33					
Cucumbers - K_c					0.76	1.04					
ET_o (mm/day)					8.21	8.93					
ET_c (mm/day)					6.21	9.31					
ET_c (mm/month)					180.22	288.55					
Squash - K_c				0.50	0.85	0.96					
ET_o (mm/day)				6.89	8.21	8.93					
ET_c (mm/day)				3.45	7.01	5.					
ET_c (mm/month)				51.71	210.19	111.46					
Melons - K_c				0.51	0.75	1.15	1.08				
ET_o (mm/day)				6.89	8.21	8.93	8.62				
ET_c (mm/day)				3.53	6.16	10.23	9.27				
ET_c (mm/month)				52.89	184.83	317.03	222.42				

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions (continued)

Tomatoes - K_c					0.63	1.15	1.14					
ET_o (mm/day)					6.89	8.21	8.93					
ET_c (mm/day)					4.35	9.42	10.20					
ET_c (mm/month)					108.63	282.64	255.08					
Apples - K_c			0.60	0.76	1.05	1.12	1.12	1.12	1.12	1.00		
ET_o (mm/day)			4.22	5.53	6.89	8.21	8.93	8.62	6.79	4.64		
ET_c (mm/day)			2.53	4.19	7.27	9.21	10.01	9.67	7.62	4.66		
ET_c (mm/month)			75.89	125.18	225.45	276.42	310.56	299.90	228.48	125.75		
Grapes - K_c			0.33	0.62	0.83	0.83	0.77	0.76				
ET_o (mm/day)			4.22	5.53	6.89	8.21	8.93	8.62				
ET_c (mm/day)			1.38	3.42	5.71	6.82	6.91	4.84				
ET_c (mm/month)			41.52	102.66	177.05	204.46	214.22	149.96				
Strawberries - K_c			0.57	0.66	0.90	0.92	0.91	0.88	0.84			
ET_o (mm/day)			4.22	5.53	6.89	8.21	8.93	8.62	6.79			
ET_c (mm/day)			2.40	3.66	6.23	7.56	8.16	7.61	5.69			
ET_c (mm/month)			71.85	109.70	193.21	226.81	253.18	235.94	125.27			
Winter wheat - K_c	1.14	1.25	1.25	1.25	1.01	0.45				0.70	0.74	0.93
ET_o (mm/day)	1.73	2.63	4.22	5.53	6.89	8.21				4.64	2.75	1.85
ET_c (mm/day)	1.98	3.30	5.29	6.95	6.95	3.66				3.25	2.03	1.72
ET_c (mm/month)	61.36	92.41	164.01	208.42	215.38	58.59				48.73	60.88	53.27
Barley - K_c	1.07	1.25	1.25	1.25	0.94	0.42				0.30	0.35	0.68
ET_o (mm/day)	1.98	3.30	5.29	6.95	6.95	3.66				3.25	2.03	1.72
ET_c (mm/day)	1.86	3.30	5.28	6.94	6.46	3.49				1.39	0.96	1.26
ET_c (mm/month)	57.57	92.31	163.81	208.17	200.19	55.76				20.88	28.67	39.12

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions (continued)

Feed Corn - K_c					0.30	0.43	1.08	1.34	1.21	0.60		
ET_o (mm/day)					6.89	8.21	8.93	8.62	6.79	4.64		
ET_c (mm/day)					2.07	3.51	9.66	11.55	8.23	2.81		
ET_c (mm/month)					31.02	105.32	299.43	358.01	246.94	47.72		
Oat Feed- K_c	0.51	1.06	1.26	1.25	0.67							0.30
ET_o (mm/day)	1.73	2.63	4.22	5.53	6.89							1.85
ET_c (mm/day)	0.88	2.80	5.32	6.90	4.63							0.55
ET_c (mm/month)	27.38	78.32	164.82	207.13	115.70							8.32
Alfalfa hay (1st) - K_c	0.69	1.26	1.20									
ET_o (mm/day)	1.73	2.63	4.22									
ET_c (mm/day)	1.20	3.32	5.07									
ET_c (mm/month)	35.96	92.83	10.14									
Alfalfa hay (2nd)-K_c			0.74	1.30								
ET_o (mm/day)			4.22	5.53								
ET_c (mm/day)			3.13	7.17								
ET_c (mm/month)			90.88	186.48								
Alfalfa hay (3rd) - K_c				0.40	0.90	1.29						
ET_o (mm/day)				5.53	6.89	8.21						
ET_c (mm/day)				2.21	6.17	10.60						
ET_c (mm/month)				8.86	191.41	212.03						
Alfalfa hay (4th) - K_c						0.40	1.07	1.28				
ET_o (mm/day)						8.21	8.93	8.62				
ET_c (mm/day)						3.30	9.54	11.08				
ET_c (mm/month)						33.05	295.71	155.07				

Table D-10. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Current Climate Conditions (continued)

Alfalfa hay (5th) - K_c								0.49	1.21	1.26		
ET_o (mm/day)								8.62	6.79	4.64		
ET_c (mm/day)								4.26	8.25	5.83		
ET_c (mm/month)								72.38	247.37	46.62		
Alfalfa hay (6th) - K_c										0.61	1.26	1.24
ET_o (mm/day)										4.64	2.75	1.85
ET_c (mm/day)										2.83	3.48	2.28
ET_c (mm/month)										65.01	104.44	4.57
Corn silage - K_c					0.30	0.85	1.33	0.99				
ET_o (mm/day)					6.89	8.21	8.93	8.62				
ET_c (mm/day)					2.07	7.02	11.92	8.59				
ET_c (mm/month)					31.02	210.47	369.53	145.95				
Oats - K_c				0.60	1.26	0.76						
ET_o (mm/day)				5.54	6.89	8.21						
ET_c (mm/day)				3.29	8.68	6.22						
ET_c (mm/month)				98.4	269.22	87.10						
Bermuda^e - K_c	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
ET_o (mm/day)	1.73	2.63	4.22	5.54	6.89	8.21	8.93	8.62	6.79	4.64	2.75	1.85
ET_c (mm/day)	1.47	2.23	3.58	4.71	5.86	6.98	7.59	7.33	5.77	3.94	2.34	1.57
ET_c (mm/month)	45.68	62.61	111.10	141.18	181.66	209.36	235.21	227.14	173.22	122.28	70.21	48.72

Notes: ^a Mean monthly K_c values calculated according to Appendix D, Section 4.

^b Mean monthly ET_o values from Appendix C, Table C-9.

^c Mean daily ET_c calculated using Equation D-1.

^d Mean monthly ET_c calculated from mean daily ET_c and the number of growing days per month (Appendix D, Section 5).

^e Bermudagrass was selected for current and upper bound monsoon climates because it is a warm season grass.

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions

Crop	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Leaf Lettuce early - K_c^a			0.73	1.02	1.02							
ET_o (mm/day) ^b			3.82	5.10	6.32							
ET_c (mm/day) ^c			2.80	5.18	6.45							
Monthly ET_c (mm/month) ^d			69.99	155.43	32.27							
Leaf Lettuce late - K_c									0.76	1.02		
ET_o (mm/day)									5.08	3.99		
ET_c (mm/day)									3.87	4.09		
ET_c (mm/month)									115.97	122.66		
Head Lettuce early - K_c			0.73	1.02	1.02							
ET_o (mm/day)			3.82	5.10	6.32							
ET_c (mm/day)			2.80	5.18	6.45							
Monthly ET_c (mm/month)			69.99	155.30	32.27							
Head Lettuce late - K_c									0.76	1.02		
ET_o (mm/day)									5.08	3.99		
ET_c (mm/day)									3.87	4.09		
ET_c (mm/month)									115.97	122.66		
Cabbage early - K_c			0.72	1.01	1.09							
ET_o (mm/day)			3.82	5.10	6.32							
ET_c (mm/day)			2.76	5.15	6.88							
ET_c (mm/month)			82.67	154.37	172.08							
Cabbage late - K_c								0.70	0.75	1.04	1.07	
ET_o (mm/day)								5.64	5.08	3.99	2.45	
ET_c (mm/day)								3.95	3.80	4.15	2.62	
ET_c (mm/month)								19.73	113.95	128.52	49.72	

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Celery early - K_c				0.70	0.89	1.09	1.09	1.06				
ET_o (mm/day)				5.10	6.32	7.36	6.25	5.64				
ET_c (mm/day)				3.57	5.65	8.01	6.80	5.95				
ET_c (mm/month)				67.82	175.09	240.16	210.95	83.26				
Celery late - K_c	1.08								0.70	0.88	1.09	1.09
ET_o (mm/day)	1.92								5.08	3.99	2.45	2.00
ET_c (mm/day)	2.07								3.56	3.51	2.68	2.19
ET_c (mm/month)	39.31								49.82	108.67	80.38	67.93
Broccoli early - K_c			0.72	1.03	1.08							
ET_o (mm/day)			3.82	5.10	6.32							
ET_c (mm/day)			2.75	5.23	6.81							
ET_c (mm/month)			82.55	156.97	136.24							
Broccoli late - K_c								0.70	0.75	1.05	1.05	
ET_o (mm/day)								5.64	5.08	3.99	2.45	
ET_c (mm/day)								3.95	3.81	4.21	2.58	
ET_c (mm/month)								19.73	114.18	130.36	36.15	
Cauliflower early - K_c			0.72	1.03	1.08							
ET_o (mm/day)			3.82	5.10	6.32							
ET_c (mm/day)			2.76	5.24	6.84							
ET_c (mm/month)			82.94	157.08	136.83							
Cauliflower late - K_c								0.70	0.75	1.05	1.06	
ET_o (mm/day)								5.64	5.08	3.99	2.45	
ET_c (mm/day)								3.95	3.82	4.20	2.59	
ET_c (mm/month)								19.73	114.74	130.35	36.27	

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions (continued)

Spinach early - K_c			0.72	1.01	1.03							
ET_o (mm/day)			3.82	5.10	6.32							
ET_c (mm/day)			2.75	5.15	6.48							
ET_c (mm/month)			41.20	154.64	32.40							
Spinach late - K_c									0.71	0.99	1.01	
ET_o (mm/day)									5.08	3.99	2.45	
ET_c (mm/day)									3.62	3.97	2.48	
ET_c (mm/month)									50.73	123.11	12.39	
Potatoes - K_c			0.50	0.55	1.10	1.20	0.92					
ET_o (mm/day)			3.82	5.10	6.32	7.36	6.25					
ET_c (mm/day)			1.91	2.82	6.96	8.81	5.73					
ET_c (mm/month)			9.54	84.57	215.82	264.39	80.19					
Onions early - K_c			0.70	0.92	1.10	1.08	0.88					
ET_o (mm/day)			3.82	5.10	6.32	7.36	6.25					
ET_c (mm/day)			2.67	4.67	6.98	7.96	5.48					
ET_c (mm/month)			13.36	140.05	216.32	238.86	76.72					
Onions late - K_c	.82								0.71	1.55	1.09	1.01
ET_o (mm/day)	1.92								5.08	3.99	2.45	2.00
ET_c (mm/day)	1.57								3.62	6.20	2.67	2.02
ET_c (mm/month)	6.28								50.70	192.07	80.04	62.65
Carrots early - K_c			0.71	1.02	1.08							
ET_o (mm/day)			3.82	5.10	6.32							
ET_c (mm/day)			2.72	5.21	6.84							
ET_c (mm/month)			40.73	156.25	205.17							

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions (continued)

Carrots late - K_c								0.70	0.89	1.09	1.03	
ET_o (mm/day)								5.64	5.08	3.99	2.45	
ET_c (mm/day)								3.95	4.51	4.34	2.51	
ET_c (mm/month)								19.73	135.26	134.44	22.63	
Sweet Corn - K_c				0.53	1.20	1.19						
ET_o (mm/day)				6.32	7.36	6.25						
ET_c (mm/day)				6.01	7.96	8.82						
ET_c (mm/month)				186.31	238.8	185.22						
Bell Peppers - K_c				0.73	1.10	1.06						
ET_o (mm/day)				6.32	7.36	6.25						
ET_c (mm/day)				4.62	8.09	6.61						
ET_c (mm/month)				115.39	242.69	152.07						
Cucumbers - K_c					0.74	0.98						
ET_o (mm/day)					7.36	6.25						
ET_c (mm/day)					5.42	6.14						
ET_c (mm/month)					157.21	190.25						
Squash - K_c				0.50	0.83	0.91						
ET_o (mm/day)				6.32	7.36	6.25						
ET_c (mm/day)				3.16	6.08	5.70						
ET_c (mm/month)				47.37	182.32	74.14						
Melons - K_c				0.51	0.71	1.07	1.00					
ET_o (mm/day)				6.32	7.36	6.25	5.64					
ET_c (mm/day)				3.22	5.25	6.69	5.63					
ET_c (mm/month)				48.33	157.46	207.47	135.17					

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions (continued)

Tomatoes - K_c					0.63	1.10	1.08					
ET_o (mm/day)					6.32	7.36	6.25					
ET_c (mm/day)					3.96	8.11	6.77					
ET_c (mm/month)					99.12	243.19	169.16					
Apples - K_c			0.60	0.72	0.96	1.01	1.01	1.01	1.01	0.91		
ET_o (mm/day)			3.82	5.10	6.32	7.36	6.25	5.64	5.08	3.99		
ET_c (mm/day)			2.29	3.68	6.04	7.42	6.30	5.68	5.12	3.64		
ET_c (mm/month)			68.72	110.48	187.14	222.55	195.45	176.21	153.66	98.22		
Grapes - K_c			0.33	0.58	0.77	0.77	0.73	0.54				
ET_o (mm/day)			3.82	5.10	6.32	7.36	6.25	5.64				
ET_c (mm/day)			1.24	2.98	4.88	5.69	4.54	3.07				
ET_c (mm/month)			37.25	89.32	151.17	170.72	140.69	95.16				
Strawberries - K_c			0.57	0.64	0.87	0.88	0.68	0.84	0.79			
ET_o (mm/day)			3.82	5.10	6.32	7.36	6.25	5.64	5.08			
ET_c (mm/day)			2.16	3.27	5.49	6.51	4.25	4.73	4.00			
ET_c (mm/month)			64.78	98.22	170.15	195.22	131.67	146.67	87.91			
Winter wheat - K_c	1.11	1.22	1.22	1.22	0.98	0.44				0.70	0.73	0.91
ET_o (mm/day)	1.92	2.96	3.82	5.10	6.32	7.36				3.99	2.45	2.00
ET_c (mm/day)	2.14	3.61	4.66	6.22	6.20	3.23				2.79	1.80	1.83
ET_c (mm/month)	66.46	100.94	144.36	186.52	192.15	51.69				41.92	53.96	56.80
Barley - K_c	1.04	1.22	1.22	1.22	0.91	0.42				0.30	0.35	0.67
ET_o (mm/day)	1.92	2.96	3.82	5.10	6.32	7.36				3.99	2.45	2.00
ET_c (mm/day)	2.01	3.60	4.66	6.21	5.77	3.08				1.20	0.85	1.34
ET_c (mm/month)	62.27	100.91	144.31	186.45	178.86	49.26				17.96	25.36	41.52

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions (continued)

Feed Corn - K_c					0.30	0.41	1.00	1.23	1.11	0.58		
ET_o (mm/day)					6.32	7.36	6.25	5.64	5.08	3.99		
ET_c (mm/day)					1.89	3.04	6.23	6.91	5.65	2.30		
ET_c (mm/month)					28.42	91.26	193.01	214.07	169.58	39.05		
Oats Feed - K_c	0.50	1.03	1.22	1.21	0.65							0.30
ET_o (mm/day)	1.92	2.96	3.82	5.10	6.32							2.00
ET_c (mm/day)	0.96	3.05	4.66	6.15	4.13							0.60
ET_c (mm/month)	29.86	85.27	144.32	184.40	103.26							9.01
Alfalfa hay (1st) - K_c	0.69	1.25	1.19									
ET_o (mm/day)	1.92	2.96	3.82									
ET_c (mm/day)	1.32	3.69	4.55									
ET_c (mm/month)	39.69	103.40	9.10									
Alfalfa hay (2nd)-K_c			0.71	1.26								
ET_o (mm/day)			3.82	5.10								
ET_c (mm/day)			2.71	6.40								
ET_c (mm/month)			75.76	172.76								
Alfalfa hay (3rd) - K_c				0.40	0.87	1.24						
ET_o (mm/day)				5.01	6.32	7.36						
ET_c (mm/day)				2.04	5.52	9.15						
ET_c (mm/month)				8.16	171.16	183.04						
Alfalfa hay (4th) - K_c						0.47	1.39	1.20				
ET_o (mm/day)						7.36	6.25	5.64				
ET_c (mm/day)						3.48	8.72	6.76				
ET_c (mm/month)						34.78	270.18	94.58				

Table D-11. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Upper Bound Monsoon Climate Conditions (continued)

Alfalfa hay (5th) - K_c								0.49	1.01	1.21		
ET_o (mm/day)								5.64	5.08	3.99		
ET_c (mm/day)								2.76	5.15	4.84		
ET_c (mm/month)								46.84	51.54	96.85		
Alfalfa hay (6th) - K_c										0.60	1.23	1.20
ET_o (mm/day)										3.99	2.45	2.00
ET_c (mm/day)										2.40	3.00	2.40
ET_c (mm/month)										55.09	90.13	4.81
Corn silage - K_c					0.30	0.85	1.23	0.87				
ET_o (mm/day)					6.32	7.36	6.25	5.64				
ET_c (mm/day)					1.89	6.22	7.67	4.88				
ET_c (mm/month)					28.42	186.59	237.85	78.02				
Oats Hay - K_c				0.58	1.22	0.74						
ET_o (mm/day)				5.10	6.32	7.36						
ET_c (mm/day)				2.97	7.70	5.42						
ET_c (mm/month)				89.14	238.57	75.90						
Bermuda^e - K_c	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
ET_o (mm/day)	1.92	2.96	3.82	5.10	6.32	7.36	6.25	5.64	5.08	3.99	2.45	2.00
ET_c (mm/day)	1.64	2.51	3.25	4.33	5.37	6.25	5.31	4.79	4.32	3.39	2.08	1.70
ET_c (mm/month)	50.71	70.35	100.60	129.97	166.43	187.57	164.73	148.52	129.62	105.19	62.43	52.76

Notes: ^a Mean monthly K_c values calculated according to Appendix D, Section 4.

^b Mean monthly ET_o values from Appendix C, Table C-9.

^c Mean daily ET_c calculated using Equation D-1.

^d Mean monthly ET_c calculated from mean daily ET_c and the number of growing days per month (Appendix D, Section 5).

^e Bermudagrass was selected for upper bound monsoon climate because it is a warm season grass.

Table D-12. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Lower Bound Future Climate Conditions

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Leaf Lettuce early - K_c^a				0.70	0.85	1.08						
ET_o (mm/day) ^b				4.30	6.01	7.96						
ET_c (mm/day) ^c				3.01	5.08	8.62						
Monthly ET_c (mm/month) ^d				21.07	157.59	172.44						
Leaf Lettuce late - K_c							0.70	0.95	1.06			
ET_o (mm/day)							8.82	8.26	6.27			
ET_c (mm/day)							6.18	7.87	6.66			
Monthly ET_c (mm/month)							98.86	243.84	73.23			
Head Lettuce early - K_c				0.70	0.76	1.05	1.07					
ET_o (mm/day)				4.30	6.01	7.96	8.82					
ET_c (mm/day)				3.01	4.56	8.37	9.41					
Monthly ET_c (mm/month)				21.07	141.43	251.15	94.09					
Head Lettuce late - K_c							0.70	0.83	1.06	1.03		
ET_o (mm/day)							8.82	8.26	6.27	4.05		
ET_c (mm/day)							6.17	6.88	6.67	4.16		
Monthly ET_c (mm/month)							98.78	213.14	200.23	4.16		
Cabbage early - K_c				0.70	0.81	1.14	1.10					
ET_o (mm/day)				4.30	6.01	7.96	8.82					
ET_c (mm/day)				3.01	4.86	9.06	9.70					
Monthly ET_c (mm/month)				21.07	150.52	271.73	67.92					
Cabbage late - K_c							0.70	0.87	1.12	1.04		
ET_o (mm/day)							8.82	8.26	6.27	4.05		
ET_c (mm/day)							6.17	7.23	7.05	4.21		
Monthly ET_c (mm/month)							80.26	224.04	211.49	4.21		

Table D-12. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Celery - K_c				0.70	0.75	1.08	1.16	1.13				
ET _o (mm/day)				4.30	6.01	7.96	8.82	8.26				
ET _c (mm/day)				3.01	4.53	8.62	10.25	9.32				
Monthly ET _c (mm/month)				21.07	140.58	258.58	317.71	102.57				
Broccoli early - K_c				0.70	0.77	1.11	1.11					
ET _o (mm/day)				4.30	6.01	7.96	8.82					
ET _c (mm/day)				3.01	4.65	8.84	9.81					
Monthly ET _c (mm/month)				21.07	144.14	265.22	147.10					
Broccoli late - K_c							0.70	0.85	1.12	1.06		
ET _o (mm/day)							8.82	8.26	6.27	4.05		
ET _c (mm/day)							6.17	7.05	7.04	4.30		
Monthly ET _c (mm/month)							92.61	218.55	211.30	30.11		
Cauliflower early - K_c				0.70	0.86	1.14						
ET _o (mm/day)				4.30	6.01	7.96						
ET _c (mm/day)				3.01	5.17	9.05						
Monthly ET _c (mm/month)				21.07	160.27	226.37						
Cauliflower late - K_c							0.70	0.78	1.10	1.04		
ET _o (mm/day)							8.82	8.26	6.27	4.05		
ET _c (mm/day)							6.17	6.45	6.91	4.21		
Monthly ET _c (mm/month)							6.17	200.06	207.42	4.21		
Spinach early - K_c				0.70	0.86	1.09						
ET _o (mm/day)				4.30	6.01	7.96						
ET _c (mm/day)				3.01	5.16	8.64						
Monthly ET _c (mm/month)				21.07	159.82	146.92						
Spinach late - K_c								0.72	1.04	1.03		
ET _o (mm/day)								8.26	6.27	4.05		

Table D-12. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET _c (mm/day)								5.97	6.51	4.18		
Monthly ET _c (mm/month)								143.24	195.16	4.18		
Potatoes - K_c				0.50	0.53	1.14	1.26	1.08				
ET _o (mm/day)				4.30	6.01	7.96	8.82	8.26				
ET _c (mm/day)				2.15	3.18	9.10	11.13	8.95				
Monthly ET _c (mm/month)				15.05	98.50	273.08	345.09	143.15				
Onions - K_c			0.76	1.10	1.14	1.14	0.98	0.86				
ET _o (mm/day)			2.85	4.30	6.01	7.96	8.82	8.26				
ET _c (mm/day)			2.16	4.75	6.86	9.05	8.65	7.10				
Monthly ET _c (mm/month)			64.94	142.52	212.81	271.37	268.25	21.29				
Carrots early - K_c				0.70	0.86	1.14	1.10					
ET _o (mm/day)				4.30	6.01	7.96	8.82					
ET _c (mm/day)				3.01	5.19	9.10	9.67					
Monthly ET _c (mm/month)				21.07	161.02	272.91	116.00					
Carrots late - K_c							0.70	1.01	1.11	1.03		
ET _o (mm/day)							8.82	8.26	6.27	4.05		
ET _c (mm/day)							6.19	8.34	6.98	4.17		
Monthly ET _c (mm/month)							111.49	258.66	209.45	4.17		
Sweet corn - K_c					0.30	0.36	1.05	1.28	1.21			
ET _o (mm/day)					5.39	6.96	7.83	7.39	5.77			
ET _c (mm/day)					6.01	7.96	8.82	8.26	6.27			
Monthly ET _c (mm/month)					42.07	238.80	273.42	256.06	37.62			
Bell peppers - K_c						0.60	0.87	1.16	1.08			
ET _o (mm/day)						7.96	8.82	8.26	6.27			
ET _c (mm/day)						4.78	7.67	9.57	6.76			
Monthly ET _c (mm/month)						105.07	237.88	296.52	108.17			

Table D-12. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cucumbers - K_c					0.60	0.84	1.05					
ET_o (mm/day)					6.01	7.96	8.82					
ET_c (mm/day)					3.61	6.66	9.27					
Monthly ET_c (mm/month)					25.24	199.95	287.25					
Squash - K_c					0.50	0.72	1.00					
ET_o (mm/day)					6.01	7.96	8.82					
ET_c (mm/day)					3.00	5.70	8.83					
Monthly ET_c (mm/month)					21.04	171.04	247.28					
Melons - K_c					0.50	0.58	1.07	1.10	0.88			
ET_o (mm/day)					6.01	7.96	8.82	8.26	6.27			
ET_c (mm/day)					3.00	4.62	9.41	9.05	5.50			
Monthly ET_c (mm/month)					21.04	138.65	291.67	280.67	27.00			
Tomatoes - K_c						0.61	1.08	1.19	0.94			
ET_o (mm/day)						7.96	8.82	8.26	6.27			
ET_c (mm/day)						4.86	9.52	9.87	5.91			
Monthly ET_c (mm/month)						106.81	295.27	305.82	23.63			
Corn silage - K_c					0.30	0.67	1.34	1.29	0.93			
ET_o (mm/day)					6.01	7.96	8.82	8.26	6.27			
ET_c (mm/day)					1.80	5.35	11.79	10.68	5.82			
Monthly ET_c (mm/month)					36.06	160.37	365.35	331.19	145.41			
Feed Corn - K_c					0.30	0.43	1.11	1.35	1.26	0.74	0.40	
ET_o (mm/day)					6.01	7.96	8.82	8.26	6.27	4.05	1.90	
ET_c (mm/day)					1.80	3.46	9.83	11.12	7.93	3.01	0.76	
Monthly ET_c (mm/month)					36.06	103.76	304.78	344.68	237.82	93.24	3.78	

Table D-12. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oat hay – K_c			0.30	0.39	1.16	1.28	1.16	0.52				
ET_o (mm/day)			2.85	4.30	6.01	7.96	8.82	8.26				
ET_c (mm/day)			0.86	1.68	6.98	10.19	10.22	4.26				
Monthly ET_c (mm/month)			2.66	50.37	216.25	305.63	316.97	68.16				
Alfalfa (1st cutting) – K_c			0.60	1.25	1.28							
ET_o (mm/day)			2.85	4.30	6.01							
ET_c (mm/day)			1.71	5.36	7.72							
Monthly ET_c (mm/month)			51.23	160.78	115.78							
Alfalfa (2nd cutting) - K_c					0.46	1.07	1.30					
ET_o (mm/day)					6.01	7.96	8.82					
ET_c (mm/day)					2.77	8.53	11.47					
Monthly ET_c (mm/month)					44.35	255.88	252.41					
Alfalfa (3rd cutting) - K_c							0.40	0.89	1.29			
ET_o (mm/day)							8.82	8.26	6.27			
ET_c (mm/day)							3.54	7.38	8.06			
Monthly ET_c (mm/month)							31.88	228.64	225.78			
Apples - K_c				0.45	0.56	0.92	1.13	1.14	1.07	0.89		
ET_o (mm/day)				4.30	6.01	7.96	8.82	8.26	6.27	4.05		
ET_c (mm/day)				1.94	3.34	7.35	10.01	9.38	6.69	3.61		
Monthly ET_c (mm/month)				15.48	103.66	220.59	310.29	290.80	200.77	18.05		
Grapes - K_c							0.30	0.60	0.84	0.77		
ET_o (mm/day)							7.96	8.82	8.26	6.27		
ET_c (mm/day)							2.39	5.25	6.92	4.81		
Monthly ET_c (mm/month)							31.12	162.70	214.59	144.25		

Table D-12. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Strawberries - K_c				0.40	0.71	0.92						
ET_o (mm/day)				4.30	6.01	7.96						
ET_c (mm/day)				1.72	4.26	7.32						
Monthly ET_c (mm/month)				5.16	131.92	219.49						
Winter wheat - K_c	0.76	0.89	1.02	1.16	1.27	1.28	1.01	0.45	0.40	0.40	0.48	0.62
ET_o (mm/day)	1.21	1.67	2.85	4.30	6.01	7.96	8.82	8.26	6.27	4.05	1.90	1.25
ET_c (mm/day)	0.92	1.45	2.92	5.00	7.64	10.18	8.93	3.68	2.51	1.62	0.91	0.77
Monthly ET_c (mm/month)	28.45	41.69	90.53	149.93	236.74	305.54	276.76	58.96	35.11	50.30	27.43	23.98
Barley - K_c				0.30	1.01	1.27	0.66					
ET_o (mm/day)				4.30	6.01	7.96	8.82					
ET_c (mm/day)				1.29	6.08	10.08	5.84					
Monthly ET_c (mm/month)				18.06	188.41	302.38	93.42					
Oat feed - K_c					0.45	1.27	0.72					
ET_o (mm/day)					6.01	7.96	8.82					
ET_c (mm/day)					2.71	10.09	6.38					
Monthly ET_c (mm/month)					43.33	302.67	70.22					
Fescue^e - K_c				0.95	0.95	0.95	0.95	0.95	0.95	0.95		
ET_o (mm/day)				4.30	6.01	7.96	8.82	8.26	6.27	4.05		
ET_c (mm/day)				4.08	5.71	7.56	8.38	7.85	5.96	3.85		
Monthly ET_c (mm/month)				122.55	176.99	226.86	259.75	243.26	178.70	119.27		

Notes: ^aMean monthly K_c values calculated according to Appendix D, Section 4.

^bMean monthly ET_o values from Appendix C, Table C-9.

^cMean daily ET_c calculated using Equation D-1.

^dMean monthly ET_c calculated from mean daily ET_c and the number of growing days per month (Appendix D, Section 5).

^eFescue was selected for lower bound future climate because it is a cool season grass.

Table D-13. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Future Climate Conditions

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Leaf Lettuce early - K_c^a				0.70	0.83	1.03						
ET_o (mm/day) ^b				3.18	4.21	5.31						
ET_c (mm/day) ^c				2.23	3.48	5.47						
Monthly ET_c (mm/month) ^d				15.58	107.82	109.40						
Leaf Lettuce late - K_c							0.70	0.93	1.03			
ET_o (mm/day)							6.50	6.15	4.44			
ET_c (mm/day)							4.55	5.72	4.55			
Monthly ET_c (mm/month)							72.80	177.17	50.09			
Head Lettuce early - K_c				0.70	0.75	1.00	1.02					
ET_o (mm/day)				3.18	4.21	5.31	6.50					
ET_c (mm/day)				2.23	3.16	5.33	6.63					
Monthly ET_c (mm/month)				15.58	98.03	159.98	66.31					
Head Lettuce late - K_c							0.70	0.82	1.03	0.99		
ET_o (mm/day)							6.50	6.15	4.44	2.50		
ET_c (mm/day)							4.55	5.04	4.56	2.47		
Monthly ET_c (mm/month)							72.80	156.13	136.72	2.47		
Cabbage early - K_c				0.70	0.79	1.08	1.05					
ET_o (mm/day)				3.18	4.21	5.31	6.50					
ET_c (mm/day)				2.23	3.34	5.74	6.82					
Monthly ET_c (mm/month)				15.58	103.63	172.33	47.74					
Cabbage late - K_c							0.70	0.86	1.08	0.99		
ET_o (mm/day)							6.50	6.15	4.44	2.50		
ET_c (mm/day)							4.55	5.28	4.81	2.49		
Monthly ET_c (mm/month)							59.15	163.60	144.16	2.49		

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Table D-13. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Celery - K_c				0.70	0.75	1.04	1.11	1.08				
ET _o (mm/day)				3.18	4.21	5.31	6.50	6.15				
ET _c (mm/day)				2.23	3.15	5.51	7.20	6.65				
Monthly ET _c (mm/month)				15.58	97.64	165.37	223.28	73.16				
Broccoli early - K_c				0.70	0.77	1.06	1.06					
ET _o (mm/day)				3.18	4.21	5.31	6.50					
ET _c (mm/day)				2.23	3.22	5.65	6.92					
Monthly ET _c (mm/month)				15.58	99.88	169.53	103.82					
Broccoli late - K_c							0.70	0.84	1.09	1.01		
ET _o (mm/day)							6.50	6.15	4.44	2.50		
ET _c (mm/day)							4.55	5.16	4.82	2.53		
Monthly ET _c (mm/month)							68.25	160.09	144.53	17.72		
Cauliflower early - K_c				0.70	0.85	1.08						
ET _o (mm/day)				3.18	4.21	5.31						
ET _c (mm/day)				2.23	3.54	5.73						
Monthly ET _c (mm/month)				15.58	109.59	143.33						
Cauliflower late - K_c							0.70	0.77	1.06	0.99		
ET _o (mm/day)							6.50	6.15	4.44	2.50		
ET _c (mm/day)							4.55	4.76	4.71	2.49		
Monthly ET _c (mm/month)							4.55	147.46	141.38	2.49		
Spinach early - K_c				0.70	0.84	1.03						
ET _o (mm/day)				3.18	4.21	5.31						
ET _c (mm/day)				2.23	3.52	5.48						
Monthly ET _c (mm/month)				15.58	109.16	93.21						
Spinach late - K_c								0.72	1.00	0.99		
ET _o (mm/day)								6.15	4.44	2.50		

Table D-13. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ET _c (mm/day)								4.43	4.45	2.47		
Monthly ET _c (mm/month)								106.32	133.57	2.47		
Potatoes - K_c				0.50	0.53	1.10	1.21	1.03				
ET _o (mm/day)				3.18	4.21	5.31	6.50	6.15				
ET _c (mm/day)				1.59	2.22	5.83	7.85	6.36				
Monthly ET _c (mm/month)				11.13	68.73	174.85	243.35	101.79				
Onions - K_c			0.75	1.05	1.09	1.08	0.93	0.81				
ET _o (mm/day)			1.99	3.18	4.21	5.31	6.50	6.15				
ET _c (mm/day)			1.50	3.35	4.58	5.74	6.05	5.00				
Monthly ET _c (mm/month)			44.90	100.59	141.89	172.29	187.62	15.00				
Carrots early - K_c				0.70	0.84	1.09	1.05					
ET _o (mm/day)				3.18	4.21	5.31	6.50					
ET _c (mm/day)				2.23	3.56	5.79	6.82					
Monthly ET _c (mm/month)				15.58	110.25	173.66	81.81					
Carrots late - K_c							0.70	0.98	1.08	0.99		
ET _o (mm/day)							6.50	6.15	4.44	2.50		
ET _c (mm/day)							4.56	6.05	4.78	2.48		
Monthly ET _c (mm/month)							82.14	187.55	143.37	2.48		
Sweet corn - K_c					0.30	0.36	1.02	1.23	1.15			
ET _o (mm/day)					4.21	5.31	6.50	6.15	4.44			
ET _c (mm/day)					1.26	1.90	6.61	7.58	5.12			
Monthly ET _c (mm/month)					8.84	56.93	204.83	234.86	30.74			
Bell peppers - K_c						0.60	0.85	1.11	1.03			
ET _o (mm/day)						5.31	6.50	6.15	4.44			
ET _c (mm/day)						3.19	5.52	6.85	4.58			
Monthly ET _c (mm/month)						70.09	171.08	212.50	73.30			

Table D-13. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cucumbers - K_c					0.60	0.82	1.01					
ET_o (mm/day)					4.21	5.31	6.50					
ET_c (mm/day)					2.53	4.34	6.55					
Monthly ET_c (mm/month)					17.68	130.09	203.15					
Squash - K_c					0.50	0.70	0.96					
ET_o (mm/day)					4.21	5.31	6.50					
ET_c (mm/day)					2.10	3.72	6.24					
Monthly ET_c (mm/month)					14.74	111.48	174.79					
Melons - K_c					0.50	0.58	1.03	1.06	0.84			
ET_o (mm/day)					4.21	5.31	6.50	6.15	4.44			
ET_c (mm/day)					2.10	3.06	6.70	6.49	3.71			
Monthly ET_c (mm/month)					14.74	91.69	207.85	201.33	14.87			
Tomatoes - K_c						0.61	1.05	1.15	0.90			
ET_o (mm/day)						5.31	6.50	6.15	4.44			
ET_c (mm/day)						3.24	6.81	7.07	3.99			
Monthly ET_c (mm/month)						71.17	211.02	219.18	15.94			
Corn silage - K_c					0.30	0.65	1.27	1.23	0.86			
ET_o (mm/day)					4.21	5.31	6.50	6.15	4.44			
ET_c (mm/day)					1.26	3.44	8.26	7.54	3.83			
Monthly ET_c (mm/month)					25.26	103.23	256.03	233.89	95.73			
Feed Corn - K_c					0.30	0.43	1.07	1.28	1.21	0.72	0.39	
ET_o (mm/day)					4.21	5.31	6.50	6.15	4.44	2.50	0.98	
ET_c (mm/day)					1.26	2.26	6.93	7.90	5.36	1.79	0.39	
Monthly ET_c (mm/month)					25.26	67.92	214.68	244.57	160.68	55.63	1.93	

Table D-13. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Oat hay – K_c			0.30	0.38	1.10	1.21	1.10	0.50				
ET_o (mm/day)			1.99	3.18	4.21	5.31	6.50	6.15				
ET_c (mm/day)			0.60	1.22	4.62	6.41	7.12	3.06				
Monthly ET_c (mm/month)			1.79	36.62	143.26	192.45	220.83	48.93				
Alfalfa (1st cutting) – K_c			0.59	1.19	1.22							
ET_o (mm/day)			1.99	3.18	4.21							
ET_c (mm/day)			1.17	3.79	5.15							
Monthly ET_c (mm/month)			35.01	113.78	77.25							
Alfalfa (2nd cutting) - K_c					0.46	1.03	1.24					
ET_o (mm/day)					4.21	5.31	6.50					
ET_c (mm/day)					1.92	5.45	8.08					
Monthly ET_c (mm/month)					30.80	163.62	177.75					
Alfalfa (3rd cutting) - K_c							0.40	0.87	1.24			
ET_o (mm/day)							6.50	6.15	4.44			
ET_c (mm/day)							2.61	5.33	5.49			
Monthly ET_c (mm/month)							23.49	165.16	153.81			
Apples - K_c				0.45	0.54	0.87	1.05	1.05	0.98	0.80		
ET_o (mm/day)				3.18	4.21	5.31	6.50	6.15	4.44	2.50		
ET_c (mm/day)				1.43	2.29	4.61	6.85	6.49	4.37	2.00		
Monthly ET_c (mm/month)				11.45	71.00	138.27	212.43	201.13	130.98	9.99		
Grapes - K_c							0.30	0.56	0.78	0.72		
ET_o (mm/day)							5.31	6.50	6.15	4.44		
ET_c (mm/day)							1.60	3.65	4.78	3.19		
Monthly ET_c (mm/month)							20.75	113.22	148.25	95.58		

Table D-13. Mean Monthly Crop Coefficients (K_c), Reference Evapotranspiration (ET_o), and Crop Evapotranspiration (ET_c) for Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Strawberries - K_c				0.40	0.69	0.88						
ET_o (mm/day)				3.18	4.21	5.31						
ET_c (mm/day)				1.27	2.89	4.69						
Monthly ET_c (mm/month)				3.82	89.65	140.62						
Winter wheat - K_c	0.73	0.85	0.97	1.10	1.20	1.20	0.96	0.43	0.40	0.40	0.47	0.60
ET_o (mm/day)	0.62	1.10	1.99	3.18	4.21	5.31	6.50	6.15	4.44	2.50	0.98	0.58
ET_c (mm/day)	0.45	0.93	1.93	3.49	5.04	6.40	6.22	2.66	1.78	1.00	0.46	0.35
Monthly ET_c (mm/month)	14.00	26.17	59.93	104.69	156.17	191.90	192.80	42.49	24.86	31.05	13.94	10.79
Barley - K_c				0.30	0.96	1.19	0.63					
ET_o (mm/day)				3.18	4.21	5.31	6.50					
ET_c (mm/day)				0.95	4.02	6.32	4.10					
Monthly ET_c (mm/month)				13.36	124.74	189.69	65.67					
Oats - K_c					0.44	1.19	0.69					
ET_o (mm/day)					4.21	5.31	6.50					
ET_c (mm/day)					1.85	6.33	4.48					
Monthly ET_c (mm/month)					29.57	189.98	49.25					
Fescue^e - K_c				0.95	0.95	0.95	0.95	0.95	0.95	0.95		
ET_o (mm/day)				3.18	4.21	5.31	6.50	6.15	4.44	2.50		
ET_c (mm/day)				3.02	4.00	5.04	6.18	5.84	4.22	2.38		
Monthly ET_c (mm/month)				90.63	123.99	151.34	191.43	181.12	126.54	73.63		

Notes: ^aMean monthly K_c values calculated according to Appendix D, Section 4.

^bMean monthly ET_o values from Appendix C, Table C-9.

^cMean daily ET_c calculated using Equation D-1.

^dMean monthly ET_c calculated from mean daily ET_c and the number of growing days per month (Appendix D, Section 5).

^eFescue was selected for future climate because it is a cool season grass.

Lettuce early - Current climate

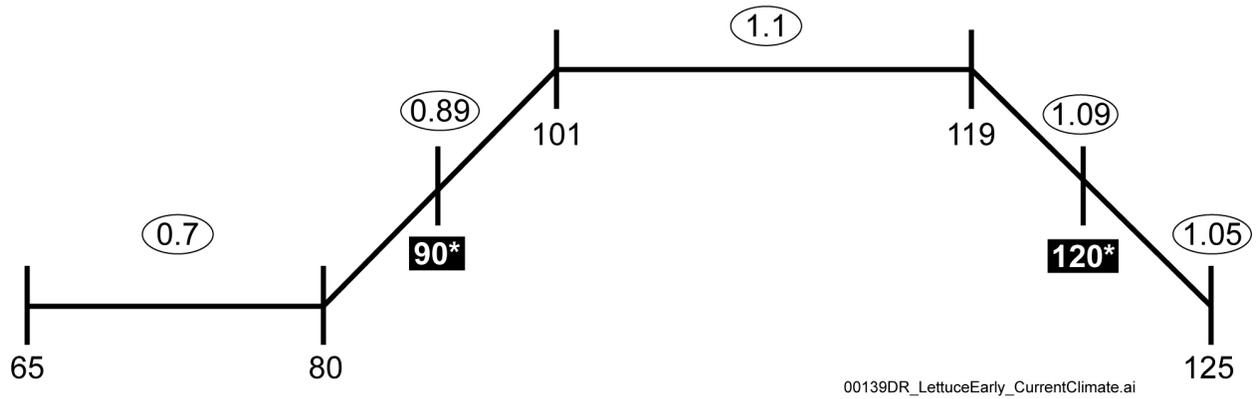


Figure D-1. Crop coefficient curve for early lettuce under current climate conditions. Circled numbers are crop coefficients. Numbers are Julian Days (JD). Initial stage = JD 65 through 80, development stage = JD 81 through 101, midseason stage = JD 102 through 119, and the late stage = JD 120 through 125. 90* and 120* are the last Julian Days of March and April for which calculation of K_{ci} was required in order to calculate monthly means (see text).

APPENDIX E

METHODS FOR DERIVING SEASONAL WATER REQUIREMENTS, LEACHING REQUIREMENTS, DEEP PERCOLATION, AND IRRIGATION APPLICATION AMOUNTS

APPENDIX E. METHODS FOR DERIVING SEASONAL WATER REQUIREMENTS, LEACHING REQUIREMENTS, DEEP PERCOLATION, AND IRRIGATION APPLICATION AMOUNTS

1. INTRODUCTION

Seasonal water requirements (W_s) and net irrigation requirements (In) are related variables and are used to determine several parameters including Annual Average Irrigation Rate (IR), Daily Average Irrigation Rate (IRD_j), Irrigation Application (IA_j) and Overwatering Rate (OW). Seasonal water requirements were derived from water lost from the soil-plant system (monthly ET_c) and water added to the system (monthly effective precipitation [Pe] and leaching requirements [LR]). In addition to ET_c , Pe , and LR , determination of In requires information on stored soil moisture at the beginning of the growing season (Wb), and groundwater contribution to the water requirement (Ge).

A Leaching Fraction (LF , the actual amount of water that must be added to leach salts below the crop root zone in addition to water needed to balance ET_c) was determined from W_s for each crop. This was compared to deep percolation of precipitation below the root zone (DP) and the greater of the two values was used as the Overwatering Rate (OW). Depending on whether LR was met by precipitation or irrigation, either W_s or In was used to calculate Annual Average Irrigation Rate (IR), and Daily Average Irrigation Rate (IRD_j). Seasonal crop evapotranspiration (ET_c), deep percolation below the root zone (DP), stored soil moisture in the rooting zone (Wb), and leaching requirements (LR) were needed to estimate W_s , In , Irrigation Application (IA_j) and Overwatering Rate (OW) (see Section 6).

Methods for deriving ET_c are in Appendix D. Methods for deriving W_s , In , IA_j , IR , IRD_j , and OW are described below.

2. METHODS

2.1 EFFECTIVE PRECIPITATION

Not all precipitation is available for plant use. Precipitation that collects on the soil surface can be lost to evaporation and surface flow can be lost as runoff. Some of the rainfall that percolates through the soil can be lost below the root zone (Doorenbos and Pruitt 1977). The portion of rainfall that percolates through the soil and remains in the root zone is available for plant use (Pe). Thus, Pe is the total rainfall minus the losses that occur from the system.

There are several methods for direct measurement of Pe (Brouwer and Heibloem 1986, Section 4.2) however none of those methods were employed under the climate conditions in this analysis. Empirically developed formulae also exist, but are specific to the conditions under which they were developed, and in most cases their use elsewhere is not recommended (Dastane

1978, Sections 2.2 and 2.3). Doorenbos and Pruitt (1977, pp. 74 and 75) use the evaporation/precipitation ratio method developed by the USDA (1969, from Doorenbos and Pruitt, 1977, p. 74) to estimate Pe . This method was included in an evaluation of 12 direct and empirical methods for estimating Pe (Dastane 1978, Section 2.4). It was rated as satisfactory for preliminary planning purposes with medium accuracy and low relative cost. This compared to four other empirical methods, two of which were rated low for accuracy, one medium, and one low to high. Only direct measurement methods were given high and very high accuracy ratings. Based on this information and the lack of direct measurements of Pe , the evaporation/precipitation ratio method was selected for use in this analysis.

The evaporation/precipitation ratio method requires mean monthly rainfall measurements (Section 4, Tables 4.1-2, 4.1-3, 4.1-4, and 4.1-5), mean monthly ET_c (Appendix D, Tables D-10 through D-13), and the net depth of water that could be effectively stored over the root zone (Doorenbos and Pruitt 1977, p. 74).

2.1.1 Soil Water Availability (TAW)

The concept of total available water in the root zone (TAW) discussed by Allen et al. (1998, pp. 161 and 162) was used to estimate the net depth of water that could be effectively stored over the root zone for the 26 crops and turf in a sandy loam soil. A sandy loam soil was chosen because the common soils in northern Amargosa Valley (Arizo, Corbilt, Sanwell, Shamock, Yermo) are sandy to sandy loam, well drained, and have a moderate to rapid permeability (CRWMS M&O 1999b; Figure 1 and pp. C-1, C-2, C-25, C-27, C-39, C40). After rainfall or irrigation, the hydraulic gradient in the soil causes some of the water to rapidly drain downward until field capacity is reached. Field capacity is the amount of water left in the soil after this downward movement becomes negligible (Jensen et al. 1990, p. 20; Allen et al. 1998, p. 161). As crops deplete water from the rooting zone, soil water potentials become more negative, making it increasingly difficult for crops to extract soil moisture. With no additional water input, the soil will continue to dry out and plants will begin to wilt to conserve moisture during the day (Jensen et al. 1990, p. 21). When soil water potentials become so negative that water can no longer be extracted by plants, the permanent wilting point is reached (Jensen et al. 1990, p. 21; Allen et al. 1998, p. 161). At the permanent wilting point, water remains in the soil, but is held too tightly by matric and osmotic forces to allow absorption by plant roots. TAW can be estimated from the difference between field capacity and the permanent wilting point (Allen et al. 1998, Equation 82, p. 162):

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \quad (\text{Eq. E-1})$$

where

θ_{FC} = soil water content at field capacity ($\text{m}^3 \text{m}^{-3}$),

θ_{WP} = soil water content at the wilting point ($\text{m}^3 \text{m}^{-3}$),

Z_r = rooting depth (m).

For a sandy loam soil, typical ranges for θ_{FC} and θ_{WP} are 0.18 - 0.28 m³ m⁻³ and 0.06 - 0.16 m³ m⁻³, respectively (Allen et al. 1998, Table 19, p. 144). The midpoint of each range was chosen for this analysis ($\theta_{FC} = 0.23$ and $\theta_{WP} = 0.11$).

Mean monthly rooting depths required for *TAW* were calculated by taking the maximum effective rooting depths ($Z_{r \max}$, Table E-1) for the 26 crops and turf from Allen et al. (1998, Table 22, pp. 163 through 165), and using minimum root depths ($Z_{r \min}$) of 0.15 (plants with $Z_{r \max}$ of 0.3 to 0.5 m) and 0.20 m (plants with $Z_{r \max} > 0.5$ m) in the following equation (Allen et al. 1998, Equation 8-3, p. 279):

$$Z_{ri} = Z_{r \min} + (Z_{r \max} - Z_{r \min}) \frac{J - J_{start}}{J_{\max} - J_{start}} \text{ for } J_{start} \leq J \leq J_{\max} \quad (\text{Eq. E-2})$$

where

Z_{ri} = effective depth of the root zone on day *i* (m),

J_{start} = Day of year that Z_{ri} increases beyond $Z_{r \min}$,

J_{\max} = Day of year that maximum rooting depth is attained.

For annual plants, Z_{ri} was set equal to $Z_{r \min}$ for days 1 through 5 of the initial growth stage (see Tables D-1 and D-2 for timing of growth seasons and Tables D-3 and D-4 for stage lengths). Z_{ri} was calculated according to Equation E-2 for day 6 through the last day of the development stage. Z_{ri} was set equal to $Z_{r \max}$ for the mid-season and late growth stages. Monthly means were calculated from the daily values generated from Equation E-2 for each annual crop and used in Equation E-1 to calculate mean monthly *TAW*.

Example: Using early lettuce and current climate conditions:

planting day = 65

$J_{start} = 71$

$J_{\max} = 101$

$Z_{r \min} = 0.15$

$Z_{r \max} = 0.30$

Example calculations using Equation E-2.

Julian day	Rooting depth (Z_{ri})	Monthly Mean
65 - 70	0.15	
71	$0.15+(0.3-0.15)*(71-71)/(101-71)=0.15$	
72	$0.15+(0.3-0.15)*(72-71)/(101-71)=0.155$	
73	$0.15+(0.3-0.15)*(73-71)/(101-71)=0.16$	
74	$0.15+(0.3-0.15)*(74-71)/(101-71)=0.165$	
75	$0.15+(0.3-0.15)*(75-71)/(101-71)=0.17$	
76	$0.15+(0.3-0.15)*(76-71)/(101-71)=0.175$	
77	$0.15+(0.3-0.15)*(77-71)/(101-71)=0.18$	
78	$0.15+(0.3-0.15)*(78-71)/(101-71)=0.185$	
79	$0.15+(0.3-0.15)*(79-71)/(101-71)=0.19$	
80	$0.15+(0.3-0.15)*(80-71)/(101-71)=0.195$	
81	$0.15+(0.3-0.15)*(81-71)/(101-71)=0.2$	
82	$0.15+(0.3-0.15)*(82-71)/(101-71)=0.205$	
83	$0.15+(0.3-0.15)*(83-71)/(101-71)=0.21$	
84	$0.15+(0.3-0.15)*(84-71)/(101-71)=0.215$	
85	$0.15+(0.3-0.15)*(85-71)/(101-71)=0.22$	
86	$0.15+(0.3-0.15)*(86-71)/(101-71)=0.225$	
87	$0.15+(0.3-0.15)*(87-71)/(101-71)=0.23$	
88	$0.15+(0.3-0.15)*(88-71)/(101-71)=0.235$	
89	$0.15+(0.3-0.15)*(89-71)/(101-71)=0.24$	
90	$0.15+(0.3-0.15)*(90-71)/(101-71)=0.245$	0.188
91	$0.15+(0.3-0.15)*(91-71)/(101-71)=0.25$	
92	$0.15+(0.3-0.15)*(92-71)/(101-71)=0.255$	
93	$0.15+(0.3-0.15)*(93-71)/(101-71)=0.26$	
94	$0.15+(0.3-0.15)*(94-71)/(101-71)=0.265$	
95	$0.15+(0.3-0.15)*(95-71)/(101-71)=0.27$	
96	$0.15+(0.3-0.15)*(96-71)/(101-71)=0.275$	
97	$0.15+(0.3-0.15)*(97-71)/(101-71)=0.28$	
98	$0.15+(0.3-0.15)*(98-71)/(101-71)=0.285$	
99	$0.15+(0.3-0.15)*(99-71)/(101-71)=0.29$	
100	$0.15+(0.3-0.15)*(100-71)/(101-71)=0.295$	
101	$0.15+(0.3-0.15)*(101-71)/(101-71)=0.3$	0.291
102 - 120	0.3	0.3

Example calculations for TAW using equation E-1:

Month (J-day)	Rooting depth (m)	TAW (mm)
March (90)	0.19	$1000 \times (0.23 - 0.11) \times 0.19 = 22.8$
April (120)	0.29	$1000 \times (0.23 - 0.11) \times 0.29 = 34.8$
May (151)	0.30	$1000 \times (0.23 - 0.11) \times 0.30 = 36.0$

It was assumed that perennial crops were established for this analysis, and so maximum rooting depths were used for each month to calculate *TAW*. Equation E-2 was used to calculate monthly rooting depths for the first cutting of alfalfa. $Z_{r \text{ max}}$ was used for subsequent cuttings. Mean monthly rooting depths and effective storage (*TAW*) for each crop are listed in Tables E-2 and E-3.

2.1.2 Evapotranspiration/Precipitation Ratio Method for Estimating Effective Precipitation

Pe was derived using methods from Doorenbos and Pruitt (1977, Table 34, p. 75) using mean monthly precipitation (Section 4, Tables 4.1-2 through 4.1-5), mean monthly *ET_c* (Tables D-10 through D-13), and effective storage in the root zone (*TAW*, Tables E-2 and E-3). For direct use of Table 34 (reproduced below in Table E-4), Doorenbos and Pruitt assumed an effective root zone storage of 75 mm. This was rarely the case for the representative crops and so the correction factors for storage were used (Doorenbos and Pruitt 1977, p. 75, see example below). The mean monthly precipitation values in Table 34 (Doorenbos and Pruitt 1977, p. 75) were listed in 12.5 mm increments, and mean monthly *ET_c* in 25 mm increments. The closest table values to the calculated mean monthly precipitation and *ET_c* were used. If mean monthly precipitation was less than 8 mm, *Pe* was set equal to zero (recommended by Dastane 1978, Section 2.1). If the adjusted table *Pe* values were greater than the monthly mean *ET_c*, effective precipitation was set equal to mean monthly *ET_c* because precipitation in excess of what is used by the crop cannot be considered effective.

Example: Using early lettuce in March for current climate conditions, mean monthly precipitation = 11.68 mm (Section 4, Table 4.1-2), mean monthly *ET_c* = 77.62 mm (Table D-10), and effective storage = 22.6 mm (Table E-2).

From Table E-4 below, the closest mean monthly precipitation and *ET_c* values were 12.5 mm and 75 mm, respectively. These values correspond to an average monthly *Pe* of 9 mm (Table E-4). The correction factor for effective storage of 22.6 mm was 0.77 (Table E-4). Thus, effective precipitation for lettuce in March was $9 \times 0.77 = 6.93$ mm.

Table E-4. Average monthly effective precipitation determined from mean monthly precipitation and average monthly crop evapotranspiration. Partial table redrawn from Doorenbos and Pruitt (1977, Table 34, p. 75).

		Monthly mean precipitation (mm)									
		12.5	25.0	37.5	50	62.5	75.0	87.5	100.0	112.5	
		Average monthly effective precipitation (mm)									
Average	25	8	16	24							
monthly	50	8	17	25	32	39	46				
ET_c	75	9*	18	27	34	41	48	56	62	69	
(mm)	100	9	19	28	35	43	52	59	66	73	
	125	10	20	30	37	46	54	62	70	76	
	150	10	21	31	39	49	57	66	74	81	
	175	11	23	32	42	52	61	69	78	86	
	200	11	24	33	44	54	64	73	82	91	
	225	12	25	35	47	57	68	78	87	96	
	250	13	25	38	50	61	72	84	92	102	
		Correction factors for soil water storage depths that are not equal to 75 mm.									
Effective	20	25	37.5	50	62.5	75	100	125	150	175	
storage											
Storage											
factor	.73	.77*	.86	.93	.97	1.00	1.02	1.04	1.06	1.07	

Mean monthly Pe for the current, lower bound monsoon, lower bound future, and future climate conditions are in Tables E-2 and E-3. Seasonal totals for Pe are in Tables E-5, E-6, E-7, and E-8.

2.2 Stored Soil Moisture (Wb), Leaching Requirement (LR), and Deep Percolation (DP)

Soil moisture can be stored in the root zone if precipitation is greater than ET_c when a crop is actively growing, or if precipitation is greater than evaporation from the soil surface when no crop is present. It is dependant on the water holding capacity of the soil and depth of the root zone. Deep percolation (DP) occurs after a rain or irrigation event that causes soil moisture in the root zone to reach and exceed field capacity. Field capacity is the amount of water held against gravitational forces when downward drainage following a rain or irrigation event has markedly decreased. Soil moisture stored in the root zone and DP were derived using soil water balance calculations across months. The soil water balance is based on water holding capacity of the soil in the root zone and the portion of that water that can be used by the crop (TAW), total evaporable water from the soil surface (TEW , Allen et al. 1998, p. 144), Pe , and ET_c .

2.2.1 Stored soil moisture and deep percolation

TEW is the amount of water (mm) that can be depleted from the upper soil layers through direct evaporation during a complete drying cycle (Allen et al. 1998, Equation 73, p. 144):

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_e \quad (\text{Eq. E-3})$$

where

θ_{FC} = soil water content at field capacity ($\text{m}^3 \text{m}^{-3}$),

θ_{WP} = soil water content at wilting point ($\text{m}^3 \text{m}^{-3}$),

Z_e is the depth of the soil surface layer (m) that is subject to drying through the process of evaporation.

In the absence of site specific data, Allen et al. (1998) recommended a range of 0.10 to 0.50 m for Z_e , and provided typical values for TEW for a sandy loam soil which ranged from 15 - 20 mm (Allen et al. 1998, Table 19, p. 144). The midpoint of this range (17.5 mm) was selected for the analysis.

Moisture can be stored in the soil when precipitation is greater than ET_c from a cropped surface or when precipitation is greater than TEW from a fallow field. Percolation below the root zone can only occur when the soil water content in the root zone exceeds θ_{FC} .

Annual Crops—The following guidelines were used for annual crops:

- early and late season crops were planted on the same land
- the land was fallow outside of the growing season
- of the monthly precipitation that entered the system outside of the growing season, TEW was evaporated, the rest percolated into the soil
- of the monthly precipitation that entered the system during the growing season, ET_c was evaporated, the rest percolated into the soil
- TAW was the maximum amount of water that could be stored in the root zone and used by plants
- deep percolation occurred when precipitation outside of the growing season exceeded $\theta_{FC} - TEW$ or when precipitation during the growing season exceeded $\theta_{FC} - ET_c$.

Example: For future climate conditions, the growing seasons for early and late head lettuce were April 23 - July 10 and July 15 - Oct 1, respectively (Appendix D, Table D-2). During this time monthly ET_c (see Table D-13) exceeded precipitation so no moisture was stored over the growing seasons. The soil plot was fallow Oct. 2 - April 23. The maximum amount of plant available water that can be stored in the lettuce root zone (TAW) was 36 mm (Table E-3), TEW was 17.5 mm, and θ_{FC} of the root zone was 69 mm (θ_{FC} of the root zone = $1000 * \theta_{FC} * Z_r$, from equation E-1). Table E-9 shows monthly precipitation inputs, water available for percolation

into the soil, water stored in the root zone, percolation below the root zone, and stored soil water at the time of planting. The calculations start in October with the assumption that there is no soil moisture left the month of harvest:

October_{water balance} = precipitation (25.2 mm) - *TEW* (17.5 mm) = 7.7 mm. The θ_{FC} of the soil in the root zone was 69 mm, therefore, 7.7 mm of water was stored in the root zone, but no percolation below the root zone occurred in October.

November_{water balance} = precipitation (54.6 mm) + water stored in October (7.7 mm) - *TEW* (17.5 mm) = 44.8 mm. 44.8 mm of water was stored in the root zone; no water percolated below the root zone.

December_{water balance} = precipitation (61.5 mm) + water stored in November (44.8 mm) - *TEW* (17.5 mm) = 88.8 mm. Of this amount, 69 mm was stored in the root zone and 19.8 mm percolated below the root zone.

Calculations for January, February, and March were the same as those for November and December (Table E-9). Cumulative DP for October through March was 93.2 mm.

In April, there were 22 days before planting the early season crop. Therefore, $TEW = (17.5/30)*23 = 13.4$ mm and precipitation = $(30.0/30)*23 = 23.0$ mm. The water balance equals precipitation (23.0 mm) + water stored in March (69 mm) - *TEW* (13.4 mm) = 78.6 mm. Of this amount, 69 mm was stored in the root zone and 9.6 percolated below the root zone. Not all of the water at field capacity can be used by the crop (see Section 2.1.1 above). For future climate conditions when soil water in the rooting zone reached θ_{FC} it was necessary to use Equation 3 to estimate *TAW* to determine *Wb*. For this example, $TAW = Wb = 36$ mm and cumulative *DP* = 103.0 mm.

Table E-9. Monthly Stored Water and Deep Percolation Totals (mm)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lettuce												
Monthly Precip (mm)	50.3	37.8	37.8	23.0						25.2	54.6	61.5
Monthly Precipitation + stored moisture from previous month - Evaporation (I.e., Percolation)	101.8	89.3	89.3	78.6						7.7	44.8	88.8
Water Stored in Root Zone	69.0	69.0	69.0							7.7	44.8	69.0
Cumulative Percolation Below Root Zone (DP)	52.6	72.9	93.2	102.8						0	0	19.8
Stored Water at the time of Planting (<i>Wb</i>)				36								

For current and lower bound future climate conditions, water was rarely stored in the root zone at the beginning of the planting season. Because θ_{FC} was never reached, *Wb* was simply the water stored in the root zone prior to planting (it was not necessary to calculate *TAW* to determine *Wb*).

Water stored in the root zone and cumulative *DP* are in Tables E-5, E-6, E-7, and E-8.

Perennial Crops - The same methods used to calculate Wb and DP for annual crops were used for perennial crops with the following exception:

During low growth and dormant periods, perennials were assumed to continue to lose water at low rates. To reflect this, initial K_c values were used to calculate monthly mean ET_c for non-growing periods (see Appendix D for information regarding K_c and ET_c calculations). This ET_c was used instead of TEW to calculate the water balance for perennials during non-growing periods.

Water stored in the in the root zone at the onset of active growth and cumulative DP for perennials are in Tables E-5, E-6, E-7, and E-8.

2.3 Leaching Requirement (LR)

Salt build up in agricultural soils can occur when crops are irrigated with water containing significant quantities of soluble salts. In a well-drained soil, addition of enough water to cause drainage below the root zone can eliminate salt build up that can be harmful to plants. If downward drainage is insufficient, salts that are left in the soil can precipitate in the root zone and increase soil salinity as evaporation occurs. Soil salinity is measured by the electrical conductivity (EC) of the saturated soil solution. The leaching requirement (LR) is the fraction of infiltrated water that must pass through the root zone to remove excess salts. It is a function of the salinity of the irrigation water, and crop tolerance to salts. For a sandy loam to clay loam soil in arid to semi-arid environments, LR can be calculated according the following equation (Doorenbos and Pruitt 1977, pp. 77 and 78):

$$LR = \frac{EC_w}{5EC_e - EC_w} \times \frac{1}{LE} \quad (\text{Eq. E-4})$$

where

EC_w = electrical conductivity of the irrigation water (mmhos/cm),

EC_e = crop salt tolerance under acceptable yield reduction,

LE = leaching efficiency which varies with soil type.

As described in Section 4.1.7, an EC_w of 0.50 dS/m was selected for this analysis.

Crop salt tolerance values with no reduction in yield were taken from Doorenbos and Pruitt (1977, Table 36, p. 78) for EC_e (Table E-10). There were no EC_e values available for celery, cauliflower, squash, oats, or fescue so values for similar crops in the same crop type were chosen for each. The value for cabbage was used for celery, broccoli was used for cauliflower, cucumber was used for squash, winter wheat for oats, and bermudagrass for tall fescue (Table E-10).

The common soils in northern Amargosa Valley (Arizo, Corbilt, Sanwell, Shamock, Yermo) are sandy to sandy loam so an LE of 0.7 for a medium textured soil (Doorenbos and Pruitt 1977, p. 79) was used for LR calculations.

Example: Using early lettuce, $EC_e = 1.3$ mmhos/cm (Table E-10), $EC_w = 0.50$ mmhos/cm, and $LE = 0.7$.

$$LR = \frac{0.50}{5 \times 1.3 - 0.50} \times \frac{1}{0.7} = 0.12 \quad (\text{Eq. E-4})$$

For the lettuce crop, about 12 percent of the total water entering the soil must pass through and out of the root zone.

The LR s for the 26 crops and turf grass are in Tables E-5, E-6, E-7, and E-8.

2.4 Seasonal Water Requirements (W_s), Net Irrigation Requirements (In), Leaching Fraction (LF), and Overwatering Rate (OW)

Seasonal water requirements (W_s) were estimated using the following equation from Doorenbos and Pruitt (1977, p. 79):

$$W_s = \frac{ET_c - Pe}{1 - LR} \quad (\text{Eq. E-5})$$

where

ET_c = monthly mean crop evapotranspiration summed over the growing season (mm),

Pe = monthly mean effective precipitation summed over the growing season (mm),

LR = leaching requirement (unitless).

Example: For early lettuce and current climate conditions, seasonal $ET_c = 287.5$ mm (Table E-5), seasonal $Pe = 6.93$ mm (Table E-5), and $LR = 0.12$ (Table E-5).

$$W_s = \left(\frac{287.5 - 6.93}{1 - 0.1216} \right) = 319.4 \text{ mm} \quad (\text{Eq. E-5})$$

The W_s values for the 26 crops and turf are in Tables E-5, E-6, E-7, and E-8.

Once LR and W_s were determined, it was necessary to evaluate whether seasonal precipitation resulted in cumulative DP that was greater than LR . This directly impacts the net irrigation requirement (In) and the Overwatering Rate (OW). If precipitation results in cumulative DP that equals or exceeds LR , then additional irrigation water for leaching calculated into W_s is not required. The Overwatering Rate (OW), which is defined as the “average amount of groundwater or precipitation that percolates through the root zone and leaches salts and

radionuclides out of that zone” (Section 1), is equal to DP or the Leaching Fraction (LF), depending on which is greater.

Leaching Fraction, which is the amount of water that percolates below the root zone, can be determined from:

$$LF = W_s - (ET_c - Pe) \quad (\text{Eq. E-6})$$

Example: From the previous example for lettuce and current climate conditions, $W_s = 319.4$ mm, $ET_c = 287.5$, and $Pe = 6.93$.

$$LF = 319.4 \text{ mm} - (287.5 \text{ mm} - 6.93 \text{ mm}) = 38.8 \text{ mm}. \quad (\text{Eq. E-6})$$

The cumulative DP for early lettuce was 0. Therefore, LF was the value selected for lettuce that would be included in development of the distribution for OW and was included in the net irrigation requirement (In). Because of the aridity of current and lower bound future climate conditions, DP never occurred, making LR a necessary inclusion to all net irrigation calculations. Additionally, for current climate, LF for each crop and turf was used to generate the distribution of OW (see Section 6.9).

For upper bound monsoon and future climate conditions, DP often exceeded LF (Tables E-6 and E-8, respectively). Under these circumstances, LR was not needed to meet the net irrigation requirements and Equation E-7 was used to calculate In . For crops that didn’t require additional water to meet LR , DP was used to generate the distribution of OW .

In a few cases, DP occurred but did not meet the crop LR . Under these circumstances, LR was included in the calculation for In (Equation E-8) and DP was subtracted from the total to compensate for the extra water in the system. Leaching Fraction was used to generate the distribution of OW .

One of the following equations from Doorenbos and Pruitt (1977, p. 70) were used to calculate net irrigation requirements (In) depending on whether DP was greater or less than LF :

$$In = \sum_{i=1}^n ET_{c \text{ monthly}} - (\sum_{i=1}^n P_e + Ge + Wb) \quad (\text{Eq. E-7})$$

$$In = W_s - (Ge + Wb) \quad (\text{Eq. E-8})$$

where

ET_c = monthly mean crop evapotranspiration summed over the growing season (mm),

Pe = monthly mean effective precipitation summed over the growing season (mm),

Ge = groundwater contribution to the water requirement (mm, direct plant use),

Wb = stored soil moisture in the root system (mm).

Groundwater contribution (Ge) to the water requirement was set to zero for all calculations. Data collected by the U.S. Geological Survey from Well AD-2 located in the Amargosa Valley showed that depth to groundwater was about 99 m (325 feet, Locke 2001, Figure 1, p. 3 and Figure 4, p. 35). This depth remained relatively constant from 1987 through 1999 (Locke 2001, Figure 4, p. 35). Groundwater contribution from a water table that is more than about 1 m below the bottom of a crop rooting zone is generally considered negligible (Allen et al. 1998, p. 171). Therefore a water table as deep as 99 m would not contribute to crop water requirements.

Net seasonal irrigation requirements (Tables E-5, E-6, E-7, and E-8) were used to calculate Annual Average Irrigation Rates (IR , Section 6.5) for current, upper bound monsoon, lower bound future, and future climates. Net seasonal irrigation requirements for current and future climates (Tables E-5 and E-8) were used to calculate Daily Average Irrigation Rates (IRD_j , Section 6.8).

2.5 Irrigation Application (IA_j)

Average amount of water applied per irrigation event during the 30 days prior to harvest for each crop type was needed to develop the distribution for Irrigation Application (IA_j , Section 6.7) for current and future climates. Irrigation application rates for each crop were calculated using a soil water balance approach and the soil moisture threshold at which crop stress was expected to occur.

2.5.1 Readily Available Water (RAW)

As described in Section 2.1.1, field capacity, permanent wilting point, and crop specific rooting depth were used to estimate the total available water (TAW) in the rooting zone. In theory, water is available to plants until the wilting point is reached. However, decreases in hydraulic conductivity as the soil dries decreases the rate at which plant roots can extract water from the soil. Thus, crop water uptake is reduced long before soil moisture is extracted to the wilting point (Allen et al. 1998, p. 162). Crops will begin to experience stress at the soil moisture threshold at which root absorption and transport of water are less than transpiration demands. Readily available soil water (RAW) is expressed as the fraction of TAW that can be extracted from the root zone before crop water stress occurs (Allen et al. 1998, Equation 83, p. 162):

$$RAW = pTAW \quad (\text{Eq. E-9})$$

where

p is a crop specific average fraction of TAW that can be depleted from the root zone before moisture stress occurs.

Values for p from Allen et al. (1998, Table 22, pp. 163 through 165), TAW at maximum root depth, and RAW for each crop are in Table E-11.

2.5.2 Soil Water Balance Approach

Irrigation application for each crop was determined by calculating a simplified soil water balance over the 30 days prior to harvest using the following parameters:

- TAW at maximum root depth (Table E-11)
- RAW (Table E-11)
- average daily ET_c per month for 30 days prior to harvest (calculated from Tables D-10 and D-13)
- irrigation requirement (In) for 30 days prior to harvest (calculated from Equations E-7 and E-8, and Tables E-5 and E-8)
- average daily effective precipitation (P_d) for 30 days prior to harvest (calculated from Tables E-2 and E-3).

RAW is the fraction of TAW that can be extracted from the soil before moisture stress occurs. Therefore, irrigation water should be applied when RAW is depleted. $TAW - RAW$ was used as the threshold at which irrigation water should be applied to avoid onset of crop stress. If the amount of irrigation exceeds field capacity of the soil in the root zone, percolation below the root zone will occur. Excessive watering could cause nutrient leaching, changes in nutrient availability due to microbial responses to wet soil conditions, and water waste. Therefore, to avoid exceeding field capacity, irrigation was calculated such that TAW would not be exceeded in the root zone. Average daily ET_c was used to estimate daily water loss from the soil system, and average daily effective precipitation was used as water input to the soil system.

The following guidelines were observed:

- soil moisture at the beginning of the 30 day period was set equal to TAW for a given crop
- When RAW was depleted (within +/- 2 mm), irrigation water was applied the following morning to increase soil moisture to TAW
- daily ET_c was subtracted at the end of the day
- average daily precipitation was added to the balance at the end of each day.

Thus, the soil water balance at the end of each day (SWB_d) was calculated as:

$$SWB_d = Irr + P_d - ET_c, \text{ with } SWB_d \leq TAW \quad (\text{Eq. E-10})$$

where

Irr = the irrigation water applied in the morning (when applicable) (mm),

P_d = the average daily precipitation input (mm),

ET_c = the average daily crop evapotranspiration calculated for 30 days prior to harvest (mm/day).

Equation E-10 was derived from Allen et al. (1998, Equation 85, p. 70).

Example: Using early lettuce and current climate conditions the following parameters were determined from the appropriate Tables:

The last Julian day of the growing season = 125 = May 5 (Table D-1). Therefore, for the last 30 days of the growing season, 25 days were in April and 5 days were in May.

Effective precipitation for April and May = 0 (Table E-2). Therefore, mean daily effective precipitation for the last 30 days of the growing season was equal to 0.

Mean daily ET_c for April = 5.79 mm day^{-1} (Table D-10).

Mean daily ET_c for May = 7.25 mm day^{-1} (Table D-10).

Irrigation requirement for 25 days in April = 144.75 mm (5.79×25).

Irrigation requirement for 5 days in May = 36.25 mm (7.25×5).

TAW at maximum root depth = 36 (Table E-11).

RAW = 10.8 (Table E-11).

The water balance calculations (Equation E-10) for the 30 days prior to harvest for early lettuce are illustrated in Table E-12 using the values above. Irrigation water was added when RAW was depleted. This occurred on days 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 26, 27, 28, 29, and 30. Irrigation events occurred the on days following RAW depletion for days 1 through 25. Because of high daily ET_c on days 25 through 30, irrigation was applied prior to RAW depletion so that soil moisture would not go below RAW on a daily basis. Enough water was added so that soil moisture equaled, but did not exceed TAW .

Table E-12. Water Balance Calculations Over the Thirty-Day Time Period Prior to Harvest for Early Season Lettuce and Current Climate Conditions

Day	TAW	ETc	Pe	Irrigation	Balance
1	36	5.79	0	36.0-25.2=10.8	25.2+10.8-5.79=30.21
2	36	5.79	0		30.21-5.79=24.4
3	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.21
4	36	5.79	0		30.21-5.79=24.4
5	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.21
6	36	5.79	0		30.21-5.79=24.4
7	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.21
8	36	5.79	0		30.21-5.79=24.4
9	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.21
10	36	5.79	0		30.21-5.79=24.4
11	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.21
12	36	5.79	0		30.21-5.79=24.4
13	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.21
14	36	5.79	0		30.21-5.79=24.4
15	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.2
16	36	5.79	0		30.21-5.79=24.4
17	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.2
18	36	5.79	0		30.21-5.79=24.4
19	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.2
20	36	5.79	0		30.21-5.79=24.4
21	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.2
22	36	5.79	0		30.21-5.79=24.4
23	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.2
24	36	5.79	0		30.21-5.79=24.4
25	36	5.79	0	36-24.4=11.6	24.4+11.6-5.79=30.2
26	36	7.25	0	36-30.2=5.8	30.2+5.8-7.25=28.8
27	36	7.25	0	36-28.8=7.2	28.8+7.2-7.25=28.8
28	36	7.25	0	36-28.8=7.2	28.8+7.2-7.25=28.8
29	36	7.25	0	36-28.8=7.2	28.8+7.2-7.25=28.8
30	36	7.25	0	36-28.8=7.2	28.8+7.2-7.25=28.8

Mean irrigation application amounts for each crop for current and future climate conditions are in Tables E-13 and E-14, respectively.

2.6 Crop Moisture Stress

In order to quantify uncertainty in irrigation management practices that could affect the distributions of irrigation parameters, the soil moisture balance method described above in Section 2.5 was used to determine the percent reduction in irrigation water that would be required to cause crop water stress. It was concluded that under-watering would likely result in visible crop stress that would signal the farmer or gardener to make adjustments in order to avoid loss in yield (Sections 6.5, 6.7, 6.8, and 6.9).

2.6.1 Under-Watering

To avoid crop water stress, irrigation water should be applied when *RAW* is depleted (Allen et al. 1998, p. 171). Because most crop species are fairly sensitive to stress caused from lack of water, it was concluded that withholding water for 2 days after depletion of *RAW* at each irrigation event would cause visible signs of stress. The water balance calculations for the last 30 days

prior to harvest were altered by withholding irrigation for 2 days after depletion of *RAW* at each irrigation event. After 2 days, enough irrigation water was added to bring soil moisture to *TAW*. The resulting percent decrease in irrigation water and the number of days the crop experienced water stress were calculated. The percent decrease per crop was determined for current and future climate conditions. The results of this analysis indicated that small percent decreases in irrigation resulted in several (nonconsecutive) days of water stress (Tables E-16 and E-17). Based on this analysis, a 10 percent reduction was used to assess the lower ends of the distributions for the irrigation parameters to determine whether adjustments were necessary (Sections 6.5, 6.7, 6.8, and 6.9).

Example: Using early lettuce and current climate conditions the following parameters were determined from the appropriate Tables:

The last Julian day of the growing season = 125 = May 5 (Table D-1). Therefore, for the last 30 days of the growing season, 25 days were in April and 5 days were in May.

Effective precipitation for April and May = 0 (Table E-2). Therefore, mean daily effective precipitation for the last 30 days of the growing season was equal to 0.

Mean daily ET_c for April = 5.79 mm day⁻¹ (Table D-10).

Mean daily ET_c for May = 7.25 mm day⁻¹ (Table D-10).

Irrigation requirement for 25 days in April = 144.75 mm (5.79 × 25).

Irrigation requirement for 5 days in May = 36.25 mm (7.25 × 5).

TAW at maximum root depth = 36 (Table E-11).

RAW = 10.8 (Table E-11).

The water balance calculations with water withheld to cause water stress for the 30 days prior to harvest for early lettuce are illustrated in Table E-15 using the above values. Irrigation water was added two days after depletion of *RAW* (i.e., when soil water balance was at or just below 36 mm – 10.8 mm = 25.2 mm at the end of the day). Enough water was added so that soil moisture was equal to but did not exceed *TAW*. Irrigation events occurred on days 1, 5, 9, 13, 17, 21, 25, and 29. The total amount of irrigation for the 30-day period decreased from 181 mm to 177 mm (a 2.2% decrease) and the crop experienced some degree of water-stress for 14 days.

Table E-15. Water Balance Calculations Over Thirty Days Prior to Harvest with Water Withheld to Cause Crop Water-Stress.

Day	TAW	ETc	Pe	Irrigation	current balance
1	36	5.79	0	36-25.2=10.8	25.2+10.8-5.79=30.2
2	36	5.79	0		30.2-5.79=24.4
3	36	5.79	0		24.4-5.79=18.6
4	36	5.79	0		18.6-5.79=12.9
5	36	5.79	0	36-12.9=23.1	12.9+23.1-5.79=30.2
6	36	5.79	0		30.2-5.79=24.4
7	36	5.79	0		24.4-5.79=18.6
8	36	5.79	0		18.6-5.79=12.9
9	36	5.79	0	36-12.9=23.1	12.9+23.1-5.79=30.2
10	36	5.79	0		30.2-5.79=24.4
11	36	5.79	0		24.4-5.79=18.6
12	36	5.79	0		18.6-5.79=12.9
13	36	5.79	0	36-12.9=23.1	12.9+23.1-5.79=30.2
14	36	5.79	0		30.2-5.79=24.4
15	36	5.79	0		24.4-5.79=18.6
16	36	5.79	0		18.6-5.79=12.9
17	36	5.79	0	36-12.9=23.1	12.9+23.1-5.79=30.2
18	36	5.79	0		30.2-5.79=24.4
19	36	5.79	0		24.4-5.79=18.6
20	36	5.79	0		18.6-5.79=12.9
21	36	5.79	0	36-12.9=23.1	12.9+23.1-5.79=30.2
22	36	5.79	0		30.2-5.79=24.4
23	36	5.79	0		24.4-5.79=18.6
24	36	5.79	0		18.6-5.79=12.9
25	36	5.79	0	36-12.9=23.1	12.9+23.1-5.79=30.2
26	36	7.25	0		30.2-7.25=23.0
27	36	7.25	0		23.0-7.25=15.7
28	36	7.25	0		15.7-7.25=8.5
29	36	7.25	0	36-8.5=27.5	8.5+27.5-7.25=28.7
30	36	7.25	0		28.7-7.25=21.5

Mean percent decreases in irrigation application amounts for each crop under current and future climates are in Tables E-16 and E-17, respectively.

Table E-1. Minimum and Maximum Rooting Depths for 26 Crops and Turf

Crop	Minimum Rooting Depth (m) ^a	Maximum Rooting Depth (m) ^b
Lettuce	0.15	0.3
Cabbage	0.15	0.5
Celery	0.15	0.3
Broccoli	0.15	0.4
Cauliflower	0.15	0.4
Spinach	0.15	0.3
Potatoes	0.15	0.4
Onions	0.15	0.3
Carrots	0.15	0.5
Sweet corn	0.20	0.8
Bell peppers	0.15	0.5
Cucumbers	0.20	0.7
Squash	0.20	0.6
Melons	0.20	0.8
Tomatoes	0.20	0.7
Alfalfa hay	0.20	1.0
Oat hay	0.20	1.0
Apples	0.20	1.0
Grapes	0.20	1.0
Strawberries	0.15	0.2
Winter wheat	0.20	1.5
Barley	0.20	1.0
Feed Corn	0.20	1.0
Corn silage	0.20	1.0
Oats	0.20	1.0
Bermuda	0.15	0.5
Fescue	0.15	0.5

Notes: ^aSource for minimum rooting depth: Allen et al. (1998, p. 279).

^bSource for maximum rooting depth: Allen et al. (1998, Table 22, pp. 163-165).

Table E-2. Mean Monthly Rooting Depths (m), Effective Storage Depths (mm), and Effective Precipitation (mm) for 26 Crops and Turf for Current and Upper Bound Monsoon Climate Conditions

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Leaf Lettuce early												
Rooting depth ^a			0.19	0.29	0.30							
Effective storage ^b			22.6	34.9	36.0							
Effective precip. ^c			6.9	0	0							
Effective precip. ^d			13.9	8.6	6.9							
Leaf Lettuce late												
Rooting depth									0.20	0.30		
Effective storage									24.0	36.0		
Effective precip.									7.7	0		
Effective precip.									23.1	31.8		
Head Lettuce early												
Rooting depth			0.19	0.29	0.30							
Effective storage			22.6	34.9	36.0							
Effective precip.			6.93	0	0							
Effective precip.			13.9	8.6	6.9							
Head Lettuce late												
Rooting depth									0.20	0.30		
Effective storage									24.0	36.0		
Effective precip.									7.70	0		
Effective precip.									23.1	31.8		
Cabbage early												
Rooting depth			0.23	0.45	0.50							
Effective storage			27.3	53.5	60.0							
Effective precip.			6.9	0	0							
Effective precip.			13.9	9.3	8.1							
Cabbage late												
Rooting depth								0.15	0.26	0.47	0.50	
Effective storage								18.0	31.5	56.7	60.0	
Effective precip.								0	7.7	0	0	
Effective precip.								19.7	25.8	34.4	16.5	
Celery early												
Rooting depth				0.17	0.25	0.30	0.30	0.30				
Effective storage				19.9	29.6	36.0	36.0	36.0				
Effective precip.				0	0	0	0	0				
Effective precip.				6.6	8.1	11.2	78.3	59.3				

Table E-2. Mean Monthly Rooting Depths (m), Effective Storage Depths (mm), and Effective Precipitation (mm) for 26 Crops and Turf for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Celery late												
Rooting depth	0.30								0.16	0.24	0.30	0.30
Effective storage	36.0								19.2	29.1	36.0	36.0
Effective precip.	13.8								6.6	0	0	7.7
Effective precip.	21.5								18.2	27.0	15.5	23.2
Broccoli early												
Rooting depth			0.21	0.37	0.40							
Effective storage			25.3	44.7	48.0							
Effective precip.			6.9	0	0							
Effective precip. ^d			13.9	9.3	8.1							
Broccoli late												
Rooting depth								0.15	0.24	0.39	0.40	
Effective storage								18.0	28.3	46.7	48.0	
Effective precip.								0	7.7	0	0	
Effective precip.								19.7	23.1	34.4	14.9	
Cauliflower early												
Rooting depth			0.21	0.37	0.40							
Effective storage			25.1	44.4	48.0							
Effective precip.			6.9	0	0							
Effective precip.			13.9	10.2	8.1							
Cauliflower late												
Rooting depth								0.15	0.23	0.39	0.40	
Effective storage								18.0	28.02	46.4	48.0	
Effective precip.								0	7.7	0	0	
Effective precip.								19.7	23.1	39.1	15.9	
Spinach early												
Rooting depth			0.17	0.29	0.30							
Effective storage			20.8	34.3	36.0							
Effective precip.			5.8	0	0							
Effective precip.			12.4	8.6	6.9							
Spinach late												
Rooting depth									0.17	0.29	0.30	
Effective storage									20.4	34.3	36.0	
Effective precip.									6.6	0	0	
Effective precip.									18.2	31.8	13.8	

Table E-2. Mean Monthly Rooting Depths (m), Effective Storage Depths (mm), and Effective Precipitation (mm) for 26 Crops and Turf for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Potatoes												
Rooting depth			0.15	0.23	0.38	0.40	0.40					
Effective storage			18.0	27.4	45.7	48.0	48.0					
Effective precip.			5.8	0	0	0	0					
Effective precip.			9.5	6.9	8.1	12.1	64.2					
Onions early												
Rooting depth			0.15	0.24	0.30	0.30	0.30					
Effective storage			18.0	29.1	36.0	36.0	36.0					
Effective precip.			5.8	0	0	0	0					
Effective precip.			11.7	7.7	8.1	11.2	59.3					
Onions late												
Rooting depth	0.30								0.17	0.28	0.30	0.30
Effective storage	36.0								20.1	33.9	36.0	36.0
Effective precip.	5.8								6.6	0	0	6.9
Effective precip.	6.3								18.2	37.8	15.5	23.2
Carrots early												
Rooting depth			0.19	0.45	0.50							
Effective storage			23.2	53.9	60.0							
Effective precip.			6.2	0	0							
Effective precip.			13.1	9.3	8.1							
Carrots late												
Rooting depth								0.15	0.35	0.50	0.50	
Effective storage								18.0	42.5	60.0	60.0	
Effective precip.								0	9.46	0	0	
Effective precip.								19.7	25.8	35.9	15.5	
Sweet corn												
Rooting depth					0.42	0.80	0.80					
Effective storage					50.4	96.0	96.0					
Effective precip.					0	0	0					
Effective precip.					8.1	13.3	87.7					
Bell Peppers												
Rooting depth					0.28	0.50	0.50					
Effective storage					34.0	59.9	60.0					
Effective precip.					0	0	0					
Effective precip.					8.1	12.6	78.6					

Table E-2. Mean Monthly Rooting Depths (m), Effective Storage Depths (mm), and Effective Precipitation (mm) for 26 Crops and Turf for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Jan	Feb	Mar	April	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Cucumbers												
Rooting depth						0.42	0.70					
Effective storage						50.0	84.0					
Effective precip.						0	0					
Effective precip.						9.3	91.0					
Squash												
Rooting depth					0.24	0.51	0.60					
Effective storage					29.0	61.5	72.0					
Effective precip.					0	0	0					
Effective precip.					6.2	10.7	69.0					
Melons												
Rooting depth					0.25	0.61	0.80	0.80				
Effective storage					30.2	73.2	96.0	96.0				
Effective precip.					0	0	0	0				
Effective precip.					6.2	10.0	92.8	77.5				
Tomatoes												
Rooting depth					0.32	0.70	0.70					
Effective storage					37.8	84.0	84.0					
Effective precip.					0	0	0					
Effective precip.					7.7	13.0	86.0					
Apples												
Rooting depth			1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		
Effective storage			120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0		
Effective precip.			9.4	0	0	0	0	0	9.1	0		
Effective precip.			18.7	9.4	8.1	12.5	94.6	89.4	32.2	36.4		
Grapes												
Rooting depth			1.00	1.00	1.00	1.00	1.00	1.00				
Effective storage			120.0	120.0	120.0	120.0	120.0	120.0				
Effective precip.			8.3	0	0	0	0	0				
Effective precip.			18.7	10.4	8.1	13.5	94.6	75.9				
Strawberries												
Rooting depth			0.20	0.20	0.20	0.20	0.20	0.20	0.20			
Effective storage			24.0	24.0	24.0	24.0	24.0	24.0	24.0			
Effective precip.			6.9	0	0	0	0	0	7.7			
Effective precip.			13.1	6.9	8.1	10.0	66.2	66.2	21.6			

Table E-2. Mean Monthly Rooting Depths (m), Effective Storage Depths (mm), and Effective Precipitation (mm) for 26 Crops and Turf for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Jan	Feb	Mar	April	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Winter Wheat												
Rooting depth	1.29	1.50	1.50	1.50	1.50	1.50				0.24	0.51	0.90
Effective storage	154.8	180.0	180.0	180.0	180.0	180.0				28.6	61.5	108.1
Effective precip.	18.0	9.6	11.7	0	0	0				0	0	8.2
Effective precip.	28.9	20.3	22.5	11.8	8.1	8.6				24.6	16.5	25.5
Barley												
Rooting depth	0.88	1.00	1.00	1.00	1.00	1.00				0.22	0.39	0.64
Effective storage	105.6	120.0	120.0	120.0	120.0	120.0				26.4	46.8	76.8
Effective precip.	17.3	9.4	11.4	0	0	0				0	0	8.0
Effective precip.	26.0	19.8	21.8	11.4	8.1	8.3				18.0	16.3	26.0
Alfalfa 1st cutting												
Rooting depth	0.53	1.00	1.00									
Effective storage	64.0	120.0	120.0									
Effective precip.	15.5	9.4	8.3									
Effective precip.	24.2	19.8	9.1									
Alfalfa 2nd cutting												
Rooting depth			1.00	1.00								
Effective storage			120.0	120.0								
Effective precip.			9.4	0								
Effective precip.			18.7	11.4								
Alfalfa 3rd cutting												
Rooting depth				1.00	1.00	1.00						
Effective storage				120.0	120.0	120.0						
Effective precip.				0	0	0						
Effective precip.				4.1	8.1	11.4						
Alfalfa 4th cutting												
Rooting depth						1.00	1.00	1.00				
Effective storage						120.0	120.0	120.0				
Effective precip.						0	0	0				
Effective precip.						20.6	89.4	31.				
Alfalfa 5th cutting												
Rooting depth							1.00	1.00	1.00			
Effective storage							120.0	120.0	120.0			
Effective precip.							0	9.1	0			
Effective precip.							31.4	89.4	26.0			

Table E-2. Mean Monthly Rooting Depths (m), Effective Storage Depths (mm), and Effective Precipitation (mm) for 26 Crops and Turf for Current and Upper Bound Monsoon Climate Conditions (continued)

Crop	Jan	Feb	Mar	April	May	Jun	July	Aug	Sept	Oct	Nov	Dec
Alfalfa 6th cutting												
Rooting depth										1.00	1.00	1.00
Effective storage										120.0	120.0	120.0
Effective precip.										0	0	4.57
Effective precip.										33.3	18.7	25.0
Oats hay												
Rooting depth				0.50	1.00	1.00						
Effective storage				59.6	120.0	120.0						
Effective precip.				0	0	0						
Effective precip.				8.7	8.1	9.4						
Bermudagrass												
Rooting depth	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Effective storage	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0
Effective precip.	16.5	8.7	8.7	0	0	0	0	0	10.7	0	0	7.8
Effective precip.	23.2	15.5	16.3	7.7	8.1	8.5	82.7	78.4	27.9	34.0	15.5	23.2
Feed Corn												
Rooting depth					0.24	0.50	0.87	1.00	1.00	1.00		
Effective storage					28.4	60.2	104.5	120.0	120.0	120.0		
Effective precip.					0	0	0	0	9.1	0		
Effective precip.					6.9	10.7	92.8	99.8	33.3	33.3		
Corn silage												
Rooting depth					0.26	0.73	1.00	1.00				
Effective storage					31.8	87.3	120.0	120.0				
Effective precip.					0	0	0	0				
Effective precip.					6.9	11.2	106.1	71.8				
Oat feed												
Rooting depth	0.51	0.80	1.00	1.00	1.00							0.24
Effective storage	61.5	96.1	120.0	120.0	120.0							28.8
Effective precip.	15.5	9.2	11.4	0	0							6.2
Effective precip.	23.3	18.4	21.8	11.4	8.1							9.0

Notes: ^a Mean monthly rooting depth calculated according to Equation E-2.
^b Mean monthly effective storage depth for sandy loam soil calculated from Equation E-1.
^c Mean monthly effective precipitation for current climate calculated according to Appendix E, Section 2.1.2.
^d Mean monthly effective precipitation for upper bound monsoon climate calculated according to Appendix E, Section 2.1.2

Table E-3. Mean Monthly Rooting Depths, Effective Storage Depths, and Effective Precipitation for 26 Crops and Turf for Upper and Lower Bound Future Climate Conditions

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Leaf Lettuce early												
Rooting depth ^a				0.15	0.23	0.30						
Effective storage ^b				18.2	27.8	36.0						
Effective precip. ^c				11.7	21.6	24.1						
Effective precip. ^d				11.7	16.2	9.5						
Leaf Lettuce late												
Rooting depth							0.17	0.27	0.30			
Effective storage							19.9	31.8	36.0			
Effective precip.							6.6	9.5	6.9			
Effective precip.							0	10.7	7.7			
Head Lettuce early												
Rooting depth				0.15	0.21	0.29	0.30					
Effective storage				18.1	24.7	34.8	36.0					
Effective precip.				11.7	21.6	26.7	7.7					
Effective precip.				11.7	16.2	11.2	0					
Head Lettuce late												
Rooting depth							0.16	0.23	0.30	0.30		
Effective storage							19.3	28.2	36.0	36.0		
Effective precip.							6.6	7.7	8.6	2.5		
Effective precip.							0	9.4	9.5	4.2		
Cabbage early												
Rooting depth				0.15	0.30	0.49	0.50					
Effective storage				18.2	36.3	59.2	60.0					
Effective precip.				11.7	24.1	31.0	7.8					
Effective precip.				11.7	18.1	12.6	0					
Cabbage late												
Rooting depth							0.17	0.36	0.50	0.50		
Effective storage							20.3	42.8	60.0	60.0		
Effective precip.							5.8	9.5	9.7	2.5		
Effective precip.							0	10.3	10.4	4.2		
Celery												
Rooting depth				0.15	0.20	0.28	0.30	0.30				
Effective storage				18.0	24.0	34.0	36.0	36.0				
Effective precip.				11.7	21.6	27.5	10.3	7.7				
Effective precip.				11.7	16.2	11.2	0	7.7				
Broccoli early												
Rooting depth				0.15	0.25	0.39	0.40					
Effective storage				18.1	29.9	46.7	48.0					
Effective precip.				11.7	21.6	29.8	8.4					
Effective precip.				11.7	16.2	12.1	0					
Broccoli late												
Rooting depth							0.17	0.30	0.40	0.40		
Effective storage							20.1	35.4	48.0	48.0		
Effective precip.							6.6	8.6	9.3	14.9		
Effective precip.							0	10.3	10.2	14.9		

Table E-3. Mean Monthly Rooting Depths, Effective Storage Depths, and Effective Precipitation for 26 Crops and Turf for Upper and Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Cauliflower early												
Rooting depth				0.15	0.28	0.40						
Effective storage				18.1	33.9	48.0						
Effective precip.				11.7	24.1	28.8						
Effective precip.				11.7	18.1	11.2						
Cauliflower late												
Rooting depth						0.15	0.24	0.40	0.40			
Effective storage						18.0	28.3	47.5	48.0			
Effective precip.						4.6	7.7	9.3	2.5			
Effective precip.						0	8.5	10.2	4.2			
Spinach early												
Rooting depth				0.15	0.24	0.30						
Effective storage				18.1	28.7	36.0						
Effective precip.				11.7	21.6	24.1						
Effective precip.				11.7	16.2	8.6						
Spinach late												
Rooting depth								0.19	0.29	0.30		
Effective storage								22.6	35.0	36.0		
Effective precip.								6.9	8.6	2.5		
Effective precip.								7.7	9.5	4.2		
Potatoes												
Rooting depth				0.15	0.24	0.38	0.40	0.40				
Effective storage				18.0	29.1	46.0	48.0	48.0				
Effective precip.				11.1	20.8	29.8	12.1	8.4				
Effective precip.				11.7	14.6	12.1	0	9.3				
Onions												
Rooting depth			0.19	0.29	0.30	0.30	0.30	0.30				
Effective storage			23.0	34.9	36.0	36.0	36.0	36.0				
Effective precip.			19.2	16.3	26.7	27.5	9.5	6.9				
Effective precip.			13.9	18.1	21.3	11.2	0	6.9				
Carrots early												
Rooting depth				0.15	0.34	0.50	0.50					
Effective storage				18.2	41.0	60.0	60.0					
Effective precip.				11.7	24.1	31.0	8.7					
Effective precip.				11.7	18.1	12.6	0					
Carrots late												
Rooting depth							0.20	0.43	0.50	0.50		
Effective storage							23.9	52.0	60.0	60.0		
Effective precip.							6.9	10.2	9.7	2.5		
Effective precip.							0	10.7	10.4	4.2		
Sweet corn												
Rooting depth					0.20	0.39	0.72	0.80	0.80			
Effective storage					24.0	46.8	86.4	96.0	96.0			
Effective precip.					8.8	23.2	11.0	12.2	8.2			
Effective precip.					13.1	12.1	0	10.7	8.2			

Table E-3. Mean Monthly Rooting Depths, Effective Storage Depths, and Effective Precipitation for 26 Crops and Turf for Upper and Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Bell Peppers												
Rooting depth						0.20	0.39	0.50	0.50			
Effective storage						23.6	47.2	60.0	60.0			
Effective precip.						20.8	10.2	11.6	8.7			
Effective precip.						6.9	0	10.7	8.7			
Cucumbers												
Rooting depth					0.20	0.51	0.70					
Effective storage					24.3	60.9	84.0					
Effective precip.					17.7	29.1	11.0					
Effective precip.					12.3	10.7	0					
Squash												
Rooting depth					0.20	0.42	0.60					
Effective storage					24.2	50.3	72.0					
Effective precip.					14.7	26.0	11.0					
Effective precip.					12.3	10.2	0					
Melons												
Rooting depth					0.20	0.42	0.76	0.80	0.80			
Effective storage					24.2	49.8	90.7	96.0	96.0			
Effective precip.					14.7	26.0	11.2	11.2	8.2			
Effective precip.					12.3	9.3	0	10.7	8.2			
Tomatoes												
Rooting depth					0.29	0.61	0.70	0.70				
Effective storage					34.3	73.8	84.0	84.0				
Effective precip.					23.2	11.0	12.0	8.0				
Effective precip.					7.7	0	10.7	8.0				
Apples												
Rooting depth				1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Effective storage				120.0	120.0	120.0	120.0	120.0	120.0	120.0	120.0	
Effective precip.				11.4	28.1	32.2	11.4	11.4	10.4	10.0		
Effective precip.				16.6	19.8	12.5	0	10.7	10.4	16.6		
Grapes												
Rooting depth					1.00	1.00	1.00	1.00				
Effective storage					120.0	120.0	120.0	120.0				
Effective precip.					20.8	10.4	10.4	9.4				
Effective precip.					8.3	0	10.7	10.4				
Strawberries												
Rooting depth				0.20	0.20	0.20						
Effective storage				24.0	24.0	24.0						
Effective precip.				3.8	21.6	23.9						
Effective precip.				5.2	15.4	9.2						
Winter Wheat												
Rooting depth	0.85	1.02	1.18	1.36	1.49	1.50	1.50	1.50	0.21	0.34	0.51	0.68
Effective storage	102.3	122.3	142.2	162.8	178.8	180.0	180.0	180.0	25.7	40.2	60.8	81.4
Effective precip.	14.0	25.0	26.5	20.3	33.2	35.3	11.8	8.6	6.2	13.8	13.9	10.8
Effective precip.	8.2	8.3	20.1	20.1	21.3	12.7	0	8.6	6.2	14.6	7.8	8.0

Table E-3. Mean Monthly Rooting Depths, Effective Storage Depths, and Effective Precipitation for 26 Crops and Turf for Upper and Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Barley												
Rooting depth				0.28	0.86	1.00	1.00					
Effective storage				33.9	103.2	120.0	120.0					
Effective precip.				13.4	30.6	34.3	9.4					
Effective precip.				13.8	21.3	12.7	0					
Alfalfa 1st cutting												
Rooting depth			0.44	0.96	1.00							
Effective storage			52.2	115.8	120.0							
Effective precip.			22.3	20.8	28.1							
Effective precip.			15.8	20.1	20.8							
Alfalfa 2nd cutting												
Rooting depth					1.00	1.00	1.00					
Effective storage					120.0	120.0	120.0					
Effective precip.					25.0	33.3	11.4					
Effective precip.					17.7	12.7	0					
Alfalfa 3rd cutting												
Rooting depth							1.00	1.00	1.00			
Effective storage							120.0	120.0	120.0			
Effective precip.							8.3	11.4	10.4			
Effective precip.							0	10.7	10.4			
Oat feed												
Rooting depth					0.41	1.00	1.00					
Effective storage					49.4	120.0	120.0					
Effective precip.					22.3	34.3	8.3					
Effective precip.					15.8	12.7	0					
Fescue												
Rooting depth				0.50	0.50	0.50	0.50	0.50	0.50	0.50		
Effective storage				60.0	60.0	60.0	60.0	60.0	60.0	60.0		
Effective precip.				18.4	29.1	30.1	10.7	10.7	9.7	17.5		
Effective precip.				19.4	21.3	12.7	0	10.7	10.4	19.4		
Feed Corn												
Rooting depth					0.26	0.54	0.90	1.00	1.00	1.00	1.00	
Effective storage					31.4	65.6	107.4	120.0	120.0	120.0	120.0	
Effective precip.					20.6	26.2	12.2	13.5	10.4	17.7	1.9	
Effective precip.					13.8	8.7	0	10.7	10.4	19.8	3.8	
Corn silage												
Rooting depth					0.28	0.67	0.99	1.00	1.00			
Effective storage					34.1	80.6	2119.1	120.0	120.0			
Effective precip.					20.6	28.0	13.5	12.5	9.4			
Effective precip.					13.8	10.0	0	10.7	10.4			

Table E-3. Mean Monthly Rooting Depths, Effective Storage Depths, and Effective Precipitation for 26 Crops and Turf for Upper and Lower Bound Future Climate Conditions (continued)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Oat hay												
Rooting depth			0.20	0.42	0.94	1.00	1.00	1.00				
Effective storage			24.0	50.8	113.1	120.0	120.0	120.0				
Effective precip.			1.8	14.9	32.2	34.3	12.5	8.3				
Effective precip.			2.6	15.8	21.3	12.7	0	9.4				

- Notes: ^aMean monthly rooting depth calculated according to Equation E-2.
^bMean monthly effective storage depth for sandy loam soil calculated from Equation E-1.
^cMean monthly effective precipitation for upper bound future climate calculated according to Appendix E, Section 2.1.2.
^dMean monthly effective precipitation for lower bound future climate calculated according to Appendix E, Section 2.1.2

Table E-5. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Current Climate Conditions

Crop	Pe (mm) ^a	Wb (mm) ^b	DP (mm) ^c	OW (mm)	LR ^d	LF (mm) ^e	ET_c (mm) ^f	W_s (mm) ^g	In (mm) ^h
Leaf Lettuce early	6.9	0	0	38.85	0.12	38.85	287.49	319.41	319.41
Leaf Lettuce late	7.7	0	0	40.91	0.12	40.91	303.17	336.38	336.38
Head Lettuce early	6.9	0	0	38.85	0.12	38.85	287.49	319.41	319.41
Head Lettuce late	7.7	0	0	40.91	0.12	40.91	303.17	336.38	336.38
Cabbage early	6.9	0	0	42.23	0.09	42.23	456.75	492.05	492.05
Cabbage late	7.7	0	0	36.32	0.09	36.32	394.64	423.26	423.26
Celery early	0	0	0	94.59	0.09	94.59	1007.66	1102.25	1102.25
Celery late	28.1	0	0	33.71	0.09	33.71	387.13	392.76	392.76
Broccoli early	6.9	0	0	23.52	0.05	23.52	418.87	435.46	435.46
Broccoli late	7.7	0	0	21.32	0.05	21.32	381.17	394.79	394.79
Cauliflower early	6.9	0	0	23.63	0.05	23.63	420.78	437.48	437.48
Cauliflower late	7.7	0	0	21.40	0.05	21.40	382.61	396.32	396.32
Spinach early	5.8	0	0	20.69	0.08	20.69	254.69	269.54	269.54
Spinach late	6.6	0	0	18.54	0.08	18.54	229.46	241.43	241.43
Potatoes	5.8	0	0	76.41	0.09	76.41	767.44	838.02	838.02
Onions early	5.8	0	0	122.09	0.13	122.09	803.70	919.95	919.95
Onions late	19.2	0	0	54.60	0.13	54.60	376.04	411.43	411.43
Carrots early	6.2	0	0	85.76	0.16	85.76	448.92	528.52	528.52
Carrots late	9.5	0	0	76.03	0.16	76.03	401.99	468.56	468.56
Sweet corn	0	0	0	61.24	0.09	61.24	610.33	671.57	671.57
Bell Peppers	0	0	0	74.65	0.10	74.65	641.56	716.21	716.21
Cucumbers	0	0	0	30.33	0.06	30.33	468.77	499.10	499.10
Squash	0	0	0	24.15	0.06	24.15	373.35	397.51	397.51
Melons	0	0	0	58.01	0.07	58.01	777.17	835.18	835.18
Tomatoes	0	0	0	41.82	0.06	41.82	646.35	688.17	688.17
Apples	18.5	0	0	165.52	0.09	165.52	1668.13	1815.15	1815.15

Table E-5. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Current Climate Conditions (continued)

Crop	Pe (mm) ^a	Wb (mm) ^b	DP (mm) ^c	OW (mm)	LR ^d	LF (mm) ^e	ET_c (mm) ^f	W_s (mm) ^g	In (mm) ^h
Grapes	8.3	0	0	102.58	0.10	102.58	889.87	984.13	984.13
Strawberries	14.6	0	0	232.69	0.16	232.69	1215.95	1434.01	1434.01
Winter Wheat	47.5	0	0	23.19	0.02	23.19	963.05	938.75	938.75
Barley	46.1	0	0	15.42	0.02	15.42	866.47	835.75	835.75
Alfalfa 1st	33.2	0	0	8.79	0.08	8.79	138.92	114.52	114.52
Alfalfa 2nd	9.4	0	0	22.29	0.08	22.29	277.36	290.28	290.28
Alfalfa 3rd	0	0	0	34.29	0.08	34.29	412.30	446.59	446.59
Alfalfa 4th	0	0	0	40.23	0.08	40.23	483.83	524.06	524.06
Alfalfa 5th	9.1	0	0	29.71	0.08	29.71	366.37	386.94	386.94
Alfalfa 6th	4.6	0	0	14.09	0.08	14.09	177.02	183.54	183.54
Oats feed	42.3	0	0	14.17	0.02	14.17	601.67	573.54	573.54
Bermuda	50.8	0	0	34.52	0.02	34.52	1628.37	1610.51	1610.51
Feed Corn	9.1	0	0	101.32	0.09	101.32	1088.45	1180.62	1180.62
Corn silage	0	0	0	71.06	0.09	71.06	756.98	828.03	828.03
Oats hay	0	0	0	8.56	0.02	8.56	455.26	463.82	463.82

Notes: ^a Effective precipitation calculated according to Appendix E, Section 2.1.2.

^b Water stored in the root zone prior to planting (annuals) or onset of growth (perennials) calculated according to methods in Appendix E, Section 2.2.1.

^c Deep percolation of soil moisture below the root zone calculated according to methods in Appendix E, Section 2.2.1.

^d Leaching requirement calculated according to Equation E-4.

^e Leaching fraction calculated according to Appendix E, Section 2.4, Equation E-6.

^f Crop evapotranspiration. Values from Appendix D, Table D-10, were summed over the growing season.

^g Seasonal water requirement calculated from Equation E-5.

^h Net irrigation requirement calculated from Equation E-8.

Table E-6. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Upper Bound Monsoon Climate Conditions

Crop	P_e (mm) ^a	W_b (mm) ^b	DP (mm) ^c	OW (mm)	LR ^d	LF (mm) ^e	ET_c (mm) ^f	W_s (mm) ^g	In (mm) ^h
Leaf Lettuce early	29.3	36.0	0	31.62	0.12	31.62	257.69	259.97	223.97
Leaf Lettuce late	54.9	36.0	112.15	112.15	0.12	25.44	238.64	209.15	147.72
Head Lettuce early	29.3	47.3	0	31.60	0.12	31.60	257.56	259.82	212.50
Head Lettuce late	54.9	36.0	112.15	112.15	0.12	25.44	238.64	209.15	147.72
Cabbage early	31.2	46.6	0	35.47	0.09	35.47	409.12	413.30	366.65
Cabbage late	96.4	60.0	51.61	51.61	0.09	20.23	311.92	235.72	155.49
Celery early	163.5	22.3	0	57.62	0.09	57.62	777.27	671.41	649.08
Celery late	105.4	36.0	125.58	125.58	0.09	22.60	346.11	263.30	204.71
Broccoli early	31.3	47.0	0	19.67	0.05	19.67	375.77	364.15	317.12
Broccoli late	92.1	48.0	71.70	71.70	0.05	11.89	300.42	220.20	160.31
Cauliflower early	32.2	47.0	0	19.68	0.05	19.68	376.84	364.30	317.27
Cauliflower late	97.7	48.0	74.61	74.61	0.05	11.61	301.09	215.00	155.39
Spinach early	27.9	36.0	0	16.66	0.08	16.66	228.24	217.01	181.01
Spinach late	63.8	36.0	125.58	125.58	0.08	10.18	186.23	132.58	86.40
Potatoes	100.9	48.0	148.05	148.05	0.09	55.55	654.52	609.21	505.66
Onions early	98.0	31.3	0	89.86	0.13	89.86	685.31	677.15	645.83
Onions late	101.1	36.0	120.12	120.12	0.13	44.48	391.73	335.14	254.67
Carrots early	30.5	51.5	0	71.98	0.16	71.98	402.15	443.61	392.12
Carrots late	96.9	60	48.70	48.70	0.16	41.67	312.06	256.79	155.12
Sweet corn	109.1	96.0	40.90	50.29	0.09	50.29	610.33	551.51	455.51
Bell Peppers	99.3	60.0	102.2	102.2	0.10	47.8	510.15	458.6	350.8
Cucumbers	100.3	84.0	200.19	200.19	0.06	15.99	347.46	263.15	163.16
Squash	85.83	72.0	91.17	91.17	0.06	14.10	303.83	232.10	146.00
Melons	186.5	96.0	0	27.01	0.07	27.01	548.43	388.94	292.94
Tomatoes	106.7	84.0	100.36	100.36	0.06	26.18	511.47	430.92	320.73
Apples	301.4	0	0	91.41	0.09	91.41	1212.43	1002.43	1002.43

Table E-6. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Upper Bound Monsoon Climate Conditions (continued)

Crop	Pe (mm) ^a	Wb (mm) ^b	DP (mm) ^c	OW (mm)	LR ^d	LF (mm) ^e	ET _c (mm) ^f	W _s (mm) ^g	In (mm) ^h
Grapes	221.3	0	0	53.87	0.10	53.87	684.32	516.86	516.86
Strawberries	192.2	24	0	136.06	0.16	136.06	894.62	838.53	814.53
Winter Wheat	166.8	180.0	0	18.45	0.02	18.45	894.81	746.75	566.75
Barley	155.8	120.0	0	12.24	0.02	12.24	806.92	663.39	543.39
Alfalfa 1st	53.1	15.3	0	8.24	0.08	8.24	152.19	107.32	91.96
Alfalfa 2nd	30.2	0	0	18.16	0.08	18.16	248.52	236.52	236.52
Alfalfa 3rd	23.6	0	0	27.83	0.08	27.83	362.35	362.45	362.45
Alfalfa 4th	141.2	0	0	20.30	0.08	20.30	399.54	264.42	264.42
Alfalfa 5th	146.8	0	0	5.63	0.08	5.63	195.24	73.38	73.38
Alfalfa 6th	77.0	0	0	7.75	0.08	7.75	150.03	100.97	100.97
Oat hay	26.2	120	61.57	61.57	0.02	7.09	403.61	384.49	257.39
Bermuda	341.1	0	0	22.51	0.02	22.51	1368.87	1050.32	1050.32
Feed Corn	276.8	59.3	0	43.05	0.09	43.05	735.40	501.63	442.30
Corn silage	195.9	59.3	0	31.44	0.09	31.44	530.88	366.38	307.06
Oat feed	92.0	120.0	27.71	27.71	0.02	11.76	556.12	475.82	344.06

Notes: ^a Effective precipitation calculated according to Appendix E, Section 2.1.2.

^b Water stored in the root zone prior to planting (annuals) or onset of growth (perennials) calculated according to methods in Appendix E, Section 2.2.1.

^c Deep percolation of soil moisture below the root zone calculated according to methods in Appendix E, Section 2.2.1.

^d Leaching requirement calculated according to Equation E-4.

^e Leaching fraction calculated according to Appendix E, Section 2.4, Equation E-6.

^f Crop evapotranspiration. Values from Appendix D, Table D-11, were summed over the growing season.

^g Seasonal water requirement calculated from Equation E-5.

^h Net irrigation requirement calculated from Equations E-7 and E-8.

Table E-7. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Lower Bound Future Climate Conditions

Crop	Pe (mm)^a	Wb (mm)^b	DP (mm)^c	OW (mm)	LR^d	LF (mm)^e	ET_c (mm)^f	W_s (mm)^g	In (mm)^h
Leaf Lettuce early	37.3	5.29	0	43.45	0.12	43.45	351.10	357.24	351.94
Leaf Lettuce late	18.4	0	0	55.04	0.12	55.04	415.93	452.53	452.53
Head Lettuce early	39.0	5.29	0	64.90	0.12	64.90	507.74	533.62	528.33
Head Lettuce late	23.0	0	0	68.31	0.12	68.31	516.32	561.58	561.58
Cabbage early	42.4	5.29	0	44.01	0.09	44.01	511.24	512.90	507.61
Cabbage late	24.9	0	0	46.47	0.09	46.47	520.01	541.55	541.55
Celery	46.8	5.29	0	74.51	0.09	74.51	840.51	868.25	862.95
Broccoli early	39.9	5.29	0	30.69	0.05	30.69	577.53	568.29	562.99
Broccoli late	35.4	0	0	29.52	0.05	29.52	552.57	546.66	546.66
Cauliflower early	40.9	5.29	0	20.94	0.05	20.94	407.71	387.75	382.46
Cauliflower late	22.9	0	0	22.55	0.05	22.55	417.86	417.50	417.5
Spinach early	36.4	5.29	0	24.23	0.08	24.23	327.81	315.59	310.30
Spinach late	21.3	0	0	26.71	0.08	26.71	342.59	347.97	347.97
Potatoes	47.7	5.29	0	82.99	0.09	82.99	874.87	910.17	904.88
Onions	71.3	0	0	139.23	0.13	139.23	981.20	1049.15	1049.15
Carrots early	42.4	5.29	0	102.40	0.16	102.40	570.99	631.04	625.75
Carrots late	25.3	0	0	108.18	0.16	108.18	583.78	666.68	666.68
Sweet corn	44.0	6.88	0	80.66	0.09	80.66	847.97	884.59	877.71
Bell Peppers	26.4	8.42	0	83.93	0.10	83.93	747.64	805.20	796.78
Cucumbers	23.0	8.84	0	31.67	0.06	31.67	512.44	521.14	512.29
Squash	22.6	8.84	0	26.97	0.06	26.97	439.36	443.77	434.93
Melons	40.5	8.84	0	53.26	0.06	53.26	754.02	766.79	757.95
Tomatoes	26.4	8.42	0	45.62	0.06	45.62	731.54	750.72	742.30
Apples	86.6	0	0	107.66	0.09	107.66	1159.64	1180.68	1180.68
Grapes	29.4	0	0	60.88	0.10	60.88	552.66	584.12	584.12
Strawberries	29.8	0	0	63.30	0.16	63.30	356.58	390.07	390.07

Table E-7. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Lower Bound Future Climate Conditions (continued)

Crop	Pe (mm)^a	Wb (mm)^b	DP (mm)^c	OW (mm)	LR^d	LF (mm)^e	ET_c (mm)^f	W_s (mm)^g	In (mm)^h
Winter Wheat	135.8	0	0	30.13	0.02	30.13	1325.42	1219.73	1219.73
Barley	47.8	4.69	0	10.42	0.02	10.42	602.27	564.93	560.25
Alfalfa 1st cutting	56.7	0	0	22.54	0.08	22.54	327.78	293.62	293.62
Alfalfa 2nd cutting	30.4	0	0	43.43	0.08	43.43	552.64	565.69	565.69
Alfalfa 3rd cutting	21.1	0	0	38.68	0.08	38.68	486.31	503.89	503.89
Oats	28.5	7.86	0	7.29	0.02	7.29	416.23	395.00	387.14
Fescue	93.9	0	0	27.02	0.02	27.02	1327.38	1260.50	1260.50
Feed Corn	67.1	7.13	0	99.22	0.09	99.22	1124.12	1156.21	1149.08
Corn silage	44.9	7.13	0	93.26	0.09	93.26	1038.39	1086.80	1079.70
Oat hay	61.7	5.90	0	22.76	0.02	22.76	959.95	920.97	915.07

- Notes:
- ^a Effective precipitation calculated according to Appendix E, Section 2.1.2.
 - ^b Water stored in the root zone prior to planting (annuals) or onset of growth (perennials) calculated according to methods in Appendix E, Section 2.2.1.
 - ^c Deep percolation of soil moisture below the root zone calculated according to methods in Appendix E, Section 2.2.1.
 - ^d Leaching requirement calculated according to Equation E-4.
 - ^e Leaching fraction calculated according to Appendix E, Section 2.4, Equation E-6.
 - ^f Crop evapotranspiration. Values from Appendix D, Table D-12, were summed over the growing season.
 - ^g Seasonal water requirement calculated from Equation E-5.
 - ^h Net irrigation requirement calculated from Equations E-7 and E-8.

Table E-8. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Future Climate Conditions

Crop	Pe (mm)^a	Wb (mm)^b	DP (mm)^c	OW (mm)	LR^d	LF (mm)^e	ET_c (mm)^f	W_s (mm)^g	In (mm)^h
Leaf Lettuce early	57.3	36	103.47	103.47	0.12	24.30	232.80	199.78	139.48
Leaf Lettuce late	22.9	0	0.0	38.39	0.12	38.39	300.11	315.59	315.59
Head Lettuce early	67.6	36	102.81	102.81	0.12	37.70	339.90	309.96	236.26
Head Lettuce late	25.3	0	0.0	47.46	0.12	47.46	368.11	390.24	390.24
Cabbage early	74.6	60	56.81	56.81	0.09	24.85	339.29	289.58	204.73
Cabbage late	27.5	0	0.0	32.10	0.09	32.10	369.40	374.01	374.01
Celery	78.8	36	104.37	104.37	0.09	46.58	575.03	542.79	460.21
Broccoli early	71.4	48	78.08	78.08	0.05	18.12	388.82	335.57	269.45
Broccoli late	39.4	0	0.0	20.05	0.05	20.05	390.60	371.30	371.30
Cauliflower early	64.6	48	79.81	79.81	0.05	11.64	268.50	215.55	155.91
Cauliflower late	24.0	0	0.0	15.52	0.05	15.52	295.88	287.36	287.36
Spinach early	57.3	36	102.81	102.81	0.08	13.36	217.97	173.98	124.63
Spinach late	18.0	0	0.0	18.66	0.08	18.66	242.36	243.01	243.01
Potatoes	82.1	48	72.16	72.16	0.09	51.94	599.84	569.65	469.70
Onions	106.1	36	65.3	85.11	0.13	85.11	662.30	641.30	540.05
Carrots early	75.5	60	56.81	59.23	0.16	59.23	381.30	365.00	248.19
Carrots late	29.3	0	0.0	74.81	0.16	74.81	415.54	461.01	461.01
Sweet corn	63.5	0	0.0	47.43	0.09	47.43	536.20	520.14	520.14
Bell Peppers	50.4	60	82.39	82.39	0.10	55.34	526.97	530.92	415.58
Cucumbers	57.8	84	20.25	20.25	0.06	18.96	350.92	312.10	209.14
Squash	51.8	72	43.72	43.72	0.06	16.12	301.01	265.36	177.23
Melons	71.4	0	0	34.27	0.07	34.27	530.47	493.36	493.36
Tomatoes	54.2	84	28.26	29.96	0.06	29.96	517.32	493.06	380.81
Apples	115.0	0	0	66.24	0.09	66.24	775.22	726.42	726.42
Grapes	50.9	0	0	38.04	0.10	38.04	377.81	364.93	364.93
Strawberries	49.2	24	125.09	125.09	0.16	35.80	234.08	220.64	160.84

Table E-8. Seasonal Water Inputs and Requirements for 26 Crops and Turf for Future Climate Conditions (continued)

Crop	Pe (mm)^a	Wb (mm)^b	DP (mm)^c	OW (mm)	LR^d	LF (mm)^e	ET_c (mm)^f	W_s (mm)^g	In (mm)^h
Winter Wheat	219.3	0	0	16.45	0.02	16.45	868.80	666.01	666.01
Barley	87.6	0	0	5.75	0.02	5.75	393.45	311.57	311.57
Alfalfa 1st cutting	71.2	0	0	12.88	0.08	12.88	226.05	167.72	167.72
Alfalfa 2nd cutting	69.7	0	0	25.15	0.08	25.15	372.16	327.64	327.64
Alfalfa 3rd cutting	30.2	0	0	25.97	0.08	25.97	342.47	338.28	338.28
Oat hay	65.0	0	0	3.83	0.02	3.83	268.80	207.67	207.67
Fescue	126.1	0	0	17.80	0.02	17.80	938.66	830.36	830.36
Feed Corn	102.6	0	0	62.71	0.09	62.71	770.67	730.78	730.78
Corn silage	84.0	0	0	59.15	0.13	59.15	714.15	689.30	689.30
Oat feed	104.0	0	0	13.67	0.02	13.67	643.87	553.52	553.52

Notes: ^a Effective precipitation calculated according to Appendix E, Section 2.1.2.

^b Water stored in the root zone prior to planting (annuals) or onset of growth (perennials) calculated according to methods in Appendix E, Section 2.2.1.

^c Deep percolation of soil moisture below the root zone calculated according to methods in Appendix E, Section 2.2.1.

^d Leaching requirement calculated according to Equation E-4.

^e Leaching fraction calculated according to Appendix E, Section 2.4, Equation E-6.

^f Crop evapotranspiration. Values from Appendix D, Table D-13, were summed over the growing season.

^g Seasonal water requirement calculated from Equation E-5.

^h Net irrigation requirement calculated from Equations E-7 and E-8.

Table E-10. Crop Salt Tolerance Levels (EC_e , mmhos/cm) that Result in No Yield Reduction for 26 Crops and Turf

Crop	EC_e^a	Crop	EC_e^a
Lettuce	1.3	Melons	2.2
Cabbage	1.8	Tomatoes	2.5
Celery	1.8	Alfalfa hay	2.0
Broccoli	2.8	Oats	6.0
Cauliflower	2.8	Barley	8.0
Spinach	2.0	Apples	1.7
Potatoes	1.7	Grapes	1.5
Onions	1.2	Strawberries	1.0
Carrots	1.0	Winter wheat	6.0
Sweet corn	1.7	Feed Corn	1.8
Bell peppers	1.5	Corn silage	1.8
Cucumbers	2.5	Oat hay	6.0
Squash	2.5	Bermuda	6.9
		Fescue	6.9

Note: ^aElectrical conductivity. Source: Doorenbos and Pruitt (1977, Table 36, p. 78.)

Table E-11. Maximum Rooting Depths and Soil Moisture Parameters for 26 Crops and Turf

Crop	Maximum Rooting Depth (m) ^a	TAW (mm) ^b	p ^c	RAW (mm) ^d
Lettuce early	0.3	36	0.30	10.8
Lettuce late	0.3	36	0.30	10.8
Cabbage early	0.5	60	0.45	27.0
Cabbage late	0.5	60	0.45	27.0
Celery early	0.3	36	0.20	7.2
Celery late	0.3	36	0.20	7.2
Broccoli early	0.4	48	0.45	21.6
Broccoli late	0.4	48	0.45	21.6
Cauliflower early	0.4	48	0.45	21.6
Cauliflower late	0.4	48	0.45	21.6
Spinach early	0.3	36	0.20	7.2
Spinach late	0.3	36	0.20	7.2
Potatoes	0.4	48	0.35	16.8
Onions early	0.3	36	0.30	10.8
Onions late	0.3	36	0.30	10.8
Carrots early	0.5	60	0.35	21.0
Carrots late	0.5	60	0.35	21.0
Sweet corn	0.8	96	0.50	48.0
Bell peppers	0.5	60	0.30	18.0
Cucumbers	0.7	84	0.50	42.0
Squash	0.6	72	0.50	36.0
Melons	0.8	96	0.40	38.4
Tomatoes	0.7	84	0.40	33.6
Alfalfa hay	1.0	120	0.55	66.0
Oat hay	1.0	120	0.55	66.0
Feed Corn	1.0	120	0.55	66.0
Corn silage	1.0	120	0.55	66.0
Apples	1.0	120	0.50	60.0
Grapes	1.0	120	0.45	54.0
Strawberries	0.2	24	0.20	4.8
Winter wheat	1.5	180	0.55	99.0
Barley	1.0	120	0.55	66.0
Fescue	0.5	60	0.40	24.0
Bermudagrass	0.5	60	0.50	30.0

Notes: ^aSource: Allen et al. (1998, Table 22, pp. 163-165, minimum range values).

^bTotal available soil moisture in the root zone calculated from Equation E-1.

^cSoil water depletion fraction, Source: Allen et al. (1998, Table 22, pp. 163-165).

^dReadily available soil moisture in the root zone calculated from Equation E-9.

Table E-13. Irrigation Application for Crops under Current Climate Conditions

Crop	Irrigation Application^a (mm)	Number of Applications^b	30-day Total^c (mm)
Leaf Lettuce early	10.25	18	184.48
Leaf Lettuce late	9.80	15	147.00
Head Lettuce early	12.06	15	180.93
Head Lettuce late	9.80	15	147.00
Cabbage early	24.67	9	222.06
Cabbage late	22.44	5	112.21
Celery early	10.00	30	300.01
Celery late	6.78	7	47.46
Broccoli early	23.45	9	211.07
Broccoli late	20.44	7	143.09
Cauliflower early	21.22	10	212.22
Cauliflower late	20.44	6	122.65
Spinach early	6.01	30	180.30
Spinach late	8.87	15	133.06
Potatoes	18.66	15	279.89
Onions early	8.74	30	262.29
Onions late	9.26	6	55.53
Carrots early	23.01	10	230.14
Carrots late	19.36	7	135.55
Sweet corn	41.20	5	206.01
Bell Peppers	19.71	15	295.58
Cucumbers	34.91	8	279.24
Squash	32.94	7	230.56
Melons	35.47	8	283.78
Tomatoes	30.22	10	302.19
Apples	49.23	3	147.68
Grapes	48.37	3	145.12
Strawberries	6.02	30	180.51
Winter Wheat	77.93	2	155.86
Barley	48.72	3	146.17
Alfalfa hay 1 st cutting	46.53	2	93.06
Alfalfa hay 2 nd cutting	65.94	3	197.81
Alfalfa hay 3 rd cutting	65.64	4	262.56
Alfalfa hay 4 th cutting	60.71	5	303.57
Alfalfa hay 5 th cutting	55.33	4	221.32
Alfalfa hay 6 th cutting	50.88	2	101.75

Table E-13. Irrigation Application for Crops under Current Climate Conditions
(continued)

Crop	Irrigation Application^a (mm)	Number of Applications^b	30-day Total^c (mm)
Oats	50.07	3	150.22
Feed Corn	50.26	3	150.77
Corn silage	60.18	5	300.91
Oat hay	56.51	4	226.05

Notes: ^a Average amount of water applied per irrigation event for 30 days prior to harvest.

^b Number of irrigation events for 30 days prior to harvest.

^c Total irrigation requirement for 30 days prior to harvest.

Table E-14. Irrigation Application for Crops under Future Climate Conditions

Crop	Irrigation Application^a (mm)	Number of Applications^b	30-day Total^c (mm)
Leaf Lettuce early	10.1	12	121.2
Leaf Lettuce late	10.0	15	150.3
Head Lettuce early	9.5	16	152.7
Head Lettuce late	8.4	15	126.2
Cabbage early	25.7	6	154.5
Cabbage late	26.5	5	132.4
Celery	8.0	25	200.9
Broccoli early	18.9	9	169.7
Broccoli late	19.7	6	118.1
Cauliflower early	22.2	6	133.1
Cauliflower late	21.7	6	130.1
Spinach early	7.3	16	116.2
Spinach late	8.2	15	123.0
Potatoes	14.4	14	201.9
Onions	11.3	15	169.3
Carrots early	18.2	9	164.2
Carrots late	22.0	6	131.7
Sweet corn	40.3	5	201.6
Bell Peppers	17.7	9	159.2
Cucumbers	37.2	5	186.0
Squash	34.1	5	170.6
Melons	34.6	5	173.1
Tomatoes	31.4	6	188.6
Apples	54.4	2	108.9
Grapes	43.2	2	86.4
Strawberries	7.3	16	116.7
Winter Wheat	59.9	2	119.8
Barley	66.7	2	133.3
Alfalfa 1 st cutting	55.0	2	110.0
Alfalfa 2 nd cutting	51.1	4	204.4
Alfalfa 3 rd cutting	51.3	3	153.9
Oats	48.3	3	144.9
Feed Corn	32.2	1	32.2

Table E-14. Irrigation Application for Crops under Future Climate Conditions
(continued)

Crop	Irrigation Application^a (mm)	Number of Applications^b	30-day Total^c (mm)
Corn silage	61.9	2	123.7
Oat hay	46.2	3	138.7

Notes: ^a Average amount of water applied per irrigation event for 30 days prior to harvest.
^b Number of irrigation events for 30 days prior to harvest.
^c Total irrigation requirement for 30 days prior to harvest.

Table E-16. Reduction in Irrigation Requirement with Crop Stress for Current Climate Conditions

Crop	30-day Irrigation Requirement^a (mm)	30-day Reduced Irrigation^b (mm)	% Reduction^c	Number of days stressed
Alfalfa 1st cutting	93.06	86.00	7.59	4
Alfalfa 2nd cutting	197.81	186.88	5.53	6
Alfalfa 3rd cutting	262.56	242.62	7.60	9
Alfalfa 4th cutting	303.57	290.19	4.41	8
Alfalfa 5th cutting	221.32	210.41	4.93	6
Alfalfa 6th cutting	101.75	97.00	4.67	4
Bell Peppers	295.58	288.75	2.31	15
Bermuda	227.62	213.69	6.12	12
Broccoli early	211.07	201.53	4.52	12
Broccoli late	143.09	117.96	17.57	10
Cabbage early	222.06	212.16	4.46	12
Cabbage late	112.21	108.67	3.16	8
Carrots early	230.14	212.78	7.54	12
Carrots late	135.55	129.68	4.33	10
Cauliflower early	212.22	203.05	4.32	14
Cauliflower late	122.65	118.16	3.66	10
Celery early	300.01	278.06	7.3	20
Celery late	47.46	44.78	5.65	10
Feed Corn	150.77	146.56	2.79	6
Corn-silage	300.91	289.55	3.78	8
Cucumbers	279.24	265.39	4.96	10
Head Lettuce early	180.93	169.97	6.06	16
Head Lettuce late	147.0	143.40	2.45	15
Leaf Lettuce early	180.93	177.23	2.05	15
Leaf Lettuce late	147.00	143.40	2.45	15
Melons	283.78	266.58	6.06	10
Oats	150.22	142.17	5.36	4
Oat hay	226.05	219.16	3.05	6
Onions early	262.29	248.33	5.32	20
Onions late	55.53	53.43	3.79	8
Potatoes	279.89	263.15	5.98	18
Spinach early	180.30	165.65	8.12	20
Spinach late	133.06	131.15	1.43	15
Sweet Corn	206.01	197.50	4.13	8
Tomatoes	302.19	284.77	5.76	12
Squash	230.56	220.83	4.22	10

Table E-16. Reduction in Irrigation Requirement with Crop Stress for Current Climate Conditions (continued)

Crop	30-day Irrigation Requirement ^a (mm)	30-day Reduced Irrigation ^b (mm)	% Reduction ^c	Number of days stressed
Apples	147.68	138.51	6.21	5
Grapes	145.12	136.89	5.68	6
Strawberries	180.51	168.99	6.38	20
Barley	146.17	139.00	4.90	4
Winter Wheat	155.86	149.27	4.23	4

Notes: ^aIrrigation requirement with no moisture stress calculated according to Appendix E, Section 2.6.1.

^bIrrigation reduced by withholding irrigation for two days after RAW is depleted (calculated according to Appendix E, Section 2.6.1).

^cPercent reduction from column 2 to column 3.

Table E-17. Reduction in Irrigation Requirement with Crop Stress for Future Climate Conditions

Crop	30-day Irrigation Requirement (mm)	30-day Reduced Irrigation Requirement (mm)	% Reduction	Number of days stressed
Alfalfa 1st cutting	110.0	94.1	14.4	3
Alfalfa 2nd cutting	204.4	170.11	16.8	8
Alfalfa 3rd cutting	153.9	142.7	7.2	4
Apples	108.9	104.2	4.3	2
Bell Peppers	159.2	142.9	10.2	11
Fescue	174.9	164.0	6.3	10
Broccoli early	169.7	164.7	2.9	8
Broccoli late	118.1	116.3	1.5	6
Cabbage early	154.3	141.9	8.0	7
Cabbage late	132.4	125.8	5.2	8
Carrots early	164.2	159.0	3.1	7
Carrots late	131.7	128.0	2.8	6
Cauliflower early	133.1	121.3	8.9	8
Cauliflower late	130.1	127.2	2.2	10
Celery	200.9	169.7	15.5	16
Feed Corn	32.2	31.0	3.8	4
Corn silage	123.7	119.3	3.6	1
Cucumbers	186.0	166.0	10.8	9
Head Lettuce early	152.7	125.1	18.0	14
Head Lettuce late	126.2	117.5	6.9	12
Leaf Lettuce early	121.2	118.0	2.6	10
Leaf Lettuce late	150.4	139.5	7.2	14
Melons	173.1	161.0	7.0	9
Oats	144.9	138.7	4.3	2
Oat hay	138.7	133.2	4.0	41
Onions	169.3	165.8	2.1	13
Potatoes	201.9	188.2	6.7	12
Spinach early	116.2	109.4	5.9	13
Spinach late	123.0	119.5	2.9	14
Sweet Corn	201.6	191.8	4.9	8
Tomatoes	188.6	180.6	4.2	6
Squash	170.6	147.7	13.4	8
Grapes	86.2	82.8	4.2	1

Table E-17. Reduction in Irrigation Requirement with Crop Stress for Future Climate Conditions
(continued)

Crop	30-day Irrigation Requirement (mm)	30-day Reduced Irrigation Requirement (mm)	% Reduction	Number of days stressed
Strawberries	116.8	113.7	2.6	14
Barley	133.3	128.2	3.9	1
Winter Wheat	119.8	99.0	17.4	8

Notes: ^aIrrigation requirement with no moisture stress calculated according to Appendix E, Section 2.6.1.

^bIrrigation reduced by withholding irrigation for two days after RAW is depleted (calculated according to Appendix E, Section 2.6.1).

^cPercent reduction from column 2 to column 3.