AN ABSTRACT OF THE THESIS OF

Suva R. Shakya for the degree of Master of Science in Water Resources Engineering presented on December 5, 2007.

Title: Use of MIKE SHE for Estimation of Evapotranspiration in the Sprague River Basin

Abstract approved:

Richard H. Cuenca

MIKE SHE is a fully distributed, physically-based hydrologic model that can simulate water movement over and under the Earth's surface. Evapotranspiration (*ET*) is one of the components of this model. MIKE SHE uses a modification of the Kristensen -Jensen (1975) method to calculate actual *ET*. This method is based on addition of the three evapotranspiration components – interception storage, transpiration by the plant and evaporation from the soil surface, to compute total actual evapotranspiration. The validity of the Kristensen-Jensen method has been tested on an arid region within the Sprague River subbasin of the Upper Klamath basin in southern Oregon. The model was setup on a 1,000 m by 1,000 m flat surface as a one-dimensional grid cell. There are sixteen computation layers which make three soil profile layers with varying soil properties. Meteorological data from the Pacific Northwest Cooperative Agricultural Weather Network (AgriMet) were used to setup the model. Soil physical properties were taken from the Soil Survey Geographic (SSURGO) database of the Natural Resources Conservation Service (NRCS). Values of the van Genuchten parameters for soil water retention and hydraulic conductivity as a function of soil texture from Carsel and Parrish (1988) were applied.

Wetland vegetation such as duckweed and cattail, natural vegetation such as big sagebrush, ponderosa pine and juniper, and agricultural crops such as grass pasture and maize were used to test MIKE SHE evapotranspiration simulation. The length of growth stage, crop coefficient, leaf area index (*LAI*) and root depth values were taken from the literature. Actual crop *ET* rates were calculated based on AgriMet reference *ET* which uses the Kimberly Penman (Wright, 1982) method. The alfalfa reference *ET* was converted to a grass reference by multiplying by a factor of 0.833 (Jensen et al., 1990). The single crop coefficient method

was used and soil stress was accounted for using the FAO 56 method (Allen et al, 1998). Simulated irrigation was applied to maize and grass to keep the root zone soil moisture close to field capacity. Crop *ET* rates from the MIKE SHE simulation were then compared to the AgriMet based *ET* rates, resulting in a comparison of Kristensen-Jensen method against the Kimberly Penman method. Both the Kristensen-Jensen and AgriMet simulation scenarios were driven by the same reference *ET* and the same FAO 56 basal crop coefficient. Differences are therefore a function of different methods for dealing with soil moisture stress.

Results indicate that the MIKE SHE simulated evapotranspiration corresponds to the Kimberly Penman method for the duckweed and cattail wetlands species with resulting Nash and Sutcliffe (NS) efficiencies of 0.97 and 1.00, respectively. The big sagebrush, juniper, and ponderosa pine species required a soil stress correction factor for the crop coefficients and the results yielded NS efficiency values of 0.14, 0.59 and 0.68, respectively. Irrigation was automatically turned on for maize at a 20 percent soil moisture deficit to minimize the effects of water stress and the resulting NS efficiency was 0.85. For pasture, an irrigation based on average monthly water deficit for pasture in Klamath was used (Cuenca et al.,1992). This resulted in a NS efficiency of 0.77.

Each crop requires unique treatment within the model. Required vegetation parameters such as crop coefficient and *LAI*, climatic factors such as reference *ET*, and soil hydraulic properties need to be based on local conditions to the extent possible. It should be noted that the MIKE SHE simulations were run in a one-dimensional mode which precluded accounting for spatial variability or lateral flow of surface or groundwater. The simulation results indicate that converting the study area into a well irrigated pasture would require application of substantial amounts of irrigation water by sprinkler or flooding. Wetlands would require even more water to flood the land, but would be well suited for development of regional habitat. Big sagebrush, juniper and ponderosa pine survive under natural conditions but experience considerable plant stress brought on by soil water deficits which limit plant production below the maximum possible growth.

Use of MIKE SHE for Estimation of Evapotranspiration in the Sprague River Basin

by

Suva R. Shakya

A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Master of Science

Presented December 5, 2007

Commencement June 2008

Master of Science thesis of Suva R. Shakya presented on December 5, 2007

APPROVED:

Major Professor, representing Water Resources Engineering

Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Suva R. Shakya, Author

ACKNOWLEDGEMENTS

There are several people I would like to express my gratitude for successful completion of this thesis. This work would not have been possible without the direction, guidance and support of my advisor Prof. Richard H. Cuenca. I am grateful to NRCS for providing me the funding on a research project related to the subject, especially Mark Everett and Terry Nelson for providing me with data.. I would also like to thank DHI for providing the license to use MIKE SHE software. I am indebted to Jeremy Kobor from DHI for providing technical support with the model. Borge Storm I met at a conference gave me the idea of converting into a simplified 1-D model that efficiently improved my work, so thank you for that. I am thankful to the Department of Biological and Ecological Engineering for housing me all throughout my research time. Special thanks to Dr. Yutaka Hagimoto for the assistance and guidance he has given me. Thank you to the Hydrologic Science Team (HST) - Ari, Josh, Mike, Kent, Peggy and Travis and the Irrigation Team - Carole, Chadi, Charles and Lorraine for being very supportive.

Thank you to my Nepali friends and others who have given me a family close to home - Alisha , Basant, , Dipanker, Iresh, Kailash, Madhu, Maya, Mel and Rama. Every word of your encouragements has contributed to completion of this work.

I would like to say thank you to the members of my committee, Dr. Jeff McDonnell from Forest Engineering, Dr. John Bolte from Biological and Ecological Engineering and Dr. David Myrold from Crop and Soil Science.

Last and not at all the least, I would like to thank my family, half a day ahead yet very close, for having given me immense moral support. My parents visit in July enriched me with endurance and courage to carry on till the end.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF TABLES

Page

LIST OF TABLES (continued)

1 INTRODUCTION

The availability of adequate water resources, worldwide as well as in the typically arid western United States, is the subject of many conversations and policy decisions, Groundwater is being depleted, surface water is diminishing, irrigation water is rationed and water rights are in jeopardy. Transboundary water and the concomitant international stresses which can develop are an issue. Fish habitat is in danger when farmers use the water for irrigation. There is a need to save every drop of water to keep the groundwater from being depleted, rivers, lakes and wetlands from drying out, and to save endangered species from extinction.

The Klamath River Basin that lies within southern Oregon and northern California has involved some of the most controversial water resources decisions in North America. The declining surface and groundwater led to rationing of water between the competing uses such as salmon fisheries, farming, livestock production and power generation. In 2001, for example, the water shortage forecast led to closure of agricultural irrigation to maintain adequate in-stream flows for salmon runs (Timothy et al., 2006). The consequence was a $200 million loss in agricultural products (Levy, 2003). Conversely, in 2002, water was rationed to irrigation rather than to instream flows. This contributed to one of the worst fish kills in the western U.S. history claiming over 30,000 salmon and steelhead in the lower Klamath River (Levy, 2003). Forecasted rise in temperatures due to global warming brings even more concern about adequacy of water resources and maintenance of fish habitat to the basin.

Klamath Project

Fertile lands in southern Oregon and northern California have attracted farmers for over 150 years. The history dates back in 1840s when the early pioneers set across the "great American Desert" of the Great Plains to settle on the west coast of United States. Agricultural bloom in the fertile land lead to increased demand for irrigation, which lead to the initialization of what is now the Klamath Project maintained by the Bureau of Reclamation. The approval of the project came after the Oregon and California legislatures and the United States Congress passed all necessary legislation to begin the project in May 1905. One million dollars was allocated immediately (Stene, 1994).

The Klamath Project covers territory in Klamath County, Oregon, and Siskiyou and Modoc Counties in northern California. Klamath Falls, Merrill, Bonanza, and Malin, Oregon and Tule Lake, California form a group of communities included in the Klamath Project area. The water in the Klamath Project is derived from the Upper Klamath Lake and Tule Lake and Lower Klamath Lake. The air temperatures in the project area range from -31 to 41 °C (-24 to 105 °F).

The Klamath project primarily supplied irrigation water for local agriculture, irrigating over 80,937 ha (200,000 acres) on about 1,400 farms that grow a wide variety of cereals, forage, field crops, fruits and nuts. In the early years of the project (early 1900s), the major crop was forage for livestock. Based on information from 1979, the other variety of crops include cereals like barley, corn, oats, rice, fruits like apples, apricots and cherries (Reference to Klamath Project: Stene 1994)

Sprague River Subbasin

The Sprague River subbasin is a part of the Upper Klamath basin and has been a study site of the Natural Resources Conservation Service (NRCS). Water quality has been a concern in this subbasin where declining water resources have directly affected the fish and wildlife habitat. Fish species like Lost River Sucker, Shortnose Sucker, Interior Redband trout and Bull trout are listed on the Endangered Species Act either as threatened, candidate or species of concern (NRCS, 2004).

Irrigated pasture is the predominant land use in the Sprague River basin. 65 percent of the water used for irrigation is diverted from streams and 35 percent is pumped from wells. Flooding is the most common form of irrigation with relatively low efficiency (NRCS, 2004).

Modeling

There has been pressing need for a hydrologic model that is as complete as possible - a model that would take into account all the physical processes ranging from rainfall to saturated flow , from nutrient flow to plant dynamics. Increasing reliability of computer models and advances in science has taken the study of hydrology to a more sophisticated level of understanding.

Modeling groups like the Danish Hydraulics Institute (DHI) have made advances in visualizing physical processes, with the use of current mapping and animation technology, to the fully distributed level. Knowledge is transferred from a scientist to an engineer to the local entity where the project is implemented for the benefit of the state and the environment.

There are numerous hydrologic models, both open source or licensed, that would simulate portions of the water balance. But one process is affected by another process that is unaccounted for and assumptions have to be made. The challenge is to incorporate all the processes into one so that the nature is understood at the most fundamental level.

MIKE SHE is a fully distributed, finite difference model that can simulate physical properties ranging from snow melt to saturated flow from an aquifer to extraction of water by plants to meet evapotranspiration demands. It takes into account every water molecule from the time it hits the surface until it exits through deep percolation, horizontal saturated flow or back to the atmosphere by evapotranspiration. It is the evapotranspiration component of MIKE SHE that is of interest in this study.

Evapotranspiration

The focus of this study is to determine how well MIKE SHE represents evapotranspiration. Evapotranspiration is a major component of the hydrologic cycle. It is the transfer of water to the atmosphere by evaporation from the soil and plant surface as well as transpiration by the plants. Evapotranspiration varies for different vegetation types under different climatic conditions.

Different methods are available to estimate evapotranspiration including the Penman method (1948), the combined Penman-Monteith method (1965), and the Kimberly Penman (1982), to name just a few. MIKE SHE uses the modified Kristensen and Jensen (1975) method and the validity of this method is one of the key questions.

AgriMet Reference Evapotranspiration

The Pacific Northwest Cooperative Agricultural Weather Network, commonly known as AgriMet, is a network of weather stations in the Pacific Northwest operated by the U. S. Bureau of Reclamation (BUREC). As of November 2007, there are over 70 agricultural stations located throughout the Pacific Northwest. The network provides an efficient platform for the collection of weather data. AgriMet calculates alfalfa based reference evapotranspiration ET_r, using the Kimberly Penman (Wright 1982) method. This requires weather information such as daily maximum and minimum temperature, relative humidity, solar radiation and wind speed from the AgriMet stations. The data are available on the web at usbr.gov/pn/agrimet. The MIKE SHE Kristensen and Jensen method will be compared with the AgriMet Kimberly Penman method for estimating crop evapotranspiration.

Purpose statement

The purpose of the research conducted for this thesis is:

- Analyze the efficiency of the Danish Hydraulic Institute MIKE SHE hydrologic simulation model for evapotranspiration.
- Test the MIKE SHE evapotranspiration component for arid environment vegetation growth in the Sprague River subbasin, including sagebrush, juniper, Ponderosa pine and pasture.
- Test MIKE SHE evapotranspiration for wetlands vegetation such as duckweed and cattail with varying levels of the groundwater table.
- Test the irrigation model of MIKE SHE using an agricultural crop such as maize.
- Make recommendations on application of MIKE SHE with special focus on evapotranspiration.

In summary, the goal of the project is to determine how well MIKE SHE simulates evapotranspiration in an arid environment and how well the Kristensen-Jensen (1975) model performs compared to the AgriMet evapotranspiration estimating method.

2 LITERATURE REVIEW

2.1 Evapotranspiration measurement techniques

Evapotranspiration is a combination of two processes whereby water is transported to the atmosphere through evaporation from the soil surface and by transpiration by the crop (Allen et al., 1998). It is an important portion of water balance. Globally, 62 percent of the precipitation that falls on the continents is evapotranspirated. Out of this 97 percent is evapotranspirated from land surfaces and 3 percent is open air evaporation (Dingman, 2002). There are several methods developed to estimate plant and canopy evapotranspiration (Jensen et al. 1990). Lysimeters are also used to make direct measurement from experimental fields. But due to the high expense for installing lysimeters, they are only typically used only for larger research projects and typically at permanent installations. Less expensive weather station equipment such as thermometers for temperature, radiometers for radiation measurement and relative humidity probes are commonly used to calculate evapotranspiration indirectly using various methods.

Actual crop evapotranspiration, ET_c is the amount of water transported to the atmosphere from a surface for a given soil water content, climatic conditions, vegetative development and field management. Reference evapotranspiration, ET_0, is the amount of water that is transported to the atmosphere from clipped, green, actively growing dense grass with an ample water supply (Doorenbos and Pruitt 1977). Calculation of ET_0 is commonly done using the FAO Penman-Monteith equation (Allen et al. 1998).

In this project, a comparison of the Kristensen and Jensen (1975) method used by MIKE SHE and the Kimberly-Penman method (1972) used by the AgriMet weather station is performed.

2.1.1 The combined Penman method (1948)

Although this method is not used directly in this research, the equation for combined Penman method is:

$$\lambda E = \frac{\Delta(R_n - G) + \gamma f(u)\left(e_a{}^0 - e_a\right)}{\Delta + \gamma}$$ **eq 2.1**

where,

λ is the latent heat of vaporization of water, [MJ/kg]

E is the rate of evaporation,[mm/day]

λ is the slope of saturation vapor pressure curve [kPa °C-1]

R_n is net radiation [MJ m-2 day-1]

G is soil heat flux [MJ m-2 day-1]

γ is the psychometric constant

$f(u)$ is the empirical wind function

e_s is the saturation vapor pressure of air [kPa]

e_a is the actual vapor pressure [kPa]

This equation was developed to calculate evaporation from surfaces such as open water surfaces, wet soils or crop surfaces. This method uses meteorological data only and does not include physiological behavior of plant. Monteith (1965) and Rijtema (1965) applied resistances for water vapor transport to represent the control of water vapor flux from the leaves into the atmosphere.

2.1.2 FAO 56 Penman-Monteith equation

The equation,

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$ **eq 2.2**

is called the modified Penman-Monteith equation or simply the FAO 56 Penman-Monteith equation where,

ET_0 is the reference evapotranspiration

R_n is the net radiation of the crop surface (MJ m^{-2} day^{-1}),

G is the soil heat flux (MJ m^{-2} day^{-1}),

$(e_s - e_a)$ represents the vapor pressure deficit of the air (kPa),

Δ represents the slope of the saturation vapor pressure temperature relationship (kPa°C^{-1}),

γ is the psychometric constant (kPa°C^{-1}),

T is the mean air temperature at 2 m height, (°C)

u_2 is the wind speed at 2 m height. (ms^{-1})

This is a widely accepted method and recommended by FAO and the American Society of Civil Engineers (ASCE) to determine reference evapotranspiration (Allen et al., 1998; Allen et al, 2005). It is derived from the original Penman (1948) equation which calculates water transfer to the atmosphere from the free water surface (Gonzalez et al., 2005). This method uses grass as a reference crop as compared to alfalfa. It assumes that the hypothetical reference crop has a height of 0.12 m, a fixed surface resistance to water loss of 50 s/m (Allen et al, 2005) and an albedo of 0.23.

The two methods described above are not directly used in this project, but given as a comparison for the simplified Kimberly-Penman method described below.

2.1.3 1982 Kimberly-Penman method

Unlike the original Penman equation, the Kimberly-Penman (KP) (Wright, 1982) equation is not purely physically based. It has been specifically calibrated for arid, advective environments similar to those in Kimberly, Idaho where it was first developed (Wright and Jensen, 1972). It has been used by the AgriMet network of weather stations.

The general form of Kimberly-Penman equation is given by

$$\lambda ET_{ref} = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} 15.36 (Wf) \delta e$$ **eq 2.3**

where,

G is the soil heat flux (MJ m^{-2} d^{-1}),

W_f is the wind function developed by Wright given by

$W_f = a_w + b_w u_2$ where a_w and b_w are empirical regression coefficients and u_2 is the wind speed (m/s) at 2 m height. (Gochis, 1998)

δe is the vapor pressure deficit.

The Kimberly-Penman method assumes alfalfa as the reference surface. The standard height of the alfalfa reference is 0.5 m (Allen et al., 1998, Allen et al., 2005,). Conversely, the standard height for green grass reference is 0.12 m. The height of the alfalfa reference crop has a significant interaction with aerodynamic turbulence of the surrounding atmosphere. (Gochis, 1998).

The Penman-Monteith and the 1982 Kimberly-Penman method have been recommended by Jensen et al. (1990) to calculate *ET* for daily and longer time periods based on reliable estimates produced over wide range of climatic conditions. But it is also stated in Allen et al. (2005) that 1982 Kimberly-Penman method was developed for the growing season and use outside this period is questionable.

2.1.4 Kristensen and Jensen Method

The ET model in MIKE SHE is derived from the work of Kristensen and Jensen (1975). This method simply adds the evaporation from canopy storage, the transpiration from the plants and evaporation from soil surface and updates the soil water balance. The potential evapotranspiration rate, E_p, is used by Kristensen and Jensen (1975). This should not be considered synonymous to reference evapotranspiration, ET_0. Empirical parameters C_1, C_2, C_3 and C_4 are used in the Kristensen and Jensen model.
The evaporation from the canopy is given by

$$E_{can} = \min(I_{\max}, E_p \Delta t) \qquad \textbf{eq 2.4}$$

Where E_{can} is canopy evaporation [LT^{-1}/day], I_{max} is the maximum interception storage capacity [L], E_p is potential evapotranspiration rate [LT^{-1}] and Δt is the time step length for the simulation.

The plant transpiration is given by the following equation:

$$\mathrm{E}_{\mathrm{at}} = f_1(LAI) \cdot f_2(\theta).RDF \cdot E_p \qquad \textbf{eq 2.5}$$

where,

E_{at} is the actual transpiration [LT^{-1}], $f_1(LAI)$ is a function based on the leaf area index (dimensionless), $f_2(\theta)$ is a function based on the soil moisture content in the root zone (dimensionless), and RDF is a root distribution function (dimensionless).

The function, $f_1(LAI)$, expresses the dependency of the transpiration on the leaf area of the plant.

$$f_1(LAI) = C_2 + C_1 LAI \qquad \textbf{eq 2.6}$$

where C_1 and C_2 are empirical parameters that influence the ratio of soil evaporation and transpiration (Kristensen and Jensen, 1975). The estimated value of C_1 for agricultural crops and grass is approximately 0.3. C_2 has an approximate value between 0 and 0.5. See Table 3.2. The second function is given by,

$$f_2(\theta) = 1 - \left(\frac{\theta_{fc} - \theta}{\theta_{fc} - \theta_w} \right)^{\frac{C_3}{E_p}}$$

eq 2.7

where,

θ_{fc} is the volumetric soil moisture at field capacity (dimensionless),

θ_w is the volumetric soil moisture at wilting point (dimensionless),

θ is the actual volumetric moisture content (dimensionless) , and
C_3 is the empirical parameter [LT^{-1}].

The larger the value for C_3, the higher will be the transpiration, assuming all other factors remain constant.

The evaporation from the soil surface is given as

$$E_s = E_p \cdot f_3(\theta) + (E_p - E_{at} - E_p \cdot f_3(\theta)) \cdot f_4(\theta) \cdot (1 - f_1(LAI))$$

eq 2.8

where,
E_p is the potential evapotranspiration,

E_{at} is the actual transpiration, and functions $f_3(\theta)$ and $f_4(\theta)$ are given by

$$f_3(\theta) = \begin{cases} C_2 & \text{for } \theta \le \theta_W \\ C_2 \dfrac{\theta}{\theta_w} & \text{for } \theta_r \le \theta \le \theta_W \\ 0 & \text{for } \theta \le \theta_r \end{cases}$$

eq 2.9

$$f_4(\theta) = \begin{cases} \dfrac{\theta - \dfrac{\theta_W + \theta_{fc}}{2}}{\theta_{fc} - \dfrac{\theta_W + \theta_{fc}}{2}} & \text{for } \theta \ge \dfrac{\theta_W + \theta_F}{2} \\ 0 & \text{for } \theta < \dfrac{\theta_W + \theta_F}{2} \end{cases}$$

eq 2.10

2.1.5 Reference Evapotranspiration

Reference evapotranspiration is the evapotranspiration considered from a surface that is not short of water (Allen et al., 1998). It is a standardized value used to estimate crop evapotranspiration by multiplying with a suitable crop coefficient, K_c.

$$ET_c = K_c \cdot ET_0 \qquad \text{eq 2.11}$$

where,

ET_c is the crop evapotranspiration,

K_c is the crop coefficient and

ET_0 is the short green grass reference evapotranspiration.

The crop coefficient can be defined as the ratio of crop *ET* to reference *ET*.

As discussed earlier, there are two crops used as reference evapotranspiration. Some methods use an alfalfa reference, ET_r (e.g. the Kimberly-Penman method) while others use a grass reference, ET_0 (e.g. the FAO 56 Penman-Monteith method). Choosing the appropriate crop coefficients for this study was confusing. Part of this confusion was brought on by a less than satisfactory application of crop coefficients in the MIKE SHE model, as will be described later. For systematic use of crop coefficients, the term "reference crop evapotranspiration" was introduced (Doorenbos and Pruitt, 1975, 1977; Wright 1982). Crop coefficients based on an alfalfa reference need to be multiplied by a conversion factor to be able to be used with a grass reference (Allen et al, 1998).

$$K_{c(grass)} = K \cdot K_{c(alfalfa)} \qquad \text{eq 2.12}$$

The conversion factors range from 1.0 to 1.3 depending on the climatic conditions. The conversion factors from FAO 56, page 133 are presented below.

Table 2.1 Conversion factors for crop coefficients for different climatic conditions as given in FAO 56 (Allen et al. 1998).

Climatic condition	Conversion from ET_0 to ET_r	Conversion from ET_r to ET_0
Humid, calm	1.05	0.952
Semi-arid, moderately windy	1.20	0.833
Arid, windy	1.35	0.741

In this project, the FAO 56 method has been applied. This method uses vegetation that is similar to short green grass as reference crop (ET_0). The crop coefficient represents an integration of the effects of the canopy characteristics that distinguish the crop from the reference surface (Allen et al. 1998). The reference vegetation is assumed as 0.12 m tall, has a fixed surface resistance of 50 s/m and an albedo of 0.23 (Allen et al. 1994a; Allen et al, 2005). ETo is therefore only a function of meteorological variables (Peacock and Hess, 2004).

K_c varies predominantly with the specific crop characteristics and only to a limited extent with climate (Allen et al, 2005). This helps with standardization of K_c values over regions and estimation of ET_c for that region. This is the primary reason why this method has been very successful. Additionally, Peacock and Hess (2004) showed that crop coefficients vary from day to day with meteorological conditions.

2.1.6 Crop coefficient (K_c) method

The crop coefficient method estimates evapotranspiration to be a proportion of the reference evapotranspiration grown under ideal conditions (Gonzalez et al., 2005). This method was designed for agricultural crops that that would ideally not have any water stress. However, due to its simplicity and popularity, studies have proposed the use of this method even for arid vegetation by taking into account the soil stress factor, K_s (Allen et al., 2005),

$$ET_c = K_s \cdot K_c \cdot ET_0 \qquad \text{eq 2.13}$$

This method has been criticized for use in arid regions (Gonzalez et al., 2005) due to complex issues accounting for water stress. Gonzalez et al. (2005) have shown that the assumptions of Allen et al. (2005) are meant for ideal crops with non-limiting soil water capacity, which is not ideally true for arid vegetation. This research will keep in mind of the issues outlined and reviewed in the Discussion section.

Wight et al. (1986) used the K_c method to estimate ET over a sagebrush-grass range site in southwestern Idaho using the ERHYM model. They used an alfalfa reference crop coefficient 0.85 to convert the Jensen-Haise based potential evapotranspiration (ET_p) to rangeland ET_p. This K_c value was determined from mixed prairie grassland in eastern Montana (Wight and

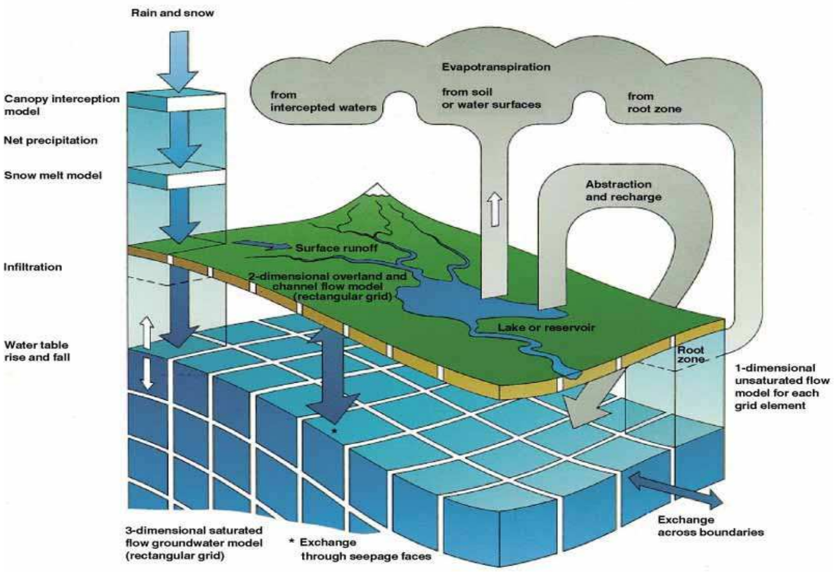
Hanks, 1981). The model gave a correlation coefficient (*r*) value of 0.98 compared to water-balance measured *ET* was and performed better than other models.

The crop coefficient method recognizes three main factors that affect evapotranspiration - meteorological conditions, crop characteristics and crop management.

2.2 MIKE SHE

2.2.1 Overview

The MIKE SHE (Systems Hydrologic European) simulation model is supported and distributed by the Danish Hydraulic Institute (DHI) with headquarters in Copenhagen, Denmark. MIKE SHE is a fully distributed water balance model for the land phase of the hydrologic cycle. It was first proposed as a blueprint for distributed hydrological modeling by Freeze and Harlan (1979) using the physics based representation of the underlying catchment processes. Water is input into the system in the form of precipitation or irrigation. After the canopy interception has been accounted for, the net precipitation either flows as overland flow or is infiltrated into the unsaturated zone as a 1–dimensional (vertical) flow for each grid element. On reaching the groundwater table, a 3-dimensional saturated flow groundwater model with rectangular grid elements models the spatial distribution of groundwater and exchange between boundaries including water bodies. The plant on the surface extracts water



from the root zone and transports water to the leaves where water is transferred to the atmosphere by transpiration. The soil and water surfaces also transport water by evaporation. The amount of water consumed during the growing season by evapotranspiration and infiltration is of interest to growers for irrigation system design and irrigation scheduling to optimize water use.

The MIKE SHE model is made up of a finite difference representation for solution of the theoretical partial differential equations of mass and energy balance, in addition to verified empirical relations (Xevi et al., 1997). The model can be applied to a single soil profile, e.g. for infiltration studies, up to regional watershed scales. It models hydrological processes such as interception, snow melt, infiltration, subsurface flow in the saturated and unsaturated zones, evapotranspiration, overland flow and flow in channels and in ditches.

2.2.2 Strengths of MIKE SHE

MIKE SHE supports a fully dynamic exchange of water between all the major hydrologic components including surface water, soil water and groundwater. It solves basic equations of flow processes within the study area. The spatial and temporal variability of meteorological, hydrological, geological and hydrogeological data across the model area are described in the finite difference grid for input as well as output. The solute transport, particle tracking, geochemical reactions, and advection-dispersion models allow for greater model flexibility and the opportunity to simulate various flow processes.

The model uses GIS data for spatial distribution and has a module to convert ArcGIS shape files (*.shp) into MIKE SHE shape files (*.dfs2). MIKE 11 is an open channel hydraulics model also supported by DHI that can be integrated with MIKE SHE to model a river basin for floods and rainfall-runoff analysis.

2.2.3 Research done on MIKE SHE

MIKE SHE has been applied to numerous hydrologic research projects around the world. It was applied in the 15,000 km^2 Narmada River basin in India within an Indo-European cooperative project aimed at transferring the SHE technology to the National Institute of Hydrology (NIH), India (Refsgaard et al. 1992; Jain et al. 1992). MIKE SHE was coupled with MIKE 11 to run hydraulic simulations. Uncertainty of the simulation output was reported due to the uncertainty of input rainfall data. The results of MIKE SHE – MIKE 11 coupling and simulation gave similar results as simpler runoff prediction models, but in addition yielded results on the impact of topography, soil, vegetation, and geology on hydrologic processes.

Table 2.2 Surface runoff as a function of vegetation cover (by varying root depth and *LAI*) on the Kolar subcatchments of the Narmada River in India. (Jain et al., 1992)

Vegetation cover	1986	1987	1988
Agricultural	805	90	180
Dense Forest	770	85	130

Xevi et al. (1997) did sensitivity analysis of the Kristensen and Jensen parameters, C_1, C_2, C_3, *Aroot*, varying one parameter at a time within the feasible limits. An approximately 1 square kilometer Neuenkirchen catchment in Germany was modeled and the root mean squared error (RMSE) and coefficient of determination (CD) were used to compare the accuracy of simulated vs. observed runoff data. The model was calibrated and then run to simulate hydrographs at the catchment outlets. The C_2 and C_3 parameters affected the peak overland flow while changes in C_1, *Aroot* and C_{int} showed limited effects. See Appendix IV for the results of the sensitivity analysis.

2.2.4 Software

The MIKE SHE software was made available by agreement with DHI and supported by the DHI office in Portland, OR. The latest version and the one used for the research is the 2007 DHI version. Details and information about other DHI software can be found at the website www.dhigroup.com.

2.3 Natural Vegetation

The vegetation found in the Wet Meadow 14-40 (NRCS plant association) over the research site in Sprague River Basin is 60 percent tufted hairgrass, 5 percent Baltic rush, 5 percent Nebraska sedge, 5 percent northern mannagrass, and 5 percent reedgrass (SSURGO v2.2 database). Oragne arnica, silverweed and small bedstraw are typical forbs of more mesic sites.

On the drier ranges of the site, Nevada bluegrass, creeping wildrye, western yarrow and rose pussytoes are subordinate to tufted hairgrass (NRCS Ecological Site Description). When there is overgrazing, tufted hairgrass becomes co-dominant with other grasses, sedges and forbs. With overgrazing on soils having a mesic soil temperature regime, Nebraska sedge could become dominant. With a lowering of the water table, Kentucky bluegrass can become co-dominant. The total annual productivity of Sprague subbasin is indicated in the figure below.

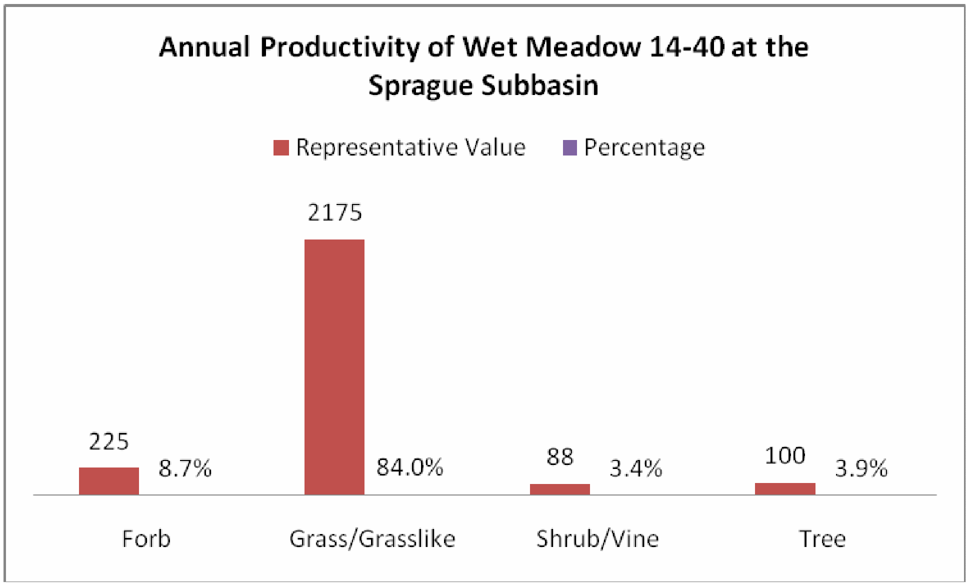


Figure 2.1: Annual Productivity of Wet Meadow 14-40 PZ, Site ID: R021XY406OR, major land resource area: 021 – Klamath and Shasta Valleys and Basins: Resource: USDA NRCS Ecological Site Description

Other types of vegetation were tested to evaluate how well MIKE SHE simulated evapotranspiration. Wetland vegetation species duckweed and cattail, natural vegetation like big sagebrush, juniper and ponderosa pine were used in this evaluation as well as maize and pasture for testing the irrigation component.

2.3.1 Wetland vegetation – Duckweed and Cattail

Wetlands represent an environment inundated by surface or groundwater at a frequency and duration sufficient to support vegetation typically adapted for life in saturated soil conditions. They typically include swamps and marshes. Wetland acts as an interface between terrestrial ecosystems and aquatic systems (Mistach and Gosselink, 1986).

Common duckweed (*Lemna minor* L.) is a perennial wetland plant that is native to the U.S. The active growth is in summer and the average rooting depth is about 1 inch (25.4 mm) (plants.usda.gov). The anaerobic tolerance is high while calcium carbonate tolerance is medium. A minimum of 100 frost free days is required to keep the plant alive and it can survive at a minimum temperature of -38 deg. F.

2.3.2 Tufted hairgrass

Tufted hairgrass [Deschampsia caespitosa (L.) Beauv.] belongs to the grass family that grows early in spring and flowers from July to September. Its seeds mature from August to September and it reproduces from seeds and litters. It is a type of vegetation native to the U.S. whose forage is excellent for livestock and produces good quality hay (Stubbendieck et al., 1997).

Tufted hairgrass comprises 60 percent of the vegetation cover over the Klamath-Ontko-Dilman association soil type (SSURGO database, NRCS) where the study site is located.

2.3.3 Sagebrush

Big sagebrush (*Artemisia tridentata*) is a shrub or a small tree native to the U.S. It grows as tall as 3 m (10 ft), typically 1-2 m tall. The leaves are wedge shaped and about 1 to 4 cm long and 0.3 to 1 cm wide. The leaves have fine silvery hair which keeps the leaves cool and minimizes transpiration. Flowering occurs in late summer or early fall. Big sagebrush has high drought tolerance and requires a minimum of 90 frost free days to survive. It can survive temperatures down to – 41.7 °C (- 43 °F) (plants.USDA.gov).

Wight (1970) showed that low sagebrush (*A. tripartite*) responded the same as big sagebrush treated to clipping in mid-summer (Tisdale and Hironaka 1981). This information will help in comparing the results of the simulation.

2.3.4 Juniper

Juniper (*Juniperus* L) is a plant that is known for its invading characteristics. It grows in environments where sagebrush is found and sucks in water from its shallow but dense rooting system. The water used by juniper restricts that available for neighboring plants. Land restoration projects have been considered in the Klamath River basin and its major tributaries to promote sagebrush by removal of western juniper (Kuhn et al., 2007). Juniper is a high water demanding vegetation and replacing it with a low water use plant community is a strategy to reduce plant related water consumption (Hibbert, 1983). However, the removal of less than 20 percent of the vegetation would not yield detectable changes in stream flow (Bosch and Hewlett, 1982).

Table 2.3 Percent of water consumed by *ET* for Juniper. Table from Timothy et al. 2007.

Research	Vegetation type	*ET* (percent of annual precip.)
Gifford (1975)	Pinyon-juniper	63-97
Lane And Barnes (1987)	*Junipers osteosperma* and *Juniperus deppeana*	80-100
Thurow and Hester (1997)	*Juniperus pinchottii* and *Junipeus ashei*	100

2.3.5 Ponderosa Pine

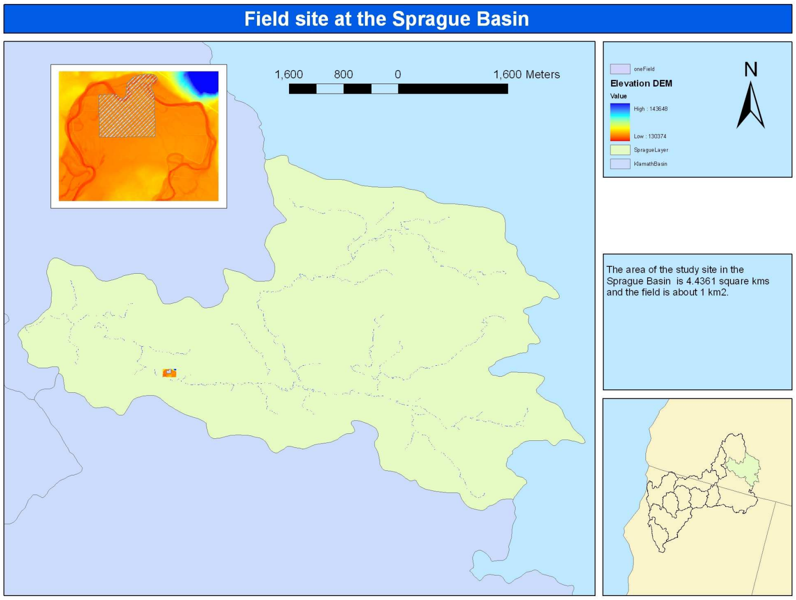
Ponderosa pine (*Pinus ponderosa*) is a large tree that lives 300 to 600 years and reaches heights of 30 to 50 m with diameters of 0.6 m to 1.3 m. The older ones can be higher than 70 m with diameters greater than 2 m (NRCS National Plants Data Center).

3 SITE DESCRIPTION AND MODEL SETUP

3.1 Site description

The Sprague River Subbasin of the Upper Klamath Basin is located 40.2 km (25 miles) northwest of Klamath Falls and covers approximately 4,128 sq km (1.02 million acres) mostly covered by juniper and sagebrush steppes rangelands. The land use in the valley floor is typically irrigated pasture. Approximately 65 percent of the water for irrigation is from streams and 35 percent is from wells. Surface water spreading is the most common form of irrigation. Private forest and rangelands are used for livestock grazing. The forest stands are significantly overstocked with timber while the rangeland has been encroached by Western juniper. The wildlife is fairly stable in the upper reaches while the lower portion of the valley would benefit from habitat improvement. Water quality degradation has impacted fish and wildlife habitat and has been a major concern in the Sprague River subbasin.

The study site is located in the Sprague River Basin, on the Oregon side of the Upper Klamath Basin (-121. 5387, 42.4837).



The area of the study site in the Sprague Basin is 4.4361 square kms and the field is about 1 km2.

Fig. 3-1: Sprague River Basin and the study site in inset. The Sprague River Basin is a subbasin of Klamath River Basin.

3.1.1 Geology and Soils

The USGS definition of soil type in the study area is Klamath-Ontko-Dilman association, soil type 34, with 55, 30 and 15 percent coverage of Klamath, Ontko and Dilman, respectively (USGS.gov). These are poorly drained, nearly level soils on flood plains. They formed in alluvium that has varying amounts of volcanic ash (SCS Soil Survey Report 1985). Elevation ranges from 1,262 to 1,341 m.

The soil is in three layers, the top layer, the middle layer and the lower layer as outlined in the table below. The association is about 55 percent Klamath soil, 30 percent Ontko soil and 15 percent Dilman soil. Klamath soil is dominant in the experimental field site as it lies adjacent to the streams (SCS Soil Survey Report, 1985).

Typically, the Klamath soil has a surface layer of very dark gray and black silty clay about 28 cm thick. The subsoil is a black silty-clay that extends to a depth of about 71 cm. The substratum is mottled, dark gray, very dark gray and dark grayish brown silty clay and silty clay loam to a depth of about 152 cm (SCS Soil Survey) where it has contact with the bedrock.

The Klamath soil has low permeability. The water table is at a depth of 0 to 91 cm during winter and 91 to over 1.83 m during the dry season.

Table 3.1 Soil classification Klamath of the Klamath-Ontko-Dilman association as provided in the SSURGO v. 2.2 database[1].

Map Symbol	Soil Name	Layer	Texture	Depth(cm)		Moist bulk density (g/cm^3)		Hydraulic Conductivity (m/s)	
			(NRCS)	lower	upper	lower	upper	low	upper
34	Klamath	upper	Silty Clay	0	28	0.6	0.9	4.23E-08	1.411E-07
		mid	Clay, Silty Clay	28	71	1.3	1.4	4.23E-08	1.411E-07
		lower	Clay loam, silty clay, silty clay loam	71	152	1.2	1.4	4.23E-08	1.411E-07

Roots commonly penetrate to a depth of more than 152 cm. The surface layer has high organic matter content. Runoff is very slow, and the hazard of erosion is slight except during

---

[1] SSURGO database is the web soil survey database provided by the NRCS at http://websoilsurvey.nrcs.usda.gov/app/

periods of flooding when channeling occurs. Available water capacity is about 28 to 41 cm (SCS soil survey).

This soil is suited for sprinkler and border irrigation. Because of the high amount of clay in the surface layer, the soil needs to be tilled within a narrow range of soil moisture content. Spring cultivation can be delayed by wetness.

3.1.2 Vegetation

The Klamath-Ontko-Dilman association soil type is suitable for native hay and pasture. A few areas that are partly drained and protected by dikes are used for cereal hay. Alfalfa hay is suited to areas where the soils are adequately drained and protected from flooding.

The vegetation composition is approximately 85 percent grass, 10 percent forbs and 5 percent shrubs. The dominant grass is tufted hairgrass (Deschampsia ceaspitosa) (NRCS ecological site description) with annual production of between 567.0 kg to 737.1 kg (1,250 lbs – 1,625 lbs). The sub dominant species are reedgrass, Baltic rush, Nebraska sedge and northern mannegrass. Please refer to Appendix II for more details.

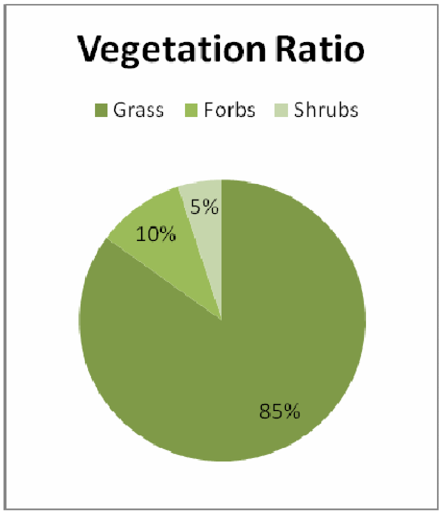


Figure 3.1: Vegetation ratio of the Klamath-Ontko-Dilman soil association.

3.1.3 Climate

The average annual precipitation is 381 to 257 mm (15 to 18 inches) (SCS 1985) and average annual air temperature is 18.0 to 23.4 °C (42 to 45 °F), and the frost free season is 50 to 70 days long. Floods are frequent in this field from March to May and the high water table is in the range from 0 - 0.91 m above the surface. The bedrock is at about 1.52 m depth.

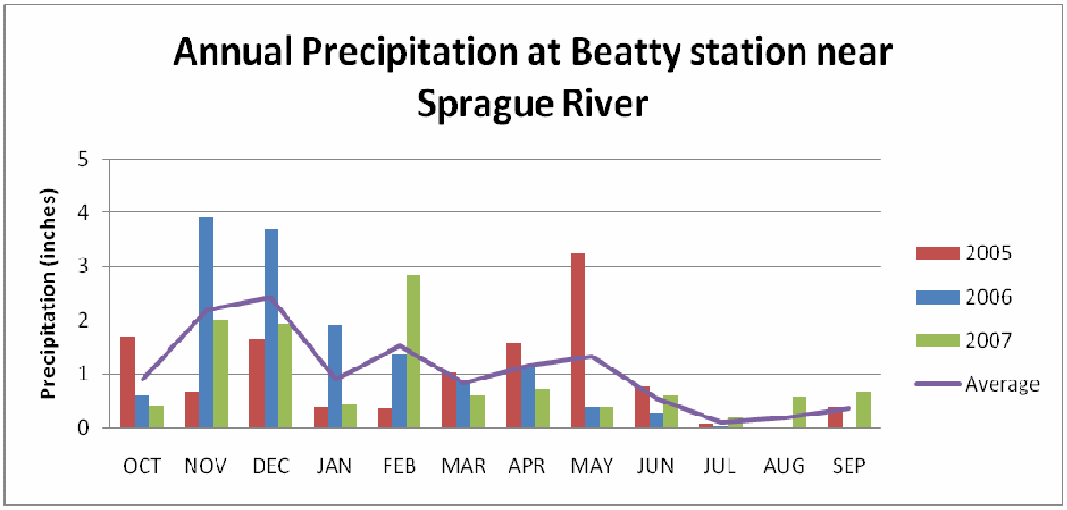


Figure 3.2: Annual Precipitation at Beatty near Sprague River averaged over the last three water years. The data are made available from the AgriMet weather station network database.

3.2 Data Collection

The model was setup for the growing season of 2005. The AgriMet weather station network was a major data source. Precipitation and reference evapotranspiration data were collected from the AgriMet Beatty station close to the study site. The evapotranspiration for the alfalfa reference crop was converted to grass reference to be able to compare with the Kristensen and Jensen method (Kristensen and Jensen, 1975). The digital elevation model (DEM) was provided by Mark Everett from the NRCS. The soil data spatial map as well as soil depths were collected from the SSURGO version 2.2 database for the Klamath County available through the NRCS website as well as the Soil Survey report of 1985 (Cahoon et al., 1985). The crop coefficients and leaf area index were taken from the FAO 56 Crop Evapotranspiration guide (Allen et al., 1998).

3.3 Model setup

This section steps through the setup of the MIKE SHE model so that it can be duplicated by another user. It is assumed that the reader has MIKE SHE software to understand the setup more practically.

3.3.1 General Setup

The model was setup for a 1,000 m by 1000 m grid cell with no spatial variation of vegetation or soil properties. The site was chosen such that there was limited variation in topography and data were available for the site in the NRCS soils database. Setting up such a 1-D model resulted in the ability to run simulations for various scenarios efficiently in terms of time. The simulation was run to focus on variation in results from the unsaturated flow (UZ) and the evapotranspiration (*ET*) modules.

The general specifications needed for model setup are display map layers, simulation specification, model domain and grid, topography, precipitation, land use, evapotranspiration, unsaturated flow, groundwater table, and how the output results are to be stored.

3.3.1.1 Display

The default map of the model domain is used, so this step can be skipped.

3.3.1.2 Simulation specification

On the simulation specification, only the unsaturated zone (*UZ*) using the full Richards equation (Richards, 1931) and evapotranspiration are selected. Either the Richards equation or the gravity flow option needs to be selected to calculate grid cell soil moisture in the soil profile unsaturated zone.

The simulation title is given and the simulation period is selected from start date to end date. The time period varies for each simulation as some growing periods are longer than others. Grass and other perennial natural vegetation could be simulated for the whole year. But if a longer period is selected, any other time series files added to the simulation has to cover this longer period.

3.3.1.3 Time step control

The initial time step of 1 hour and the maximum allowed UZ time steps of 6 hours are used here but they can be tuned according to the model requirements. The simulation starts at the initial time step and would not go beyond the maximum. The maximum precipitation depth of 100 mm is used for a given time step. The time step is reduced if the actual rainfall is greater than 100 mm within one period. For example, if the time step was 6 hours and if there was 110 mm of precipitation in 6 hours, the time step will be reduced by the increment factor (0.05) until the rainfall within the period is less than 100 mm. This is automated so that the numerical stability is improved, but can lead to excessively small time steps during big events.

The simulation periods for this project were from 01 April 2005 to 01 August 2005 for maize and from 01 April 2005 to 01 April 2006 for grass and other vegetation types.

3.3.1.4 UZ computational control parameters

The values used in this computation were set to the default values. The maximum profile water balance error is 0.001 m. The full Richards solution was set to have 100 iterations maximum and a stop criterion of 0.002. The time step reduction control for maximum water balance error in one node was set at 0.03.

3.3.2 Model Domain and Grid

A 1-D model was setup using the create button with a specified grid size and origin. The inner point-outer point method was chosen for the contents and the cell size specified as 1,000. The NX and NY was specified as 3 and the initial (X0,Y0) specified at the origin (0,0) with the final distance (NX,NY) specified as (3,3). All units are in meters. This setup produces the grid shown below.

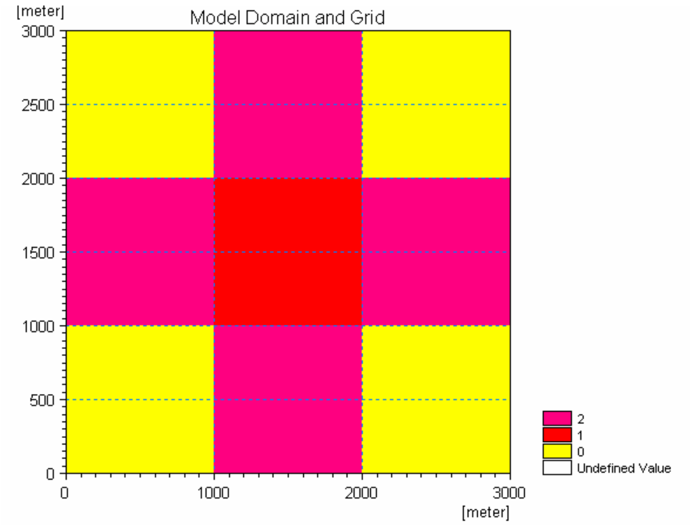


Figure 3.3 Model domain and grid size of 1,000 m by 1,000 m in MIKE SHE model setup

3.3.3 Topography

The topography was set to have a uniform spatial elevation of 1,307.6 m (Caldwell property, standpipe piezometer location #12, NRCS). Topography defines the upper boundary of the model and is used as the upper elevation for evapotranspiration. Since this setup is only 1-D, there is no variation in elevation in space and hence no horizontal gradient.

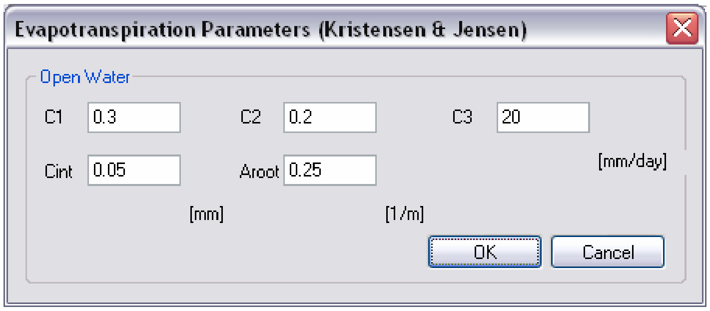
3.3.4 Precipitation

The snowmelt module was included in this setup. The simulation for the growing season may involve freezing during the winter for simulation of perennial crops. Two other inputs, the time-distributed air temperature and the snowmelt constants are required for the snowmelt module. The temperature data from the AgriMet database for Beatty station was added as a dfs0 file. The snowmelt degree day factor of 2 mm/day/°C and a threshold temperature of 0°C were used.

3.3.5 Vegetation

In the main dialog of the land use section, the irrigation is checked or unchecked according the model setup. In this project, irrigation was not used in the natural vegetation simulation.

The vegetation property file is setup using the *ET* vegetation document type available in the MIKE SHE file category. The crops and vegetation used are defined in one *.etv file. Each type can have its own irrigation definition. Default values of *ET* parameters can be chosen or modified according to research needs. In this research, default values of *ET* parameters were applied. They are given in the following window in the model. Also, see Appendix I.



Evapotranspiration Parameters (Kristensen & Jensen)

Open Water

C1 0.3

C2 0.2

C3 20

Cint 0.05

Aroot 0.25

[mm/day]

[mm]

[1/m]

Figure 3.4: The Kristensen and Jensen evapotranspiration parameters default values.

The Kristensen and Jensen method (1975) used by MIKE SHE will be compared to the *ET* obtained from the AgriMet database that uses the Kimberly Penman method (Wright 1982).

The acceptable range of values for Kristensen and Jensen (1975) parameters are given by Vazquez and Fayen (2003) as listed below.

Table 3.2 Physically acceptable Kristen and Jensen parameter ranges as used for calibration by Vazquez and Fayen (2003).

Model parameters	Intervals	
	lower	upper
Cint	0.01	1
C_1	0.01	1
C_2	0.05	0.5
C_3	5	40
Aroot	0	5

Each defined crop in a vegetation property file consists of a stage name and the number of days within that stage. Each stage will further have a row with *LAI*, root depth (mm) and K_c definition. These values are chosen from the reference text or field data. Individual vegetation files are discussed in their relevant sections. The period of vegetation growth has to cover the simulation period. If the plant is cut after a certain period, bare soil vegetation or an after-cut vegetation selection has to be added until the simulation period is covered.

3.3.6 Reference Evapotranspiration

A time series file (*.dfs0) for reference ET (ET_0) is created in MIKE ZERO, a common interface for all DHI software. The reference ET from AgriMet database was converted into grass reference ET by multiplying the factor of 0.833 for the semi-arid regions (Jensen et al., 1990, Allen et al., 1998).

$$ET_0 = 0.833 \cdot ET_r \qquad \text{eq 3.1}$$

where,

ET_0 is the grass reference ET,

$K = 0.833$ is the conversion coefficient, and

ET_r is the alfalfa reference ET.

ET_r was obtained from AgriMet database which uses Kimberly Penman method (Wright, 1982). A dfs0 file was created with the ET_0 values and linked to the model. The reference ET is satisfied by the model in the following order: 1) Evaporation is first deducted from the interception storage assuming potential ET; 2) Further evaporative demand is satisfied by water evaporation from ponded water until it is exhausted; 3) Additional evaporative demand is met from water removed from the unsaturated zone (UZ) until potential ET is satisfied or the minimum soil water content is reached. If there is additional evaporative demand remaining, it is satisfied from saturated zone. The amount of water extracted from the saturated zone (SZ) is dependent on the depth of the ground water table as described by the MODFLOW ET package (MIKE SHE manual DHI 2007) and is not dealt with in this study.

3.3.7 Overland flow

The overland flow is observed for the irrigation simulation. Manning's M from the overland flow is set to 10 $m^{1/3}$ s^{-1} (Mannings M is the inverse of Mannings n, the roughness coefficient.). The detention storage and the initial water depth were both set to zero.

3.3.8 Unsaturated Flow

Calculation in all grid points was chosen for this simulation to avoid groundwater depth classification. Since this is a 1-D model, it was not time consuming to calculate the soil moisture content in every grid cell. A uniform spatial soil profile distribution was chosen. Soil properties were defined in a different file format provided by MIKE SHE called UZ soil properties file (*.uzs). On defining a new soil type, methods for calculating the retention curve and hydraulic conductivity need to be specified. In this project, the van Genuchten method was used for both. The van Genuchten parameters and other soil properties are given in the following table. The soil as described in section 3.1, belongs to the Klamath-Ontko-Dilman association. The soil at the site mostly consists of the Klamath type, which is a silty clay (USDA texture) in the top layers mixed with clay loam and silty clay loam in the bottom layers. The selected values for the soil water retention and hydraulic conductivity parameters for silty clay were taken from Carsel and Parrish (1988) from the class notes of BRE 512 (Physical Hydrology, Cuenca, 2006).

Table 3.3 Van Genuchten parameters and other properties of retention curve for silty clay soil , NRCS soils type for Klamath soil.

Parameter	Symbol		Reference
Saturated moisture content	θs	0.36	Carsel and Parrish (1988)
Residual Moisture Content	θr	0.07	Carsel and Parrish (1988)
Moisture content at Field Capacity (cm/c m)	θ_{fc}	0.359	Brady et al. 2001, pg 145
Moisture content at Wilting Point , (cm/c m)	θ_{w}	0.338	Brady et al. 2001, pg 145
Capillary pressure at field capacity	pF_{fc}	2.477	$\text{Log}_{10}(\theta_{fc})$
Capillary pressure at wilting point	pF_{w}	4.176	$\text{Log}_{10}(\theta_{w})$
Empirical constants			
alpha (1/cm)	α	0.01	Carsel and Parrish (1988)
n	n	1.09	Carsel and Parrish (1988)
Mualem m = (1-1/n)	m	0.0826	Mualem (1976)
Saturated Hydraulic Conductivity (m/s)	K_s	-9.17E-08	SSURGO database – Klamath Soil
Shape factor	l	0.5	

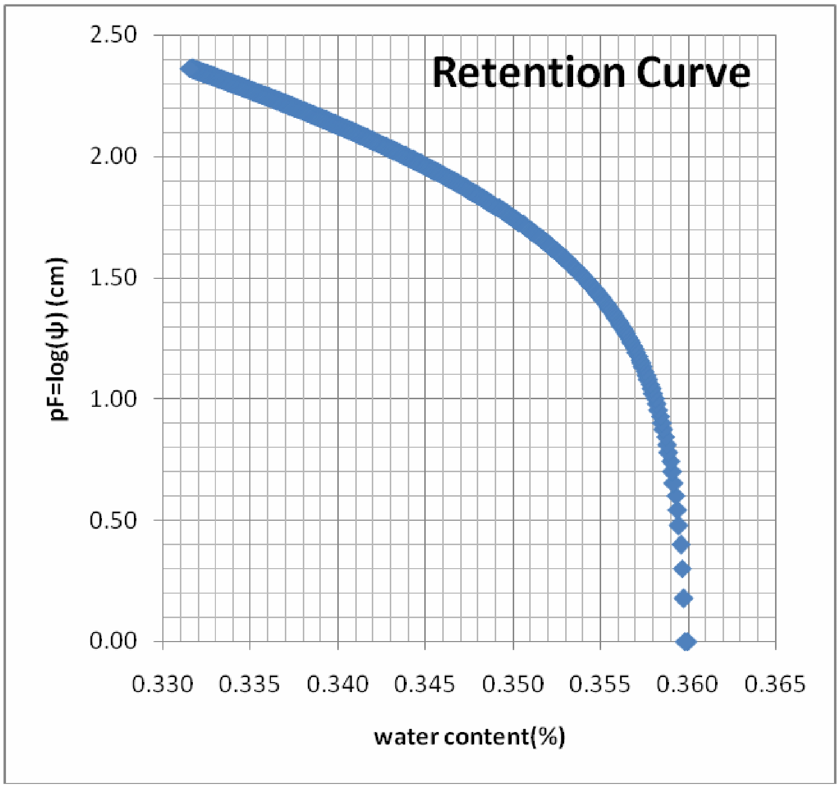


Figure 3.5 Retention curve using the values stated above.

There are 16 vertical grid cells defined in this soil model, 4 in the top layer, 6 in the mid layer and 6 in the bottom layer.

Table 3.4 Vertical discretization of Klamath soil.

from depth (m)	to depth (m)	cell height (m)	no. of cells
0	0.28	0.07	4
0.28	0.70	0.07	6
0.70	1.54	0.14	6

3.3.9 Groundwater table

The groundwater table was varied to test the response of the model. The groundwater under the soil name Klamath of the Klamath-Ontko-Dilman association (Table 3.1), varies from 0 - 0.91 m (0 to 3 ft) during the flooding season to greater than 1.83 m deep (6 feet) during the dry season (SSURGO, Klamath Soil). Brief floods occur frequently, according to the database. MIKE SHE setup without the saturated zone does not have the temporal data output for the water table.

3.3.10 Storing of results

The water balance results are stored in a sub-folder. The time interval of results could be changed as required. In this study, 24-hour output was chosen for overland flow and precipitation and for the unsaturated zone (UZ), *ET* and saturated zone (SZ) models.

Detailed actual evapotranspiration from MIKE SHE was compared with the ET_c calculated by multiplying the crop coefficient times the *ET*o obtained from the AgriMet database (Kimberly Penman method). The other types of output chosen were the water content in the unsaturated zone, infiltration to UZ, and precipitation rate.

More grid series outputs can be chosen from the check list in the Grid Series output page.

3.4 MIKE SHE setup for irrigation types

The conventional irrigation method used is flood irrigation. Since water resource allocation in the Klamath Basin has been a concern in the recent years, optimizing water use for irrigation has been a priority. MIKE SHE defines flood irrigation as “sheet” irrigation. Sheet irrigation needs a source at a higher elevation to flow over soil at a lower elevation. Since the model here is only 1-D there is no slope factor, but water can still be applied as flooding.

The irrigation demand values can be specified for each vegetation type in the vegetation property file. In this case the “Include Irrigation” option is checked. Another method is to define irrigation in the flow model description. In the setup for this project, the latter method was selected so that comparison can be made for different methods. The only two vegetation types in this project that used the irrigation component were grass and maize.

There are three types of irrigation methods used in MIKE-SHE. They are sprinkler, drip and sheet. In this project, only sprinkler was used. The irrigation demand was initially set to 5 mm/h for a time step of 2 hours. This was later changed to a time step of 12 hours when additional application was required. The time step has to be a whole number integer.

3.4.1 Sprinkler design

In the sprinkler design, the input water is considered as an addition to precipitation (DHI 1995). The results below indicate the evaporation and transpiration components of actual *ET* obtained from the simulation of 5 mm/h for 2 hours over the period of 10 days.

3.4.2 Drip

In drip design, the water is added to the surface or directly to the root zone thus saving water and fertilizers and eliminating the effects of canopy coverage. Drip irrigation has been shown to shorten time to maturity and increase crop yield while saving crops from salt damage (Goldberg and Shmueli, 1970). This method is used for application of fertilizers by irrigation and high usage helps maintain low salt levels in the root zone (Mmolawa and Or 2000).

3.4.3 Sheet

Although specified as Sheet irrigation in MIKE SHE, this method is also known as flood, or furrow or surface irrigation. If properly designed, very high uniformity of irrigation can be obtained with this method. This method has the lowest energy costs compared to other methods and so is widely used in developed as well as developing countries. The water is applied to the soil surface and infiltrates into the subsoil as it moves to the lower elevations. The speed of application and the volume added is the key to the adequacy and efficiency of this type of irrigation (Cuenca, 1989).

3.4.4 Irrigation Command and Demand

The irrigation command and demand can be setup in various ways in accordance to model needs. The maximum rate of external source for irrigation is set to 100 m^3/s. A license for use of water can be provided too so that no water is used beyond the permitted capacity. Maximum allowed deficit with field capacity was used to automate irrigation. The automation was conducted such that the soil moisture would always be kept between ranges of certain percent deficit. For example, for simulation of maize, the moisture deficit start was at 20 percent and deficit end was at 0 percent, with reference to field capacity. In this way the irrigation would be used when the soil is 20 percent dryer than the field capacity until field capacity was reached.

3.5 MIKE SHE setup for *ET* estimation for vegetation types

MIKE-SHE has a vegetation component listed under land-use component. A spatial file can be either a uniform file (*.dfs0) or a spatially distributed (*.dfs2) file. A constant value, a time series file or an vegetation file (*.etv) file can be used to input leaf area index (*LAI*) and root depth (RD) values. For simplicity, an *.etv file was created that has different vegetation types with their corresponding RD and *LAI* for defined periods.

At the Sprague River basin site, different vegetation scenarios were simulated using parameter values from the literature. Different growing scenarios of wetlands, natural vegetation and crops with irrigation were setup to evaluate the differences in *ET* estimation.

3.5.1 Duckweed

The crop coefficient (K_c) of 1.05 was used as per Doorenbos and Pruitt (1977) . If 100 percent of water surface was covered, then, K_c would be 0.9 to 0.95 (Borrelli et al.,1998) The leaf area index (*LAI*) values were taken to be 2.25 for the first 5 days of growth and then 7 for the rest of the vegetation period (Brutsaert 2005).

Table 3.5 Vegetation property file setup for common duckweed

Stages	Date begin	Days	Day end	Date end	*LAI*	Root depth (mm)	K_c
initial	4/1/2005	5	5	4/6/2005	2.5	25.4	1
growth	4/7/2005	50	55	5/27/2005	6.0	25.4	1.15
late	5/28/2005	500	555	10/10/2006	6.0	25.4	1.15
Reference					Brutsaert, 2005	NRCS	Doorenbos and Puritt, 1977

3.5.2 Cattail

Broadleaf cattail (*Typha latifolia*) is a perennial plant that is native to United States. It grows actively during the season from April to Sept. The C:N ratio is high and the average height of the mature plant is 1.5 m (5 ft) while being about 3 cm in width and growing in clusters of about 10. The root stalk is often found under saturated soil water conditions. The minimum

rooting depth is about 356 mm (14 inches). The blooming period is late spring with high seed abundance in summer (USDA.gov).
The model was run for the growing season of 2005 using the values of *LAI*, K_c and root depth shown in the table below. The values were taken from FAO 24 (Doorenbos and Puritt, 1977) and FAO 56 (Allen et al., 1998). The mean measured *ET* in an experiment in 9 different stations in the Everglades in Florida gave a measured value of 3.85 mm/day (Deras and Hall 2006)

Crop coefficient curves were developed for broadleaf cattail by greenhouse experiments. (Towler et al., 2004). The FAO 56 method was used and a linear equation of the ratio of ET_c/ETo and ratio of vegetative surface over open water surface (S_v/S_0) was developed. The mean ET_c for the growing season was obtained as 7.96 mm/ day.

Table 3.6 Vegetation development stages of cattail.

Stages	Date begin	days	day end	Date end	*LAI*	Root	K_c	Ref.
initial	5/1/2005	10	10	5/11/2005	2.0	200	0.6	FAO 56
development	5/12/2005	30	40	6/11/2005	3.0	355	1.2	FAO 56
mid	6/12/2005	80	120	8/31/2005	3.6	400	1.2	FAO 56
late	9/1/2005	20	140	9/21/2005	3.0	400	0.6	FAO 56

The *.etv file used in MIKE SHE was varied over time and growing period as per the guidelines of FAO 24 (Doorenbos and Puritt, 1977) and FAO 56 (Allen et al., 1998).

3.5.3 Big Sagebrush

Different varieties of sagebrush are found in the Sprague River basin and the one chosen for this project was big sagebrush (*A tridentata*) . Flowering usually occurs around September and ripening occurs from late October to early November (Tisdale and Hironaka, 1981).

The root system extends 1 to 2 meters deep with a lateral spread of 1.5 m. *A tridentata* roots are known to have high oxygen requirements (Lunt et al. 1973). The rooting depth of 1,800 mm (Canadell et al., 1996 ; Reynolds and Fraley 1989) and leaf area index of 0.72 (Flerchinger et al. 1996) were used. The crop coefficient values are shown in the table below.

Table 3.7 Vegetation development stages of big sagebrush *A. tridentate.*

Stages	Date begin	days	day end	Date end	*LAI*	Root	K_c
initial	4/1/2005	5	5	4/6/2005	0.72	1800	0.8
development	4/7/2005	20	20	4/27/2005	0.72	1800	1.2
mid	4/28/2005	60	60	6/27/2005	0.72	1800	1.2
harvest	6/28/2005	1000	1000	3/24/2008	0.72	1800	1.2

3.5.4 Juniper

The types of juniper found in Oregon, according to plants.USDA.gov, are common juniper (*Juniperus communis*) , western juniper (*Juniperus occidentails*), Rocky Mountain juniper (*Juniperus scopulorum*) and eastern red cedar (*Juniperus virginiana*). Common Juniper is a shrub or small tree that could reach 10 m in height and spreads up to 8.5 m in diameter. It has needle like leaves.

A study conducted in 2006 at the Freemont National Forest in Oregon revealed that the growth of juniper and Ponderosa Pine are highly dependent on winter and spring rains that recharge ground water (Kevin C. Knutson, http://hdl.handle.net/1957/889). Juniper and pine radial growth at sites with less water capacity are sensitive to future droughts and climate fluctuations.

The canopy cover plays a significant role in interception losses. The canopy cover of 20 percent to 30 percent accounts for interception loss of 51 to 76 mm (2 to 3 inches) per year, respectively (OSUES 1993).

The evapotranspiration rate of junipers vary considerably and researchers have focused on evapotranspiration from individual trees rather than on a watershed scale (Kuhn et al., 2007). The types of interception are canopy interception, litter interception, throughflow (leaf drip) and stem flow.

Juniper exhibits similar interception rates as big sagebrush (*Artemisia Triden*tata), which is a dominant plant where juniper grows. According to a study by Kuhn et al. (2007), changes in the vegetation surfaces of juniper and sagebrush due to juniper encroachment and then removal showed that there was no significant improvements in water yield in the Klamath

Basin. Some varieties of juniper are evergreen and can drain water from the entire soil profile, so water loses via transpiration are substantial.

Table 3.8 Vegetation property file for 10 year old juniper

Stages	date begin	days	day end	date end	*LAI*	Root	K_c
initial	4/1/2005	5	5	4/6/2005	0.7	660	0.95
development	4/7/2005	20	20	4/27/2005	0.7	660	0.95
mid	4/28/2005	60	60	6/27/2005	0.7	660	0.95
harvest	6/28/2005	1000	1000	3/24/2008	0.7	660	0.95
reference					Eddleman et al. 1994		FAO 56 (Conifer)

3.5.5 Maize

Maize is a seasonal crop that is planted in mid-April. Information about the plant is readily available. This was a good test for the Kristensen and Jensen *ET* compared to the *ET* calculated using the crop coefficient method with the AgriMet Kimberly Penman. The field is initially tilled with bare soil by adding a defined vegetation property file that has some properties. This is done so that when the planting starts, the soil already has some moisture due to natural rainfall or snowmelt.

Table 3.9 Vegetation property file for corn grown for grain .

Stages	Date begin	days	day end	Date end	*LAI*	Root (mm)	K_c
bare soil	1/1/2005	89	-89	3/31/2005	3	1000	0.35
initial	4/1/2005	30	30	5/1/2005	0.9	400	0.5
development	5/2/2005	30	60	6/1/2005	4	1000	0.8
mid	6/2/2005	30	90	7/2/2005	4.5	1600	1.2
harvest	7/3/2005	35	125	8/7/2005	4	1600	0.35
Reference					FAO 56	FAO56	FAO56

3.5.6 Ponderosa Pine

The maximum root depth of Ponderosa pine is 3.5 m (Candell et al., 1996), while the model soil profile is only 1.52 m deep. This created an error in MIKE SHE. The roots were cut to 1.52 m to fit the model grid cells. The *ET* results showed that the root system did not extract enough water for transpiration. The model was tested with irrigation. Sprinkler irrigation was turned on automatic for a soil moisture deficit for 60 percent of field capacity and continued until the field capacity was met. This created a steep climb in the water content in the root zone and steep drop after that because all the moisture was extracted by the plant and transpired.

3.5.7 Grass

Tufted hairgrass (*Deschampsia caespitosa (L.)* Beauv.) is the most commonly found grass at the research site under the soil association number 34. 60 percent of the vegetation over the Klamath-Ontko-Dilman Association soil is tufted hairgrass (USDA survey 12/22/2006, SSURGO database).

Tufted hairgrass is a perennial plant and is native to the U.S. It starts growing early in spring and flowers from July to September. Seeds mature from August to September (Stubbendieck et al., 1997). The re-growth after harvest is moderate. It grows in bunches with a moderate growth rate up to a height of 1.03 m (3.4 feet) A minimum of 100 frost free days is required and it uses less moisture compared to other vegetation. The precipitation requirement is between 122 mm to 182 mm (4.8 to 7.2 inches), and the minimum rooting depth is 35.56 cm (14 inches). It can survive at temperatures of -38.9 °C (-38 °F), but has a low tolerance to drought and restricted water conditions (plants.USDA.gov).

3.5.8 Water stress

The zero values of reference *ET* from AgriMet were replaced with 0.001 assuming that the data was considered insignificant. This helps avoid blanks in the calculation of actual *ET* which affects the R^2 values. The crop coefficient values were linearly interpolated between the end-point values. When the unsaturated zone showed stress, the ET_c was adjusted by the water stress coefficient as shown in the following.

$$ET_c = K_s \cdot K_c \cdot ET_0 \qquad \textbf{eq 3.2}$$

Where $$Ks = \frac{(\theta_{fc} - \theta_w) - (\theta_{fc} - \theta\ )}{(\theta_{fc} - \theta_w) - (\theta_{fc} - \theta_t)} \qquad \textbf{eq 3.3}$$

θ_{fc} = water content at field capacity

θ_w = water content at wilting point

θ_t = water content at a point where water is readily available, RAW (FAO 56, page 167) .

Here, $\theta_t = 0$

θ = is the actual water content in the unsaturated zone.

Considering $\theta_t = 0$, the equation can be simplified to

$$Ks = \frac{(\theta - \theta_w)}{(\theta_{fc} - \theta_w)} \qquad \text{eq 3.4}$$

3.5.9 Statistical Tools

MIKE SHE has built-in calibration to test the results with the observed values at the same location and time.

3.5.9.1 Root Mean Squared Error (RMSE):

The root mean squared error RMSE for the i^{th} observation is given by:

$$RMSE_i = \frac{\sqrt{\sum_t (Obs_{i,t} - Cal_{i,t})^2}}{n} \qquad \text{eq 3.5}$$

where the suffix i,t represents the i^{th} location at time t. *Obs* is the observed data while *Calc* is the calculate data.

3.5.9.2 Standard Deviation of STD_{res}

It is the standard deviation of the residuals given by

$$STDres_i = \sqrt{\frac{\sum_t (Obs_{i,t} - Cal_{i,t} - \overline{E}_i)^2}{n}} \qquad \text{eq 3.6}$$

where $\overline{E}_i$ is the mean error at location i given by

$$ME_i = \overline{E}_i = \frac{\sum_t \left(Obs_{i,t} - Cal_{i,t}\right)}{n} \qquad \text{eq 3.7}$$

3.5.9.3 Correlation Coefficient (r)

The correlation coefficient at location *i* is given by

$$r_i = \frac{\sqrt{\sum_t \left(Cal_{i,t} - \overline{Obs}_{i,t}\right)^2}}{\sum_t \left(Obs_{i,t} - \overline{Obs}_{i,t}\right)^2} \qquad \text{eq 3.8}$$

where $\overline{Obs}_{i,t}$ is the mean of the observations at location *i*.

3.5.9.4 Nash Sutcliffe Correlation Efficiency(E)

The Nash and Sutcliffe correlation coefficient (1970) is different than the correlation coefficient above. It is used mainly in hydrology for comparing the measured discharge against the observed discharge. It has been used in MIKE SHE to compare similar observations and so it has been used for comparison of evapotranspiration.

The Nash and Sutcliff Efficiency is given by

$$E = 1 - \frac{\sum_t \left(Obs_{i,t} - Cal_{i,t}\right)^2}{\sum_t \left(Obs_{i,t} - \overline{Obs}_{i,t}\right)^2} \qquad \text{eq 3.9}$$

The value of *E* can range from -∞ to 1. The efficiency approaches 1 as the fit improves. When the value is negative, it means that the observed values are more appropriate than the calculated values (DHI, 2007).

The difference between *r* and *E* is that *r* uses the sum of squared deviation from the mean of the observations while *E* is the sum of squared deviation from the actual deviation. Since evapotranspiration varies each day, the deviation of the simulated data from each observation for the same time period is a better comparison of the model relative to the weather pattern of that particular time period.

4 RESULTS AND DISCUSSION

A standard model was setup for each vegetation type for a specified period in 2005. Some periods covered the growing season while others went until the end of the year. Each vegetation type was defined with an individual vegetation property file that included period for development stages, *LAI* values, rooting depths and crop coefficients. The 1-D 1,000 m by 1,000 m model setup took about 2 minutes to run for any given seasonal or annual time series. The results below have been listed for each vegetation class.

A new flaw has been discovered in MIKE SHE. The model does not require input of crop coefficient (K_c) values below 1. However, when values < 1 are provided, the model uses them to revise the "potential" evapotranspiration as per the Kristensen and Jensen (KJ) method. In the revised results below, all K_c values are either 1 or greater than 1. The leaf area index has linear relationship with the K_c, ie, higher the K_c, the larger is the *LAI*. The *LAI* would be used to determine the potential *ET* during the stages when the actual value of K_c is less than 1.

4.1.1 Wetlands

Wetlands by definition require flooding on or above the surface. Duckweed and cattail were modeled assuming flooded conditions to 0.2 m or saturated conditions at 0 m above the ground surface. Both of these saturation conditions were tested with no significant difference in results.

4.1.1.1 Duckweed

Using the crop coefficient values given on Table 3.5, the crop evapotranspiration (ET_c) was computed using equation 2.11 on page 11 and the ET_0 values from the Beatty AgriMet station. AgriMet uses the Kimberly-Penman method (1990) with an alfalfa reference, hence the values were first converted into grass reference by multiplying by a factor 0.833 as shown in equation 2.13 on page 12 (Jensen et al., 1990).

The flooding of the field is an indication that the soil is saturated and the crop should be transpiring at a maximum rate as moisture is readily available. The Nash and Sutcliffe (NS) efficiency of 1.00 for comparing evapotranspiration between MIKE SHE results and the AgriMet values (Figure 4.11) for Duckweed vegetation show that this true.

Some tests were done by flooding the surface as high as 0.5 m. However, when the water table was dropped to -0.5 m from the surface, the model underpredicted *ET* during June to September (Figure 4.12). Obviously, a wetland plant would not survive dry conditions where there is no water in the root zone. The potential *ET* rate is about 8 mm/day for duckweed. The plant remains in a dormant state for MIKE SHE until precipitation occurred in late September (see precipitation graph on Figure 4.10).

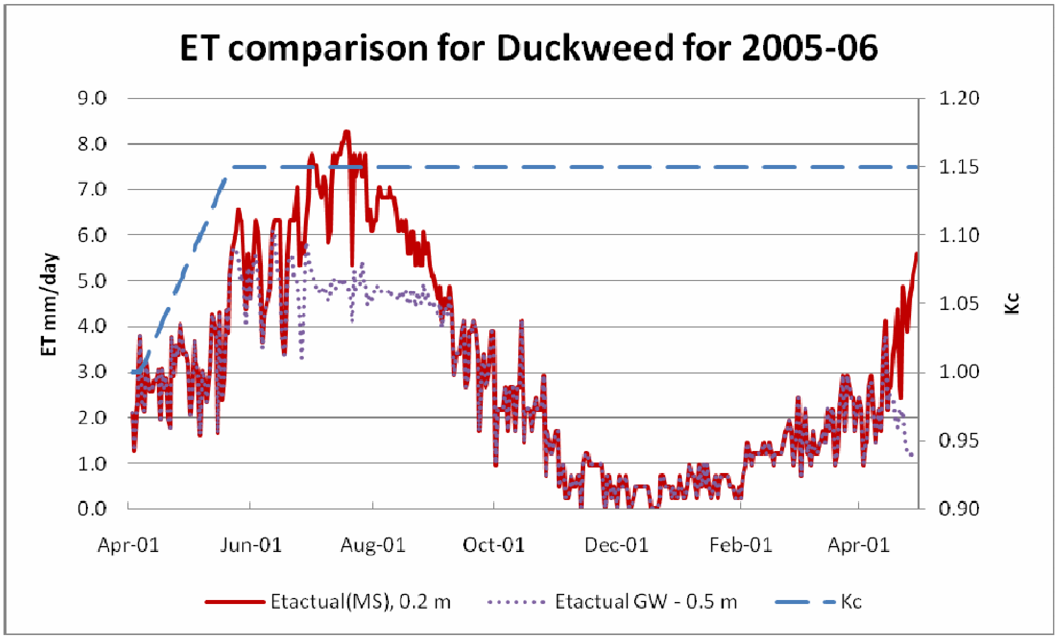


Figure 4.1 ET actual from MIKE SHE simulation for water level at 0.2 m of ponding and 0.5 m of depth for groundwater for Duckweed.

Table 4.1 Duckweed *ET* for the growing season.

Duckweed	Apr 05	May 05	Jun 05	Jul 05	Aug 05	Sep 05	12 month average
Precip (mm/month)	38.308	79.3	19.032	2.196	0	9.516	37.474
ET0 (mm/day)	2.694	3.515	4.888	6.327	5.337	3.251	2.664
ETc_AgriMet (mm/day)	2.720	3.982	5.621	7.276	6.138	3.739	3.027
MIKE SHE ET (mm/day)	2.811	3.980	5.621	7.276	6.138	3.739	3.034

The monthly *ET* and the potential *ET* for the growing season is given in Table 4.1 above. Note that the *ET* calculated and *ET* estimated are both above the reference *ET* as the K_c used is greater than 1 for most of the growing period. The precipitation is from the Beatty, OR AgriMet station. AgriMet ET_c is the adjusted crop *ET* for duckweed using the appropriate crop coefficient values. MIKE SHE ET_c is the simulated crop *ET* and ET_0 is the reference *ET* adjusted for grass reference.

4.1.2 Cattail

Setting up a similar model for cattail and raising the water level from the surface to 0.2 m ponding showed no difference in *ET* estimates (Nash-Sutcliffe efficiency > 0.95). The plausible explanation would be that the plant was transpiring at the potential rate for both methods. When the water level was dropped to -0.5 m, the correlation coefficient and NS efficiency dropped, but is still acceptable. The soil stress factor (K_s) was not considered. Different technical articles indicate different values for the length of growing season. FAO 56 recommends values for the four stages of growth, i.e. initial, crop development, maturation and harvest, to be 10, 30, 80 and 20 days, respectively, totaling 140 days. The crop coefficients recommended are 0.3, 1.2 and 0.3 for the initial, mid and late stages, respectively. In MIKE SHE all crop coefficients below 1 are corrected to 1. Table 4.2 below shows the computed efficiency of MIKE SHE ET_c compared to AgriMet ET_c. The low values of the NS efficiency with a lower groundwater table indicate that the plant is shut down due to reduced soil water content. It is indeed an expected response from the model. A wetlands plant could obviously have problems surviving in non-saturated conditions.

Table 4.2 Cattail *ET* efficiency comparison – KJ vs KP.

GW table (m)	*RMSE*	STD_{res}	*r* (Correlation)	*E* (Nash_Sutcliffe)
0.2	1.02E-05	1.02E-05	1	1
-0.5	0.6463	0.5167	0.9731	0.8707

In

Table 4.3, the results of the simulation and the precipitation have been averaged over each month of the growing season. According to the table, the average rate of *ET* per day is comparatively higher than the MIKE SHE estimate compared to the AgriMet station estimate. The computed average ET_c rates for June, July and August are higher than the potential *ET*.

Table 4.3 Cattail *ET* for the growing season for the groundwater table set at 0.2 m.

Cattail	May 05	Jun 05	Jul 05	Aug 05	Sep 05	Growing season average
Precip (mm/month)	79.3	19.0	2.2	0.0	9.5	22.0
AgriMet ET_c (mm/day)	3.717	5.818	7.592	6.401	3.772	5.460
MS ET_c (0.2 m) (mm/day)	3.711	5.814	7.592	6.402	3.783	5.460
MS ET_c (-0.5 m) (mm/day)	3.639	5.687	6.364	6.056	3.782	5.106
ET_o (mm/day)	3.515	4.888	6.327	5.337	3.251	4.664

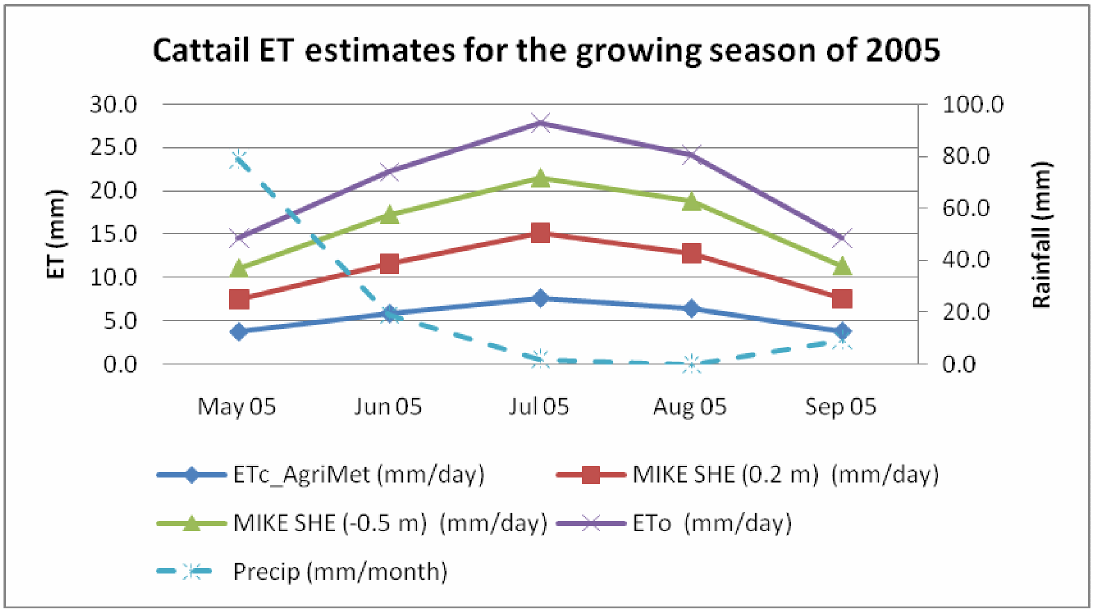


Figure 4.2 ET estimates for cattail for the growing season of 2005 at two water levels, 0.2 m ponding and 0.5 m below the surface.

4.1.3 Big Sagebrush

MIKE SHE was run with big sagebrush. The soil moisture had to be accounted for using the soil stress factor as given in equation 2.11 on page 12. The initial water tables used were -0.5 m and -1.0 m below the surface. The *ET* estimates for the 2005-06 period is given in Figure

4.3. The model predicted low *ET* as compared to the AgriMet *ET*. In the absence of precipitation or irrigation, the soil moisture condition would produce considerable plant stress during the dry season. The soil moisture profile in the unsaturated zone is given in the MIKE SHE output graph, Figure 4.4, below.

The soil moisture remains between the specified saturated moisture content (0.36 cm^3/cm^3) and wilting point (0.24 cm^3/cm^3) (see Table 3.1). The soil moisture in the uppermost soil layer has the most fluctuation, while the underlying grids respond slowly as the water penetrates the depth of the soil. The rain in the early season keeps the soil moisture close to field capacity. During mid-June, the moisture level drops to the point where water is not available for the plant and it remains dry until the rains set in late September. The underlying grid cells have a slow response to the soil moisture deficit. They are not as responsive as the top layer. There is still soil moisture available for the roots. Figure 4.16 shows the *ET* comparison between MIKE SHE and AgriMet when the soil water stress is not accounted for in summer. Soil water stress is accounted in Figure 4.17. The difference is insignificant, but it gives an acceptable correlation coefficient (0.95) and Nash-Sutcliffe coefficient (0.69).

Table 4.4 Monthly evapotranspiration rates for big sagebrush.

Veg: big Sagebrush	Units	Apr	May	Jun	Jul	Aug	Sept	Annual average
Precipitation	mm/month	38.3	79.3	19.0	2.2	0.0	9.5	37.5
AgriMet ET_c	mm/day	2.173	3.216	3.295	3.174	2.632	1.979	1.881
MIKE SHE ET_c	mm/day	2.248	3.209	3.152	2.777	2.405	1.941	1.842
ET_0	mm/day	2.694	3.515	4.888	6.327	5.337	3.251	2.664

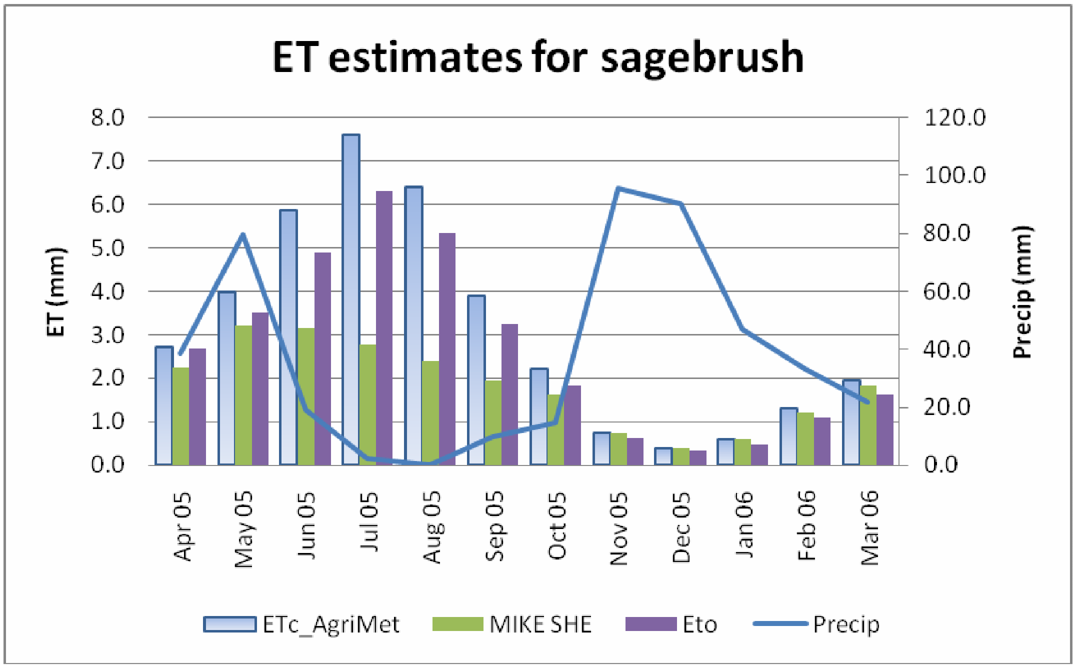


Figure 4.3 ET estimates for sagebrush for 12 month period in 2005-06.

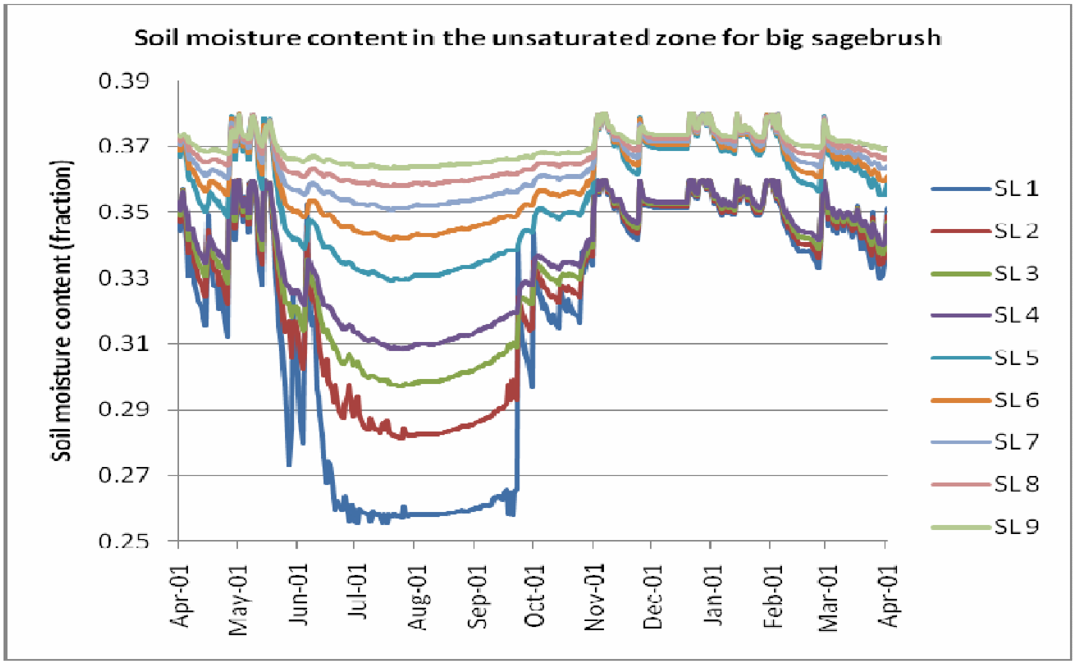


Figure 4.4 Soil moisture in the unsaturated zone for big sagebrush with initial water table at -1.0 m. The top most layer is the bottom line and the layers below follow the pattern towards decreasing soil moisture content. Here only 9 of 16 layers are graphed.

4.1.4 Juniper

The results for juniper are similar to those for big sagebrush. The MIKE SHE simulation shows that without irrigation, the water available in the root zone is not enough for juniper to grow during summer. The simulated *ET* drops down below 1 mm/day during summer whereas the water demand indicated by the crop coefficient method is as high as 6 mm/day. (see Figure 4.18). The soil moisture profile shows that the water content during the dry period falls close to the wilting point. External water has not been applied in this model to demonstrate the effects on juniper of natural conditions. Juniper is an invasive plant species that has a short but dense rooting system that withdraws water from its wider root zone. These results indicate that when juniper is covering an area, it will not allow other plants to extract soil water until its demand has been fulfilled.

When the AgriMet ET_c is corrected for soil water stress, the Nash and Sutcliffe efficiency of the model is raised to 0.83. The correlation coefficient is also raised to 0.94 (see Figure 4.20). This indicates that MIKE SHE responded to the soil stress in a similar manner as the crop coefficient method applied to the Kimberly Penman estimating method used in AgriMet.

Table 4.5 Monthly evapotranspiration rates for juniper for the growing season of 2005.

Juniper	Units	Apr	May	Jun	Jul	Aug	Sept	Annual average
Precipitation	mm/month	38.3	79.3	19.0	2.2	0.0	9.5	37.5
AgriMet ET_c	mm/day	2.14	2.91	3.40	3.60	2.82	2.04	1.83
MIKE SHE ET_c	mm/day	2.05	2.48	1.69	1.29	1.14	1.15	1.25
ET_0	mm/day	2.69	3.51	4.89	6.33	5.34	3.25	2.66

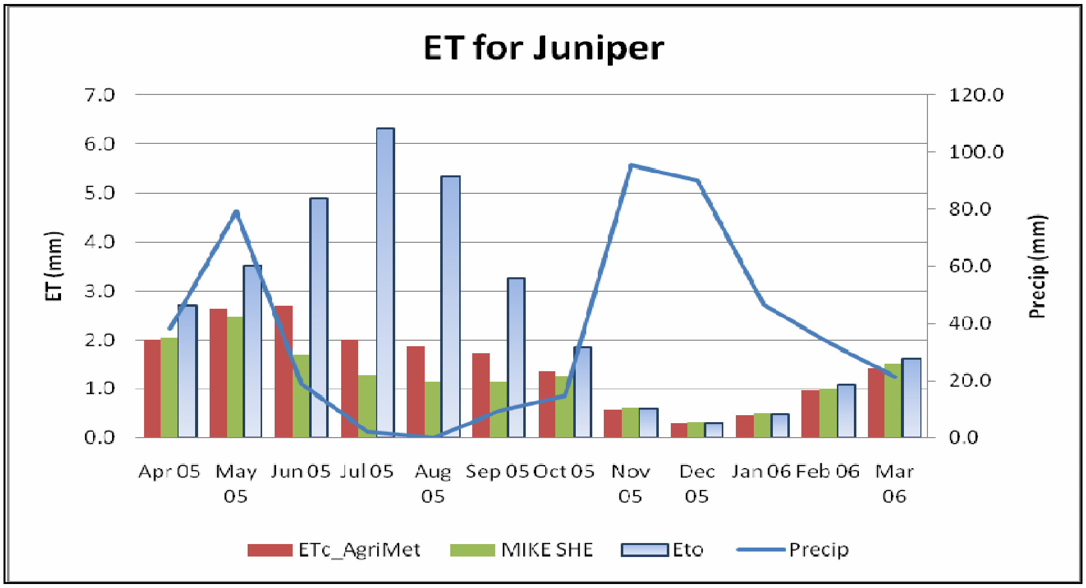


Figure 4.5 ET estimates for juniper after accounting for soil stress. Notice the difference between the AgriMet and MIKE SHE estimates during the dry season.

4.1.5 Ponderosa Pine

Results for simulation of Ponderosa Pine are similar to those of juniper (Figure 4.21). After correction for soil stress, the Nash and Sutcliffe efficiency was 0.67 and the correlation coefficient was 0.82.

Table 4.6 Monthly vegetation file for the ponderosa pine for the growing season.

Veg: Ponderosa Pine	Units	Apr	May	Jun	Jul	Aug	Sept	Annual average
Precipitation	mm/month	38.3	79.3	19.0	2.2	0.0	9.5	37.5
AgriMet ET_c	mm/day	2.285	2.945	3.001	2.563	1.753	1.236	2.015
MIKE SHE ET_c	mm/day	2.063	2.629	2.165	1.785	1.835	1.902	2.116
ET_0	mm/day	2.694	3.515	4.888	6.327	5.337	3.251	2.664

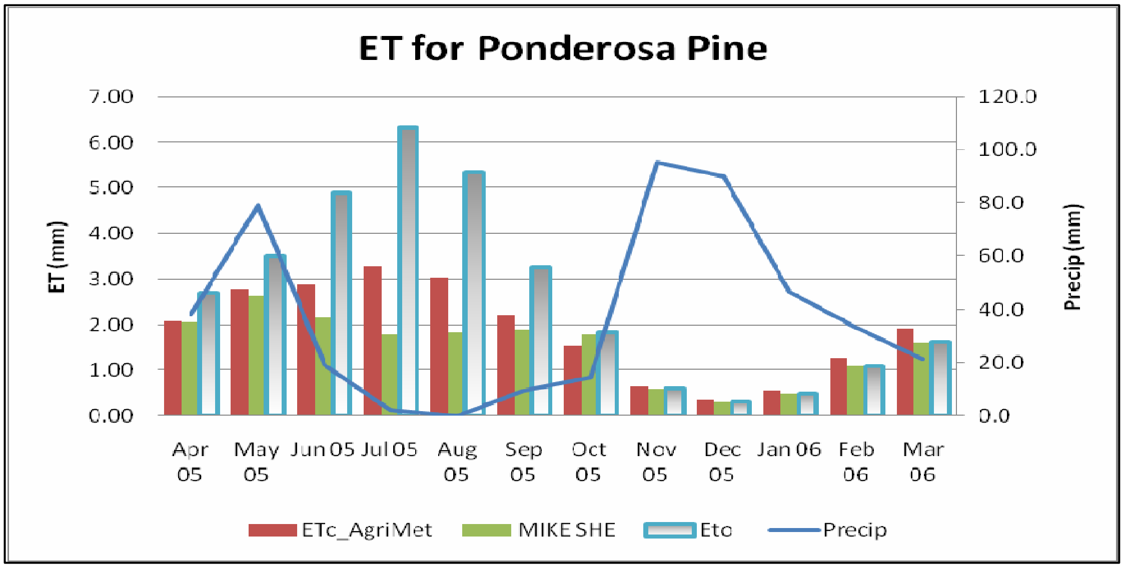


Figure 4.6 ET estimates for Ponderosa pine. Similar to juniper, the values are lower than the grass reference.

4.1.6 Maize

Maize is an agricultural crop for which more information on crop coefficients is available in the literature and one which typically requires irrigation to meet the crop water use demand. This crop has a short growing period of 125 days (see Table 3.9 on page 35).

This crop has been treated differently than the natural vegetation crops to test the model and compare the results with other methods. Initially, irrigation was turned on after the maximum allowed deficit of 60 percent of available water in the root zone was met and irrigation was continued until field capacity was reached. This means that when the plant extracted water from the root zone and the soil moisture content dropped to 60 percent of available moisture, then irrigation was turned on until the field capacity was reached (DHI, 2007). This pattern continued throughout the growing season. The irrigation was not turned on by the model, which indicates that the soil moisture did not deplete to 60 percent of available moisture. But the plant was still transpiring at a reduced rate. On the second run, the irrigation demand was changed to 20 percent of field capacity. This activated the irrigation as shown in Figure 4.23. The irrigation rate is distributed as an average for the 24 hours, which is the recording time step specified in the model.

The *ET* was calculated without the soil moisture deficit correction (unlike the natural vegetation above). The *ET* comparison between the AgriMet and MIKE SHE is given in Figure 4.22. The Nash and Sutcliffe efficiency is 0.988 and the correlation coefficient is 0.99. The irrigation application is indicated in Figure 4.23 and Figure 4.24. In the first one, the spikes appear in the graph of average water content in the unsaturated zone. As the sprinkler is turned off, the water content decreases until the next irritation schedule.

Figure 4.25 is the scatter plot showing the relationship between the MIKE SHE and the AgriMet *ET*. The R^2 regression of 0.913 indicate that there is high correlation between the two. The regression equation indicate that MIKE SHE *ET* estimates increases by 62 percent of the Agrimet *ET*.

Table 4.7 Monthly evapotranspiration rates for maize for the growing season.

Veg: Maize	Units	Apr	May	Jun	Jul	Aug	Annual average
Precipitation	mm/month	38.31	79.30	19.03	2.20	0.00	27.77
AgriMet ET_c	mm/day	1.20	2.74	2.80	2.08	1.09	1.98
MIKE SHE ET_c	mm/day	1.09	3.04	3.41	2.22	0.64	2.08
ET_0	mm/day	2.69	3.51	4.89	6.33	5.34	4.55

4.1.7 Pasture

The tufted hairgrass setup was replaced with a pasture setup to run the model for irrigation. This is because data are readily available to quantify the water demand for pasture and no specific data are available for tufted hairgrass. According to the Oregon Crop Water Use and Irrigation Requirement handbook (Cuenca et al., 1992), the 50 percent probability of seasonal *ET* (Apr to Oct) for pasture for the Klamath region (of the Klamath-Ontko-Dilman association, soil survey number 34) is 784 mm. The net irrigation requirement, subtracting expected effective precipitation, is 660 mm for the season. The graph below indicates the water deficit if this model applied to the 2005 season. The plant is expected to transpire with potential *ET* rate if the water is applied up to full field capacity.

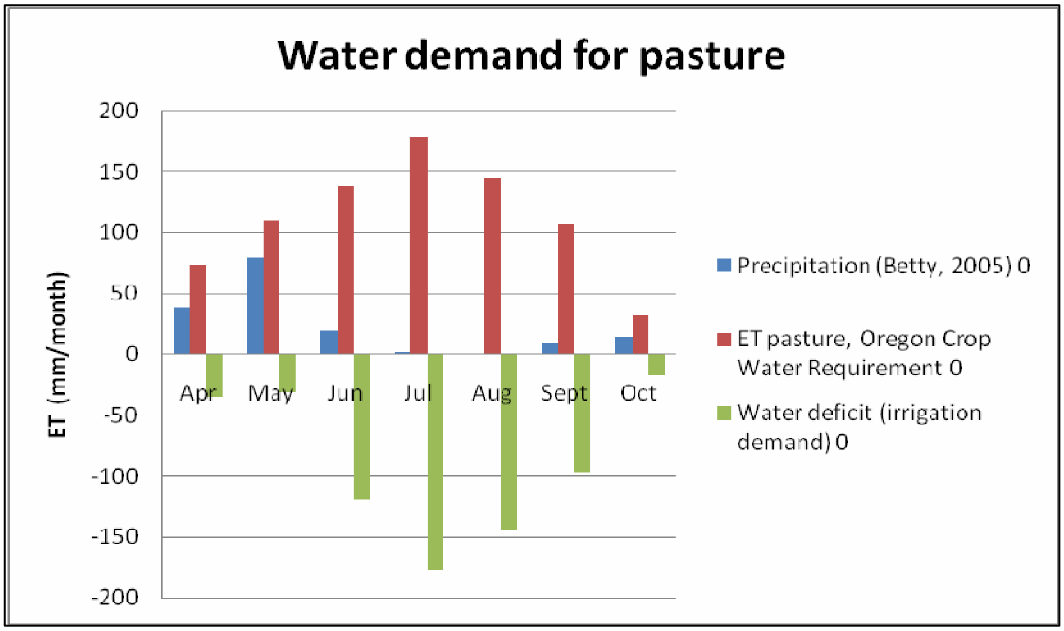
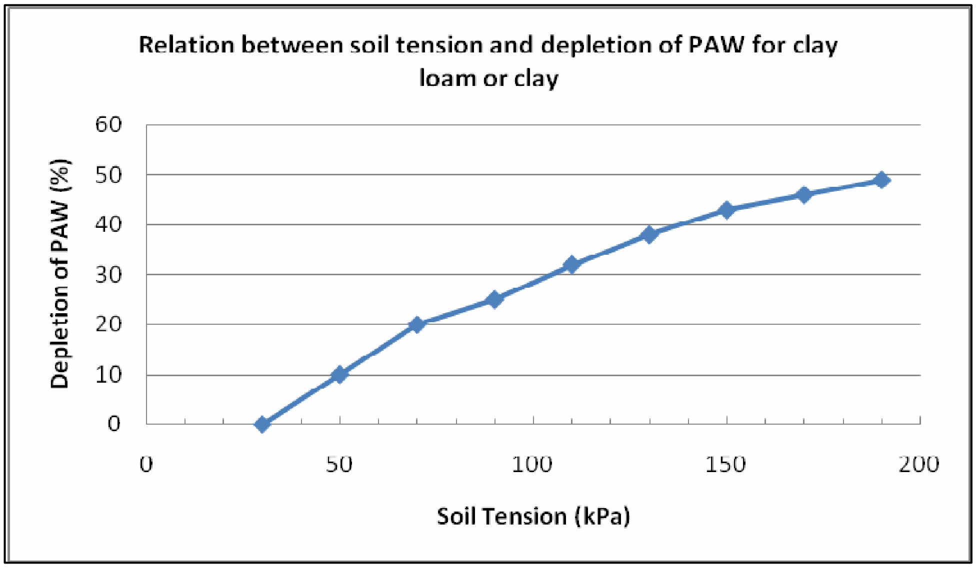


Figure 4.7 Water demand for pasture in Klamath as compared to the 50 percent (5 out of 10 years) probability *ET* rates predicted by Oregon Crop Water Use and Irrigation Requirement (Cuenca et al, 1992).

The total precipitation for Beatty is only 163 mm over the season (April through October, 2005, AgriMet) and the net water demand is 621 mm.

The dry soil conditions and limited water holding capacity of the soil does not allow the plant to get as much water as demanded. The figure below show the relation between soil water tension and depletion of the plant available water (PAW) for clay loam or clay. It shows that using 20 percent depletion of moisture would stress the soil by 70 kPa.



Source: Scheduling Irrigations When and How Much Water to Apply, Division of Agriculture and Natural Resources Publication 3396. University of California, Irrigation program. University of California, Davis, pp 106.

Figure 4.8 Relation between soil water tension and depletion of plant available water (PAW) for clay loam/ clay.

MIKE SHE allows other options for irrigation. Keeping in mind the goal, two simple methods have been used to learn about the model.

Scenario 1- Accounting for daily water deficit by sprinkler irrigation:

Using the daily crop coefficients, the daily ET_c is estimated. The water deficit is also calculated by subtracting out the rainfall from the ET_c. The deficit is input as a user specified time series irrigation demand.

The model was run with this scenario so that water was available everyday to fulfill the ET_c deficit. The resulting *ET* was comparable to the AgriMet grass reference *ET* (ET_0). The results of the run are shown in Figure 4.26. The reported value for Nash and Sutcliffe efficiency is 0.85 and the correlation coefficient is 1.00. Changing from sprinkler to drip irrigation on the same scenario had no effect on the results.

Scenario 2- Using the average monthly irrigation demand:

As per the seasonal water demand shown in Figure 4.7 above, a time series irrigation file was setup. In this scenario, the irrigation demand is based on average *ET* from the historical data and is used to forecast the irrigation. Here it is assumed that 2005 is an ideal rainfall year for Beatty.

The MIKE SHE *ET* for grass can now be compared to the reference *ET* (ET_0) from the AgriMet network. The results in Figure 4.27 show a correlation coefficient of 0.96 and Nash and Sutcliffe efficiency of 0.86. Although, in both cases the water deficit is fulfilled, the model still predicts less *ET* than the AgriMet *ET*. There is some efficiency error involved that needs investigation.

Both these above methods gave similar outputs in ET values, but the daily deficit gave higher N-S efficiency (0.8214).

Scenario 3-Automatic irrigation for moisture deficit of 20 percent of available moisture content : The above two scenarios of irrigating are not very practical. The daily deficit method requires several years of recorded data to get the average precipitation for the day and still may not meet the daily demand or could be excess of water for the particular day. The monthly deficit method would give rough estimates of the irrigation demand and may result in wilting of plants during dry conditions.

This method of irrigation when the soil moisture reaches a certain deficit, has been popular in the recent years. MIKE SHE has the built in function to turn on irrigation when the soil moisture has lowered to a certain deficit mark. Unfortunately, in this model, using the 20 percent of available soil moisture at field capacity did not turn on irrigation. The reason behind this still needs investigation. But the plausible reason would be that the clay layer has high moisture holding capacity and that would prevent the soil moisture to fall below to this mark.

Scenario 4: Application of 5 or 10 mm/h every 5 days: The other irrigation method would be to apply certain amount of water periodically. Here, different methods were tried to keep the soil moist as much as possible. The frequency of every 10 or 5 days was used but then the soil dried up very fast. The irrigation rate was rate of 5 to 20 mm/h depending on water demand in the season. It is assumed that the efficiency of sprinkler irrigation is 80 percent.

The differences in frequency of irrigation, the water was not sufficient enough for the MIKE SHE *ET* to be aligned to the AgriMet *ET*. The soil dried up faster than the ET could recover.

See Figure 4.29. This method proved inefficient for irrigation for pasture and the N-S Eff is less than 0 indicating that the AgriMet is a better estimate.

4.1.8 Overall Results

The overall results are shown in Table 4.8 and Figure 4.9 below. The comparison was done with the AgriMet ET_c as computed using the crop coefficient method with the grass reference ET_0 (converted from alfalfa).

Results show that MIKE SHE did not have any real problem predicting ET_c for the wetland plants, duckweed and cattail. For sagebrush, MIKE SHE under predicted evapotranspiration,. A water table 1 m below the soil surface was used. (The actual water table at the site fluctuates between 3 to 6 m below the soil surface in summer.) This was done for simplicity of the model to run with enough moisture so that the model predicts well. This biases the model results to be better than they would be if the more representative summer water table values for the site were used.

The model under predicted in all cases except that of the wetland plants. The model did not perform well with sagebrush with very low Nash and Sutcliffe Eff. N-S Eff values were low for the other natural vegetation species, juniper and Ponderosa pine, but not as low as for sage. Although the N-S Eff values were low, the correlation coefficient, r values, were higher than 0.80, which shows reasonable correlation between the trends in the MIKE SHE and AgriMet predictions.

Table 4.8 Comparison of AgriMet ET_c vs MIKE SHE ET_c.

Vegetation	Water table (m)	Growing period (days)	AgriMet ETc (mm)	MIKE SHE ETc (mm)	correlation coefficient, r	Nash Sutcliffe, Eff
Duckweed	0.2	366	1203	1203	0.9979	0.9743
Cattail	0.2	143	799	799	1.0000	1.0000
Maize	-1.0	122	612	462	0.9427	0.8514
Sagebrush	-1.0	366	1151	674	0.8364	0.1403
Juniper	-1.0	366	550	456	0.8327	0.5942
Ponderosa Pine	-1.0	366	978	557	0.8248	0.6780
Pasture daily deficit	-1.0	214	852	715	0.9963	0.8214
Pasture monthly deficit	-1.0	214	852	715	0.9818	0.7741

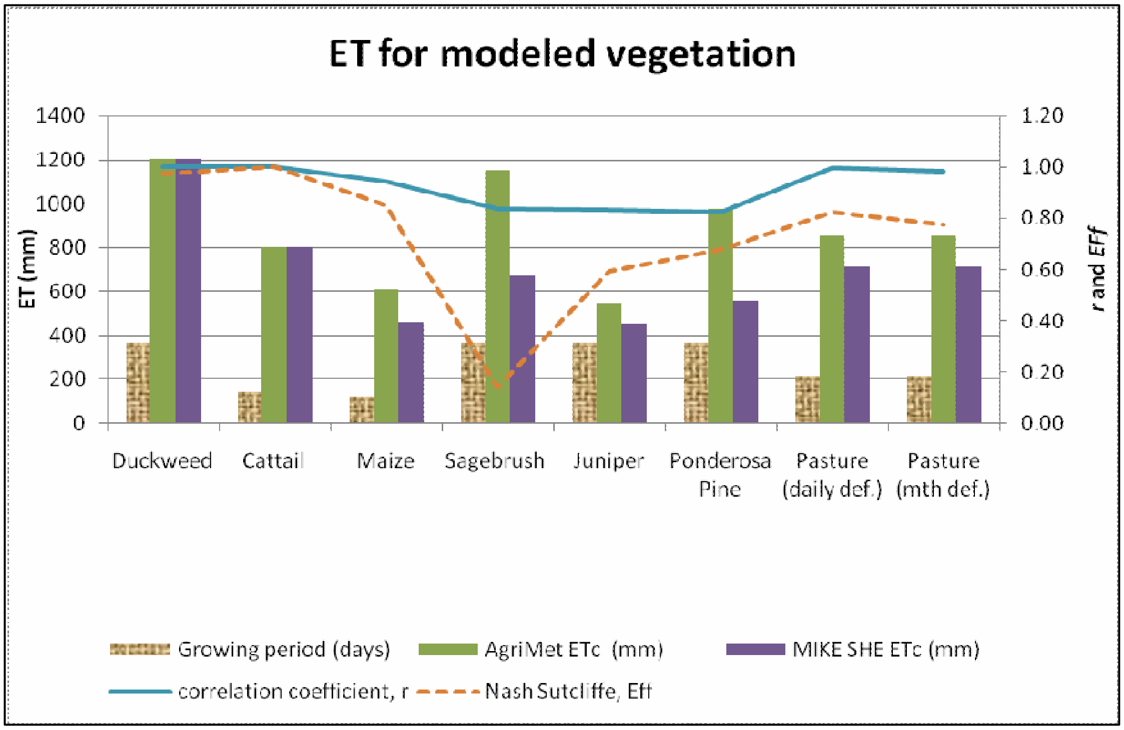


Figure 4.9 ET for the modeled vegetation. Note the dip of Nash and Sutcliffe efficiency for sagebrush.

Figures from MIKE SHE simulation discussed in chapter 4

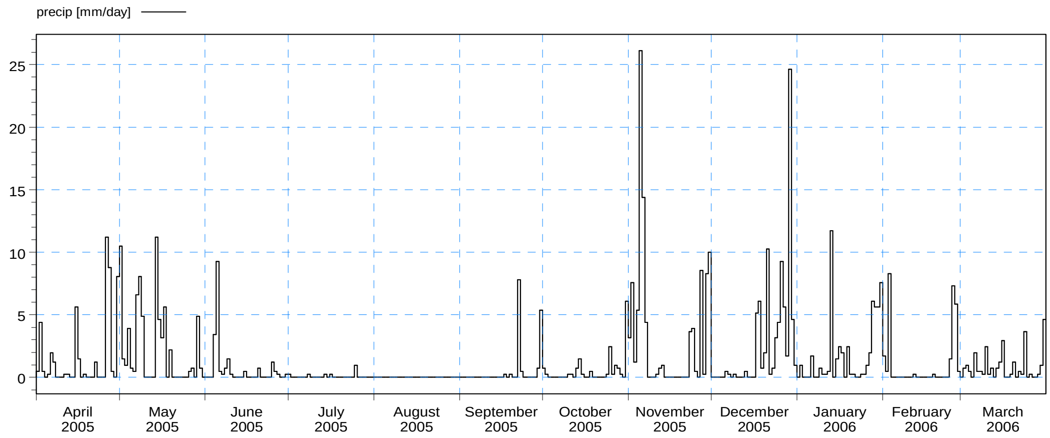
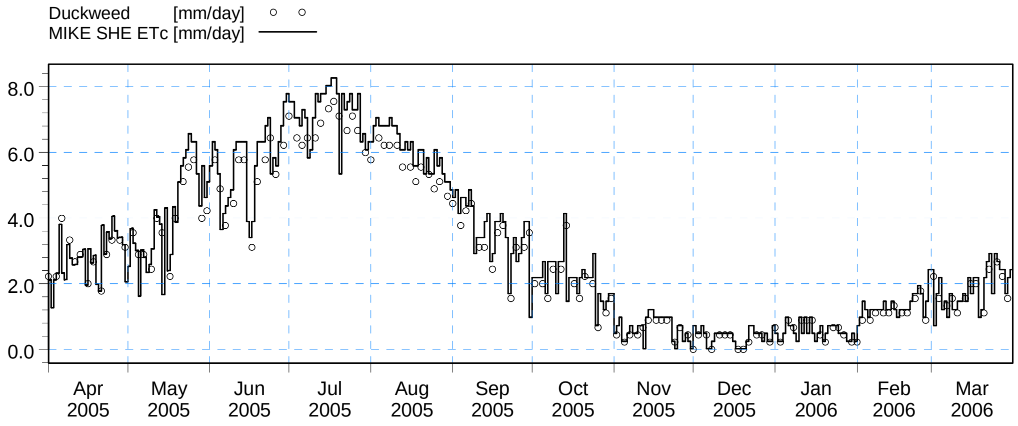
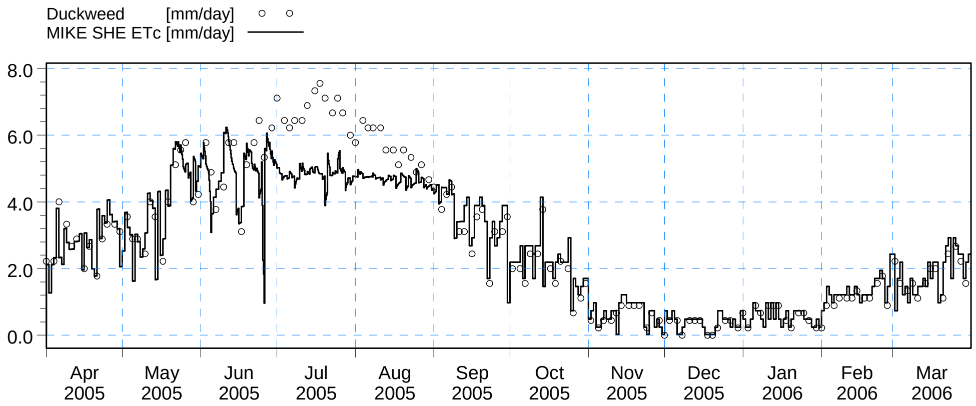


Figure 4.10 Precipitation at the Beatty station (AgriMet).



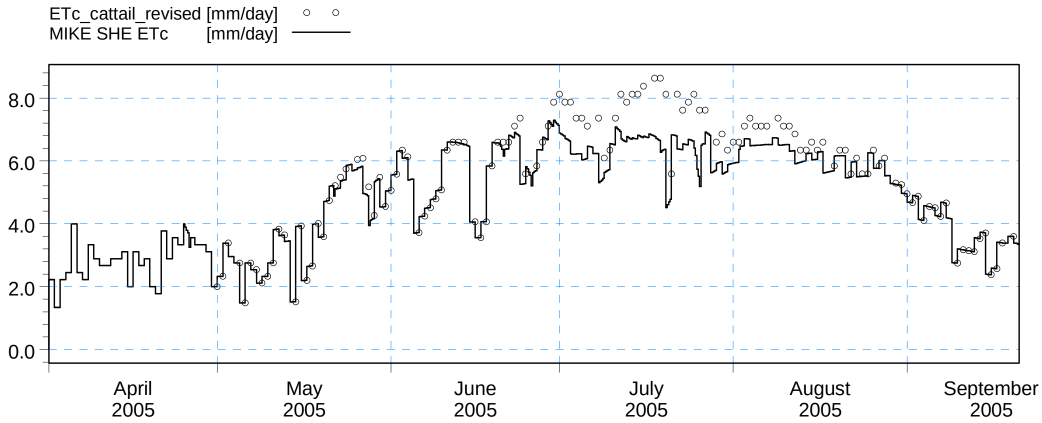
ME=-0.231788
MAE=0.252149
RMSE=0.344671
STDres=0.255093
R(Correlation)=0.997882
R2(Nash_Sutcliffe)=0.974259

Figure 4.11 Duckweed *ET* rate for 2005-2006. The simulation result was compared to the estimation using AgriMet data.



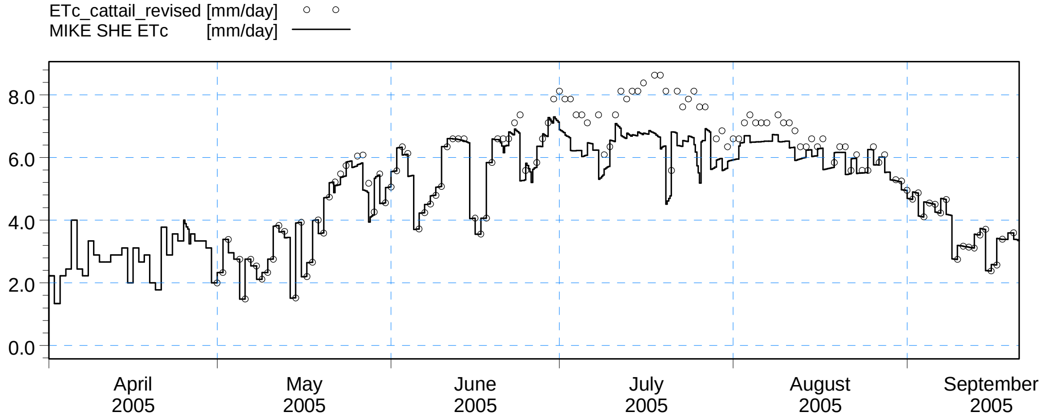
ME=0.187765
MAE=0.387886
RMSE=0.703664
STDres=0.67815
R(Correlation)=0.960156
R2(Nash_Sutcliffe)=0.892711

Figure 4.12 Duckweed *ET* at water depth of 0.5 m below surface.



ME=0.388236
MAE=0.388238
RMSE=0.646331
STDres=0.516736
R(Correlation)=0.9731
R2(Nash_Sutcliffe)=0.870732

Figure 4.13 Cattail ET_c comparison for the growing season for water table at -0.5 m.



ME=0.388236
MAE=0.388238
RMSE=0.646331
STDres=0.516736
R(Correlation)=0.9731
R2(Nash_Sutcliffe)=0.870732

Figure 4.14 Cattail *ET* comparison without including the soil stress in the AgriMet calculated values.

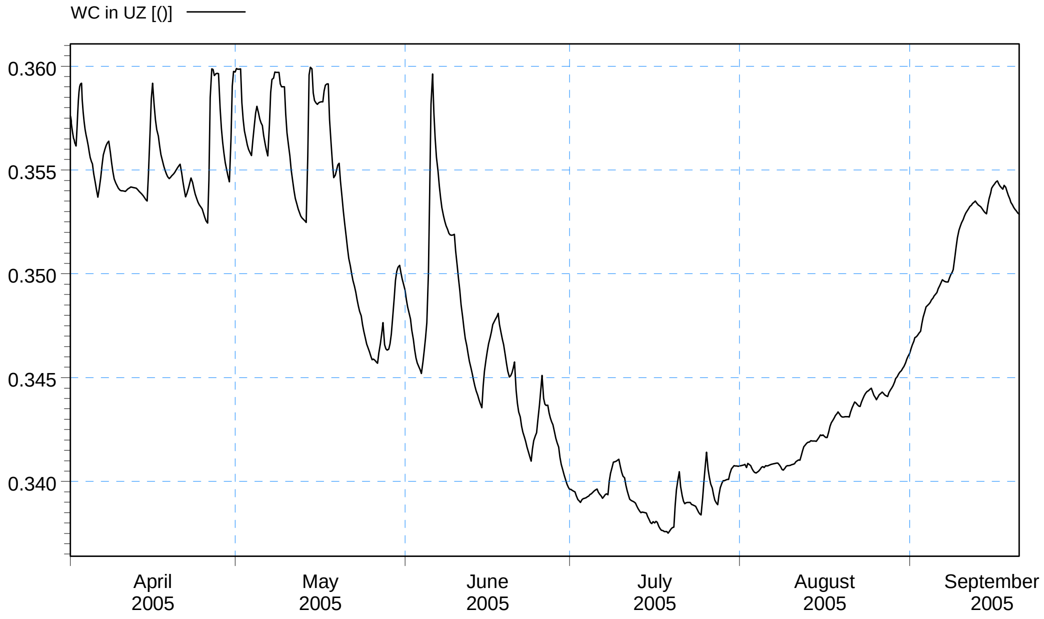
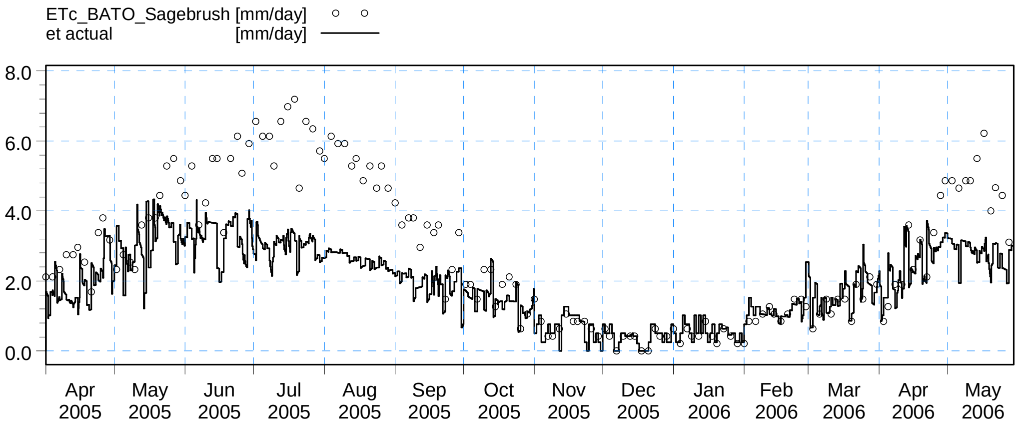
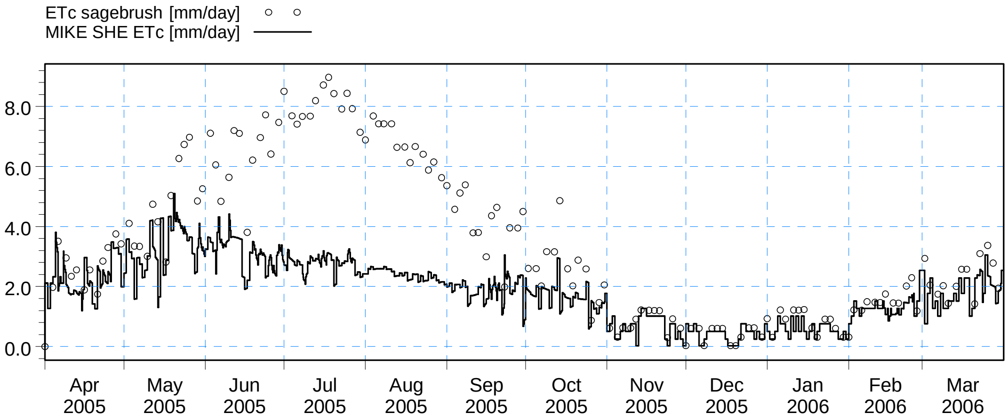


Figure 4.15 Water content in the unsaturated zone for Cattail simulation with groundwater table at -0.5 m.



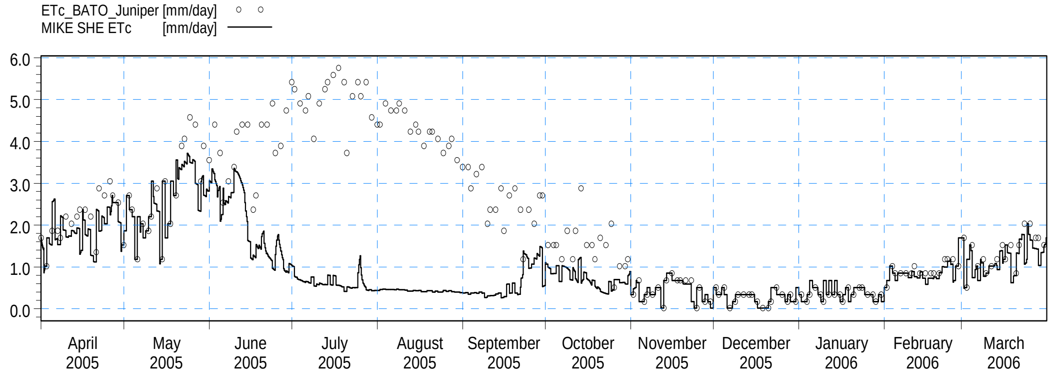
ME=0.906613
MAE=0.980985
RMSE=1.46735
STDres=1.15376
R(Correlation)=0.900068
R2(Nash_Sutcliffe)=0.459062

Figure 4.16 ***ET*** **comparison for Big Sagebrush before accounting for soil water stress.**



ME=1.5482
MAE=1.55265
RMSE=2.3653
STDres=1.78822
R(Correlation)=0.836436
R2(Nash_Sutcliffe)=0.140265

Figure 4.17 ***ET*** **comparison for Big Sagebrush. The AgriMet ET was corrected for soil moisture stress using the average soil moisture in the root zone.**



ME=1.15062
MAE=1.15062
RMSE=1.9525
STDres=1.57744
R(Correlation)=0.32064
R2(Nash_Sutcliffe)=-0.423937

Figure 4.18 ***ET*** **comparison for juniper before accounting for soil water stress.**

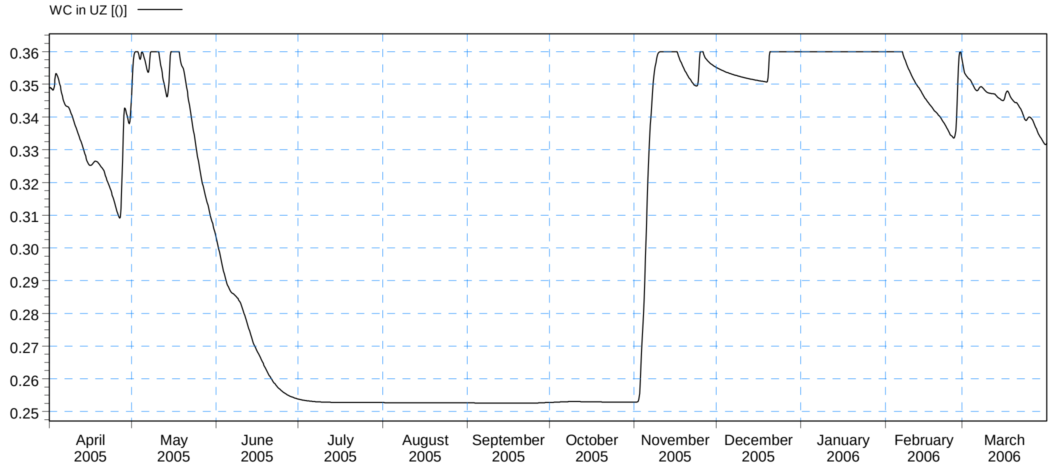
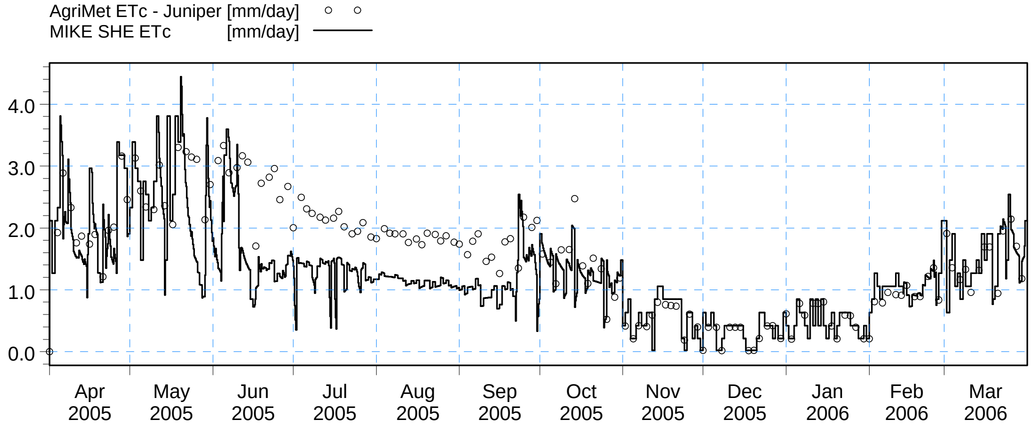
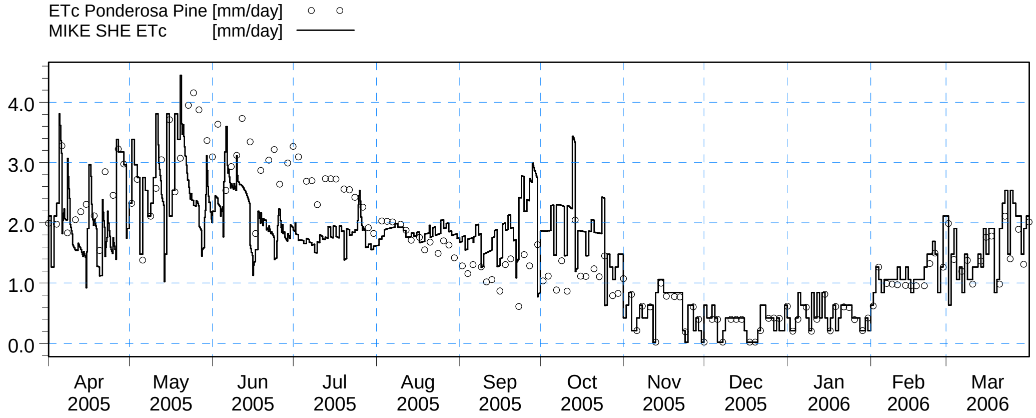


Figure 4.19 Water content in the unsaturated zone for juniper as modeled by MIKE SHE.



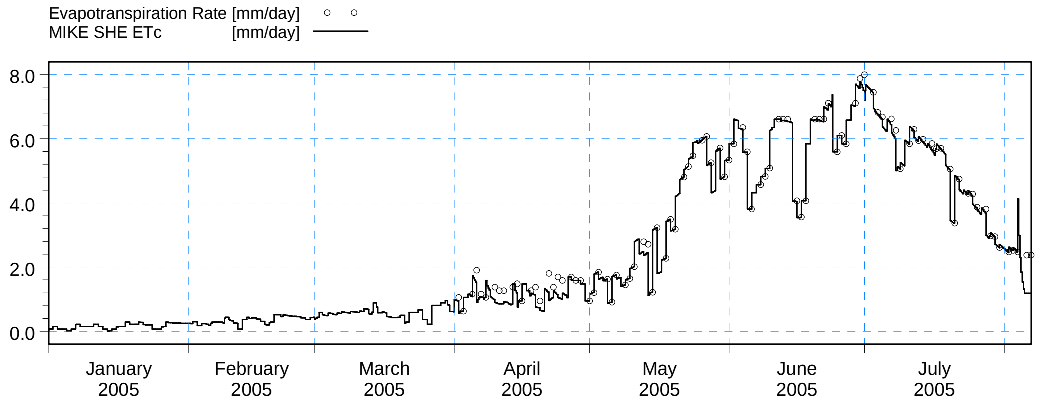
ME=0.268638
MAE=0.357256
RMSE=0.545142
STDres=0.474356
R(Correlation)=0.832703
R2(Nash_Sutcliffe)=0.594171

Figure 4.20 ***ET*** **of juniper. The AgriMet ET was adjusted for the soil moisture stress using the average water content in the root zone obtained from the model.**



ME=0.0455687
MAE=0.376928
RMSE=0.563212
STDres=0.561366
R(Correlation)=0.824784
R2(Nash_Sutcliffe)=0.67804

Figure 4.21 ***ET*** **of Ponderosa pine. The AgriMet ET was adjusted for the soil moisture stress using the average water content in the root zone obtained from the model.**



ME=0.10773
MAE=0.10773
RMSE=0.234255
STDres=0.208014
R(Correlation)=0.99575
R2(Nash_Sutcliffe)=0.988018

Figure 4.22 ***ET_c* for maize with irrigation set at 20 percent of field capacity. The soil is tilled for the first three months and planting was done April 1st.**

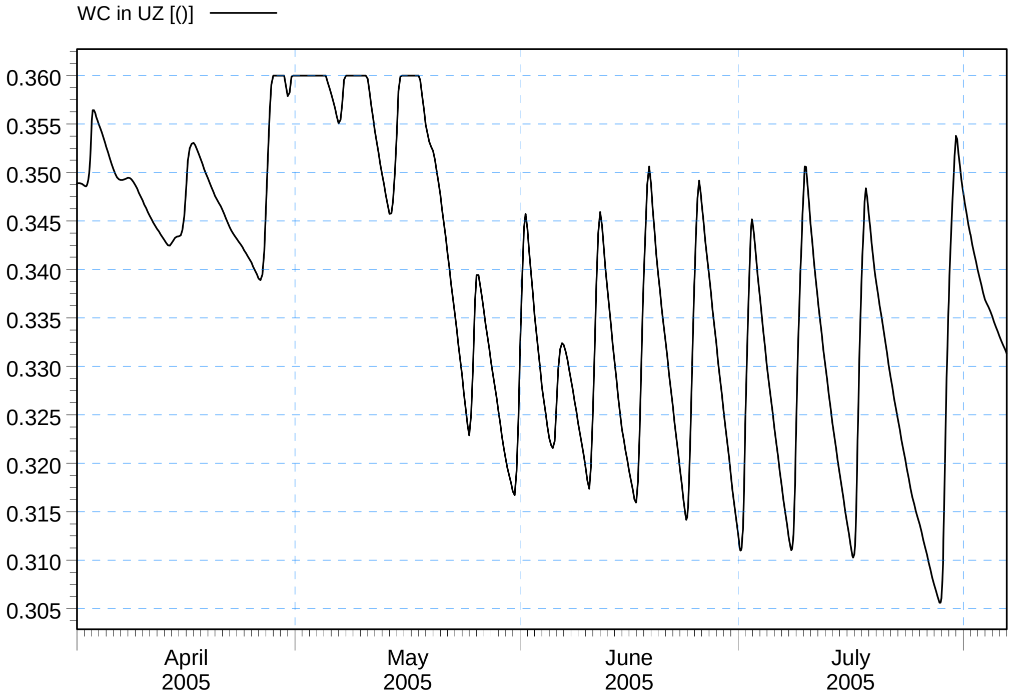


Figure 4.23 Average water content in the unsaturated zone for maize. The spikes are the irrigation applications.

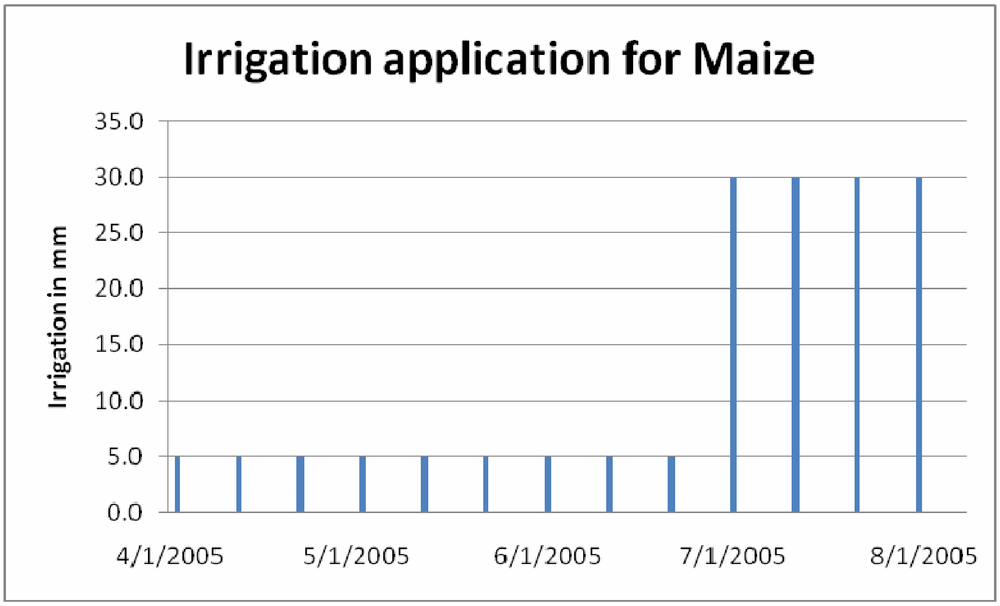


Figure 4.24 Irrigation application for maize. The application was 5 mm every 10 days in the early season and 30 mm in 10 days during the dry season.

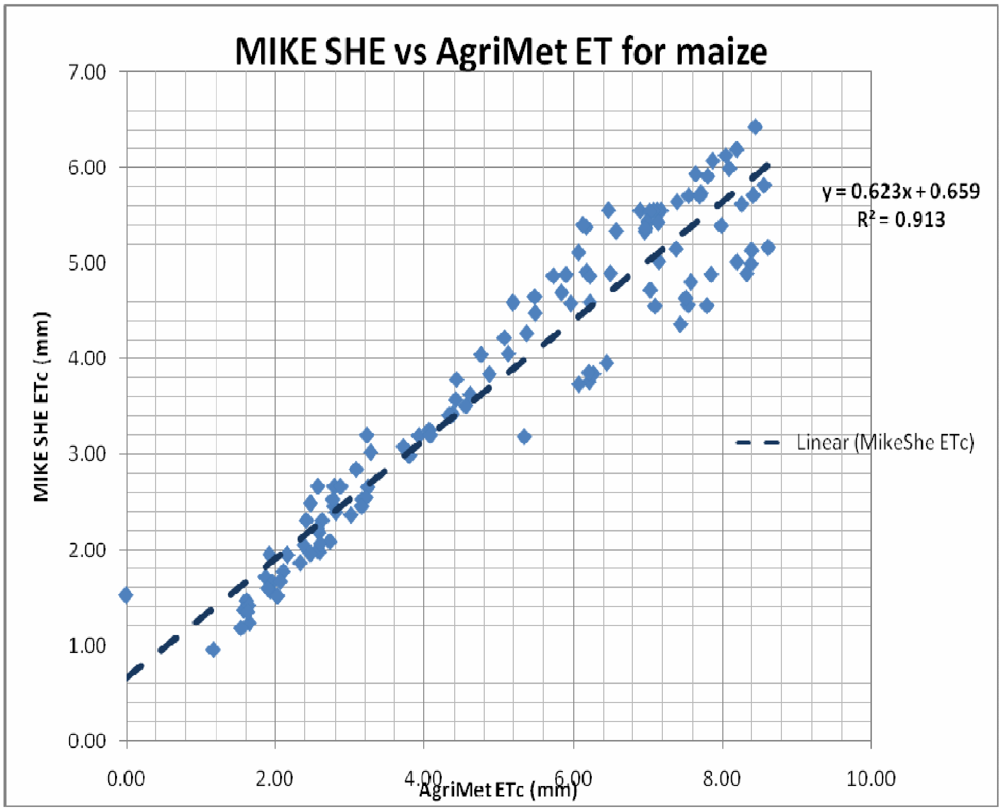
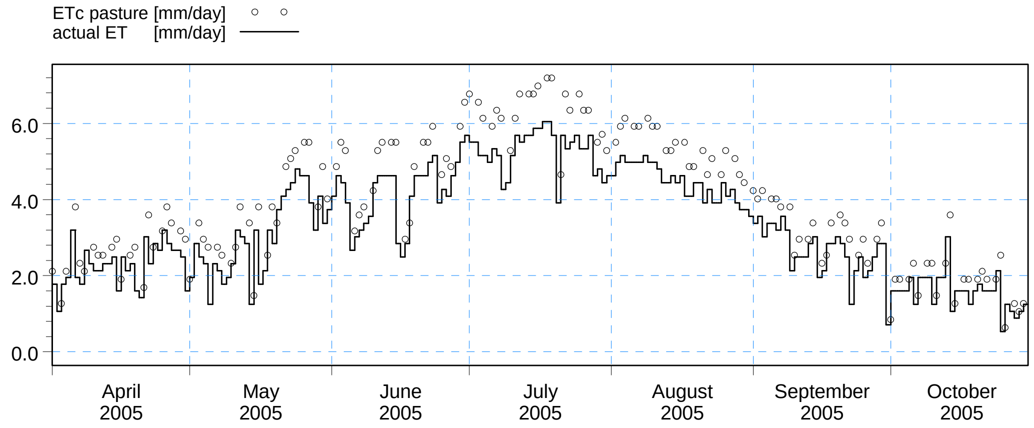
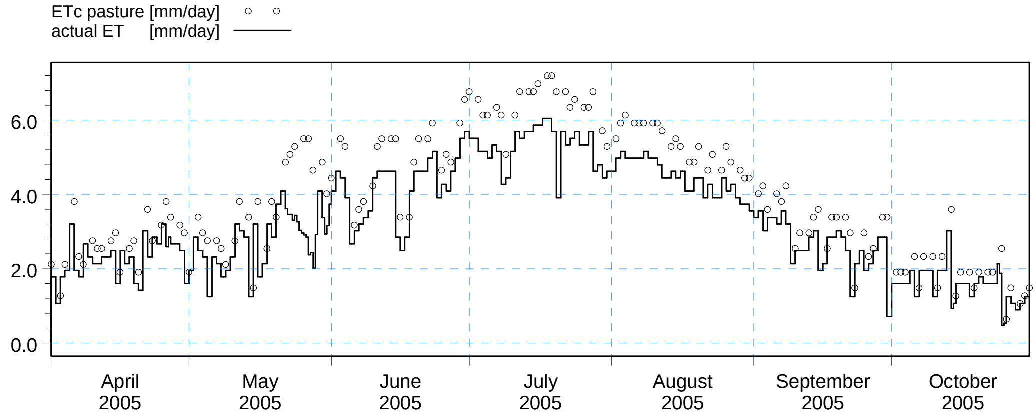


Figure 4.25 MIKE SHE ET_c vs AgriMet ET_c for the growth of maize. The high R^2 value indicates good correlation between the two methods for this particular vegetation cover.



ME=0.644326
MAE=0.644326
RMSE=0.704026
STDres=0.283719
R(Correlation)=0.99634
R2(Nash_Sutcliffe)=0.821403

Figure 4.26 ***ET*** **over grass with irrigation supply based on daily deficit.**



ME=0.68811
MAE=0.68811
RMSE=0.791767
STDres=0.391664
R(Correlation)=0.981831
R2(Nash_Sutcliffe)=0.774113

Figure 4.27 ***ET*** **for pasture with irrigation application on a monthly deficit basis.**

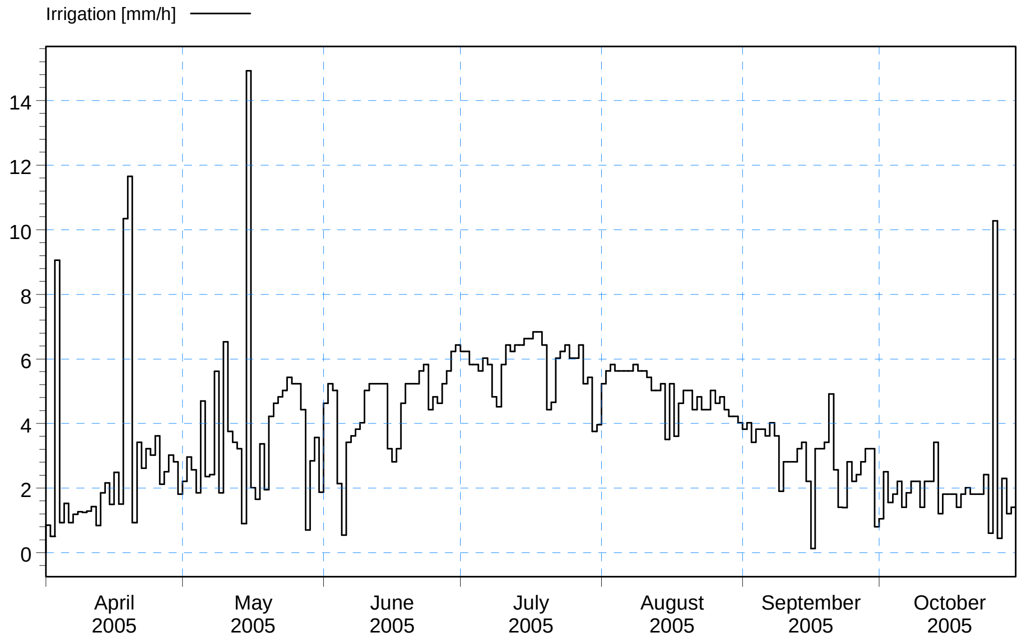
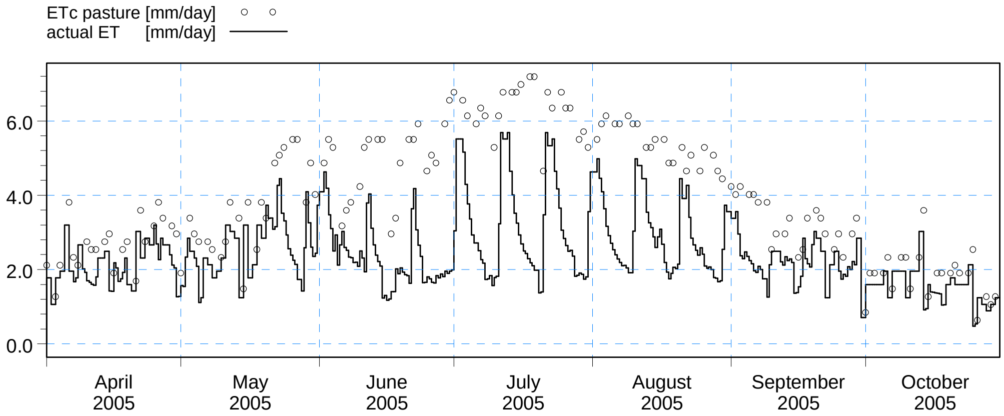


Figure 4.28 Irrigation in mm/h for grass throughout the growing season based on monthly deficit.



ME=1.55774
MAE=1.55774
RMSE=2.04141
STDres=1.31939
R(Correlation)=0.61054
R2(Nash_Sutcliffe)=-0.501609

Figure 4.29 The ET for pasture with irrigation every 5 days with rates varying from 5-20 mm/day.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Observations

5.1.1 1-D model

One dimensional modeling was possible in this project because of the assumption of homogeneity of the 1 square km study plot. The initial phase of the modeling was performed using a GIS map and actual topography over a study area of approximately 1.3 square km. Run time varied from two to three hours for each setup and calibrating the model took an extremely long amount of time. A suggestion by DHI staff to run in 1-D changed the scenario and the model was calibrated with less effort and more efficiency. No saturated flow or overland flow was considered. The focus was only in the unsaturated zone and plant cover at the surface.

5.1.2 Soils

Van Genuchten equations for hydraulic conductivity and the soil water retention curve were used. The SSURGO database gave the profile layers and physical properties of the soil at the site. The Klamath-Dilman-Onkto association of soils (map symbol 34 on SCS soil survey database) was the main soil type in the study area, with 60 percent Klamath type. It is assumed that soil with Klamath type was uniformly distributed in the study site of interest. The soil was 152 cm deep. There were three layers but all three layers had the same hydraulic conductivity according to the SSURGO database. The van Genuchten parameters were selected from Carsel and Parrish (1988) according to the USDA soil texture classification.

5.1.3 Vegetation

The vegetation used to model *ET* over this surface was selected to test the effects of changing the landscape from what is currently a rangeland to irrigated pasture, or wetlands or natural vegetation growth. The natural vegetation, such as juniper, sagebrush and ponderosa pine were simulated in natural conditions allowing rainfall and groundwater to fulfill the water requirements. The field was virtually flooded to allow wetland vegetation to grow. The field was also irrigated to test for maize and and irrigated pasture.

Most of the work time was spent on collecting the crop information. Obtaining information for values of crop coefficients, leaf area index (*LAI*) and rooting depth for the arid and semi-arid regions was difficult. The values had to be estimated in some cases where a wide range of possible values was given and just taking the mean would give biased results. MIKE SHE has the option of a vegetation property file in which the growth stage, *LAI*, rooting depth and the crop coefficient had to be supplied for each stage. There is also an option to give constant values or time series values for *LAI* and root depth. To be as close to reality as possible, the vegetation property file was used.

5.1.4 Irrigation

Sprinkler water application with an external water source was used to model maize and pasture. The other methods, drip and sheet irrigation, were unsuited for this research as the model was run only on 1-D and these methods work best with 2-D or 3-D where there is spatial variation. The soil moisture depletion did not reach the initial threshold of 60 percent of field capacity and irrigation initially was not turned on. Since a daily time step was used, the average value for the day was used for calculations. Sprinkler and drip irrigation showed no difference in the results. The simulation is such that drip method applies water directly to the soil surface as ponded water while sprinkler irrigation is added to the precipitation component. Overland flow is required for drip irrigation while this is not so for sprinkler. The 1 sq km cell size is too big for overland flow to occur, and so the water is infiltrated down to the unsaturated zone. The only difference is that drip irrigation is free of interception storage, which is not very significant for small *LAI* values. This was the reason why sprinkler irrigation was preferred over other methods.

Irrigation efficiencies and evapotranspiration are the two important parameters used to determine the amount of water withdrawal and amount of water consumptively used by irrigated crops (Borrelli et al. , 1998). Cuenca (1989) describes four types of irrigation efficiencies to evaluate irrigation systems and determine volume of water needed for design purpose. MIKE SHE does not talk about irrigation efficiency but it allows different options of satisfying irrigation demand. The options are either a maximum allowed deficit, a crop stress factor, ponding depth or user specified. The deficit method can be based on either saturation or field capacity.

In this research, the maximum allowed soil deficit with reference to field capacity was used. Initially, the allowed deficit range was between 60 percent of available soil water content and field capacity. However, for this scenario the simulation did not trigger irrigation, indicating that the soil moisture never dropped to 60 percent of available water. On the other hand, the plant showed declining *ET* rates indicating that the plant was deficient of water. When the model was run with maximum of 20 percent soil water deficit, the results were positive with *ET* close to the *ET* rates estimated from AgriMet (Nash and Sutcliffe efficiency = 0.98).

The results show that irrigation application can be done in various ways, but that the adequacy and efficiency of irrigation reflecting non-uniformity of water application still need to be accounted for in the simulation model.

5.1.5 Reference Evapotranspiration

The reference evapotranspiration provided by AgriMet was used. AgriMet uses the Kimberly-Penman (Wright, 1982) which is an alfalfa reference suitable for agricultural crops. The standard reference surface for the FAO 56 Penman-Monteith is grass while the Kristensen and Jensen (1975) method uses the concept of "potential" evapotranspiration. A conversion factor of 0.833 (Borrelli et al., 1998; Jensen et al., 1990) was used to convert the alfalfa to grass *ET*. This factor was determined by Jensen et al., 1990 after a comparison of alfalfa and grass references. This particular value has been used by Borrelli et al. (1998). They calculated the ratio of *ET*r (alfalfa reference) to *ET*o (grass reference) as 1.2, as determined by comparing the *ET* from grass to alfalfa lysimeters at Kimberly, Idaho.

In the Kristensen and Jensen method, the potential *ET* (Ep in the original 1975 article) was considered to be the upper limit on *ET*. But in reality, and as stated in FAO 56, actual *ET* can be higher than reference *ET*, as fully grown crops can transpire at rates higher than reference grass. Therefore crop coefficients (K_c) can be greater than 1. MIKE SHE adjusts for this *ET* situation based on the K_c values provided. When the K_c is smaller than 1, the *LAI* values should be used to adjust for actual *ET* in the Kristensen and Jensen method. But when K_c is greater than 1, then *Ep* is multiplied by the K_c factor to yield an updated *Ep* for this method. However, through the course of this study it was realized that the Kristensen and Jensen method, as implemented in MIKE SHE, adjusted *Ep* for *Kc* less than 1, and this updated value of *Ep* was then further adjusted using the *LAI* function. This is not the usual method of applying crop coefficients for values of *Kc* less than 1. It is for this reason that all *Kc* values less than 1 were set equal to 1 to make the simulation runs of this study.

LAI

5.1.6 Calibration

Since this is a 1-D model, calibration was faster and more efficient than running a 2-D or 3-D model. The 1,000 m by 1,000 m grid model with 16 soil profile layers ran in about two minutes. The water balance model is selected for the grid series output and the model run time is longer as more items are selected. Initially when the model was run for the distributed file on a 10 m DEM, it would take about 3 hours for one run. Running the model with the larger 1-D scale allowed for faster runs and the flexibility to calibrate the model and make observations more efficiently. A 1-D model of this scale would not work in scenarios where the gradient is steep and overland flow is expected or channel flow is to be added.

5.1.7 Time steps

The computational time steps played a significant role in running the model effectively. The storing of results was done for each 24 hours. When this storage time was changed to 6 hours, the model took longer to run but gave more information as a function of time. This is an advantage of MIKE SHE which has the capacity to run an advanced model with smaller time steps if required.

5.2 Other observations

The Kristensen and Jensen method for calculating evapotranspiration is acceptable for common agricultural crops grown on well drained clayey loam soils (Kristensen and Jensen, 1975). The original paper also suggests that for other soil and vegetation types, the constants and parameters need to be tested. In this research, the default values for parameters were used. The results obtained for irrigated scenarios were acceptable. However, the results for unirrigated natural vegetation were problematic as indicated by the relative low to very low Nash and Sutcliff Efficiency values.

This model was simplified to 1-D and assumptions were made to determine the sensitivity of the evapotranspiration component and to test the Kristensen and Jensen method. It is assumed that there are no other factors involved that would bias the results running in 1-D. The results would be more realistic in 2-D, but in the interest of the subject matter, it was assumed that spatial variation would not affect the results.

The model results indicate that the natural vegetation like juniper, ponderosa pine and sagebrush would find it difficult to survive in the relatively dry conditions of the research area. Currently, the vegetation over the field is dominated by tufted hairgrass (60%), followed by Baltic rush, Nebraska sedge, northern mannagrass and reedgrass, (5% each). The simulations were run with no external water supply and the dry summers predicted low *ET*.

The irrigation component of MIKE SHE needs some modification. For reasons yet to be determined, the irrigation did not turn on when the maximum allowed deficit feature was used at 30 percent for grass resulting in lower *ET* estimation. When 10 percent deficit was used, the results showed that the grass dried out before the next application in 3 days. Time constraints have not allowed for debugging of this problem with the simulation of irrigation.

5.3 Limitations of MIKE SHE

Plant chemistry: The model does not account for interactions of plant chemistry with the soil such as nutrient transport. It only computes the water balance within the root zone. MIKE SHE ver 2007 has a new water quality dynamics included. The plant chemistry involved in the transpiration process has been totally ignored.

Plant life: When water is not available, the plant remains in a dormant state until water is available, and there is no plant death involved. It is for the modeler to judge whether the plant is dead or just dormant.

Groundwater table: One of the big flaws of MIKE SHE is that it does not allow input of water table data which varies temporally. It asks for the initial GW table information and does its own calculation with the spatial variability and temporal variability of other input parameters. There is no result indicating where the final ground water table would be after the model is run. This model is not running the saturated flow component which would probably have something to say about groundwater, but it should certainly trace the depth of the unsaturated zone.

Root depth: MIKE SHE does not model the density growth of the root system. Plants like juniper grow laterally with dense root system and more surface area for water suction. This is difficult to model in MIKE SHE.

Stomatal conductance (or resistance): Some plants like Ponderosa pine save water during dry season by limiting the transpiration, which is controlled by the stomatal conductance of its needle-like leaves. The vegetation property file does not allow for this information to be used as input, giving erroneous simulation results during dry periods. Arid-land vegetation naturally adjusts for stomatal resistance to reduce the water transported through transpiration.

Irrigation efficiency: The irrigation component does not account for the adequacy, application uniformity and resulting deep percolation. It is necessary to know these factors to be able to simulate irrigation more efficiently.

Software: MIKE SHE is not an open source model. A license is required to use the model. There are opportunities for other open source models to perform as well as MIKE SHE and for the interested modeler to test with without having to be a professional user.

BIBLIOGRAPHY

Abtew, W. (2005). "Evapotranspiration in the Everglades :Comparison of Bowen Ratio Measurements and Model Estimations " ASAE Annual International Meeting Tampa Convention Center, Tampa, FL

Allen, R. G. (1996). "Assessing integrity of weather data for reference evapotranspiration estimation." Journal of Irrigation and Drainage Engineering-Asce **122**(2): 97-106.

Allen, R. G., L. S. Pereira, D. Raes and M. Smith (1998). Crop evapotranspiration - Guidelines for computing crop water requirements, FAO - Food and Agriculture Organization of the United Nations. Irrigation and Drainage paper 56

Allen, R. G., L. S. Pereira, M. Smith, D. Raes and J. L. Wright (2005). "FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions." Journal of Irrigation and Drainage Engineering-ASCE **131**(1): 2-13.

Allen, R. G., J. H. Prueger and R. W. Hill (1992). "Evapotranspiration from isolated stands of hydrophytes: cattail and bulrush." American Society of Agricultural Engineers, Transactions, **35**(4): 1191-1198.

Allen, R. G., W. O. Pruitt, D. Raes, M. Smith and L. S. Pereira (2005). "Estimating evaporation from bare soil and the crop coefficient for the initial period using common soils information." Journal of Irrigation and Drainage ASCE **131**(1): 14-23.

Allen, R. G., I. A. Walter, R. Elliot, T. A. Howell, D. Itenfisu, M. J. (editors), R. H. Cuenca, J. L. Wright, P. Brown, B. Mecham, R. Snyder, S. Eching, T. Spofford, M. Hattendorf and D. Martin (2005). "The ASCE Standardized Reference Evapotranspiration Equation." American Society of Civil Engineers **216 pp.**

Bernstein, L. and L. E. Francois (1973). "Comparisons of Drip, Furrow, And Sprinkler Irrigation." Soil Science **115**(1): 73-86.

Bhardwaj, A. K., D. Goldstein, A. Azenkot and G. J. Levy (2007). "Irrigation with treated wastewater under two different irrigation methods: Effects on hydraulic conductivity of a clay soil." Geoderma **140**(1-2): 199-206.

Borrelli, J., C. B. Fedler and J. M. Mgegory (1998). "Mean Crop Consumptive Use and Free-Water Evaporation for Texas." (Grant No. 95-483-137).

Bosch, J. M. and H. J. D. (1982). "A review of catchment experiments to determine the effect of vegetation chanbes on water yield and evapotranspiration." Journal of Hydrology **55**: 3-23.

Brady, N. C. (2001). The Nature and Properties of Soils, Prentice Hall.

Brutsaert, W. (2005). Hydrology An Introduction, Cambridge University Press.

Butts, M. B., J. Overgaard, D. Graham, A. Dubicki, K. Strońska, W. Szalinksa, A. Lewandowski, T. Olszewski, T. Kolerski and O. Larsen (2005). "Process-based Hydrological Modelling Framework MIKE SHE for Flood Forecasting on the Upper and Middle Odra " ICID 21st European Regional Conference 2005 Frankfurt (Oder) and Slubice - Germany and Poland

Cahoon, J., J. Tribe, L. DeMoulin, D. Taylor, J. Boda, R. Bourine and R. Obrigewitsch (1985). Soil Survey of Klamath County, Oregon Southern Part, Soil Conservation Service, USDA.

Campbell, G. S. (1985). "Soil Physics with BASIC." Elsevier.

Campbell, G. S. and G. A. Harris (1977). "Water Relations and Water use Patterns for Artemisia Tridentata Nutt. In Wet and Dry Years." Ecology **58**(3): 652-659.

Canadell, J., R. B. Jackson, J. R. Ehleninger, H. A. Mooney, O. E. Sala and E. D. Schulze (1996). "Maximum rooting depth of vegetation types at the global scale." Oecologia **108**: 583-595.

Clothier, B. (1987). "Soil physics with BASIC - transport models for soil-plant systems G.S. Campbell. Developments in soil science, 14. Elsevier, Amsterdam, 1985. 150 pp., Dfl 120.00/US$41.50, diskette: Dfl.90/US$31.00. ISBN 0-444-42557-8." Agricultural Water Management **12**(3): 252-254.

Cuenca, R. H. (1989). Irrigation Systems Design - An Engineering Approach, Prentice Hall.

Cuenca, R. H., J. L. Nuss, A. Martinez-Cob, G. G. Katul and J. M. Gonzalez (1992). Oregon

Crop Water Use and Irrigation Requirements. Extension Miscellaneous 8530. Corvallis, Oregon State University.

Davies, K. W., J. D. Bates and R. F. Miller (2007). "Environmental and vegetation relationships of the Artemisia tridentata spp. wyomingensis alliance." Journal of Arid Environments **70**(3): 478-494.

Deras, J. and S. Hall (2006). "Design and Testing of Inexpensive Water Capture Devices for Water Quality Assessment " An ASABE meeting Presentation, Paper Number: 062012 Portland, Oregon

DHI, Ed. (1995). MIKE-SHE An Integrated Hydrological Modelling System User Guide. DHI Software 2005. Horsholm, Danish Hydraulic Institute.

Dingman, S. L. (2002). Physical Hydrology, Prentice Hall.

Doorenbos, J. and W. O. Pruitt (1977). "Guidelines for Predicting Crop Water Requirements." FAO Irrigation and Drainage Paper 24.

Eddleman, L. E., P. M. Miller, R. F. Miller and P. L. Dysart (1994). Western Juniper Woodlands (of the Pacific Northwest). Corvallis, Oregon State University.

Emekli, Y., R. Bastug, D. Buyuktas and N. Y. Emekli (2007). "Evaluation of a crop water stress index for irrigation scheduling of bermudagrass." Agricultural Water Management **90**(3): 205-212.

Gaur, A., D. B. Jaynes, R. Horton and T. E. Ochsner (2007). "Surface and subsurface solute transport properties at row and interrow positions." Soil Science **172**(6): 419-431.

Gaur, A., D. B. Jaynes, R. Horton and T. E. Ochsner (2007). "Surface and subsurface solute transport properties at row and interrow positions." Soil Science **172**(6): 419-431.

Gholz, H. L. (1980). "Structure and productivity of Juniperus occidentalis in central Oregon." American Midland Naturalist **103**: 251-261.

Gifford, G. F. (1975). "Approximate Annual Water Budgets of Two Chained Pinyon-Juniper Sites." Journal of Range Management **28**(1).

Gochis, D. J. (1998). Estimated Plant Water Use and Crop Coefficients for Drip-Irrigated Hybrid Polars. Bioresource Engineering Corvallis, Oregon State University.

Goldberg, D. and M. Shmueli (1970). "Drip Irrigation - A Method Used Under Arid And Desert Conditions Of High Water And Soil Salinity." American Society Of Agricultural Engineers, Transactions, **13**(1): 38-41.

Hatfield, J. L. and R. G. Allen (1996). "Evapotranspiration estimates under deficient water supplies." Journal of Irrigation and Drainage Engineering-Asce **122**(5): 301-308.

Hibbert, R. A. (1983). "Water yield improvement potential by vegetation management on western rangelends." Water Resources Bulletin **19**: 375-81.

Jain, S. K., B. Storm, J. C. Bathurst, J. C. Refsgaard and R. D. Singh, 1992 (1992). "Application of the SHE to catchments in India--Part 2: Field experiments and simulation studies on the Kolar Subcatchment of the Narmada River." Journal of Hydrology **140**: 25-47.

Jensen, M. E., R. D. Burman and R. G. Allen (1990). Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70

Karam, F., R. Lahoud, R. Masaad, R. Kabalan, J. Breidi, C. Chalita and Y. Rouphael (2007). "Evapotranspiration, seed yield and water use efficiency of drip irrigated sunflower under full and deficit irrigation conditions." Agricultural Water Management **90**(3): 213-223.

Kuhn, T. J., K. W.Tale, D. Cao and M. R. George (2007). "Juniper removal may not increase overall Klamath River Basin water yeilds." California Agriculture **61**(4).

Lam, Y., D. C. Slaughter, W. W. Wallender and S. K. Upadhyaya (2007). "Machine vision monitoring for control of water advance in furrow irrigation." Transactions of the Asabe(2): 371-378.

Lam, Y., D. C. Slaughter, W. W. Wallender and S. K. Upadhyaya (2007). "Machine vision monitoring for control of water advance in furrow irrigation." Transactions of the Asabe **50**(2): 371-378.

Lascano, R. J. and C. H. M. van Bavel (2007). "Explicit and Recursive Calculation of Potential and Actual Evapotranspiration." Agron J **99**(2): 585-590.

Levy, S. (2003). "Turbulence in the Klamath River Basin." Bioscience **53**: 315-320.

Lohani, V. K., J. C. Refsgaard, T. Clausen, M. Erlich and B. Storm (1993). "Application of the

SHE for irrigation command area studies in India." Journal of Irrigation and Drainage Engineering **119**(1): 34-49.

Mata-Gonzalez, R., T. McLendon and D. W. Martin (2005). "The Inappropirate use of Crop Transpiration Coefficients (Kc) to Estimate Evapotranspiration in Arid Ecosystems: A review." Arid Land Research and Management **19**: 285-295.

McMichael, C. E., A. S. Hope and H. A. Loaiciga (2006). "Distributed hydrological modelling in California semi-arid shrublands: MIKE SHE model calibration and uncertainty estimation." **317**(3-4): 307-324.

Miranda, F. R., R. S. Gondim and C. A. G. Costa (2006). "Evapotranspiration and crop coefficients for tabasco pepper (Capsicum frutescens L.)." Agricultural Water Management **82**(1-2): 237-246.

Mmolawa, K. and D. Or (2000). "Root zone solute dynamics under drip irrigation: A review." Plant and Soil **222**(1): 163-190.

NRCS (2004). Upper Klamath Basin: Opportunities for Conserving and Sustaining Natural Resources on Private Lands. Klamath Basin Rapid Subbasin Assessments.

OSUES (1993). Western Juniper Its Impact and Management in Oregon Rangelends. Corvallis, Oregon State University Extension Service.

Refsgaard, J. C., S. M. Seth, J. C. Bathurst, M. Erlich, B. Storm, G. H. Jørgensen and S. Chandra (1992). "Application of the SHE to catchments in India-- Part 1: General Results. ." Journal of Hydrology **140**: 1-23.

Richards, L. A. (1931). "Capillary conduction of liquids through porous media." Physics **1**: 318-333.

Simonin, K., T. E. Kolb, M. Montes-Helu and G. W. Koch (2006). "Restoration thinning and influence of tree size and leaf area to sapwood area ratio on water relations of Pinus ponderosa." Tree Philosophy **26**: 493-503.

Stene, E. A. (1994). The Klamath Project (Seventh Draft). Denver, Colorado, Bureau of Reclamation History Program, Research on Historic Reclamation Projects.

Stubbendieck, J., S. L. Hatch and C. H. Butterfield (1997). North American Range Plants, University of Nebraska Press Lincoln and London.

Thompson, M. L., B. E. Ewers, R. Sivanpillai and E. Pendall (2006). "Scaling Vegetation Cover From Plots to Regions in a Sagebrush Ecosystem." AGU.

Tisdale, E. W. and M. Hironaka (1981). "The Sagebrush-Grass Region: A Review of the Ecological Literature." **33**.

Towler, B. W., Joel E. Cahoon and O. R. Stein (2004). "Evapotranspiration Crop Coefficients for Cattail and Bulrush." Journal of Hydrologic Engineering **9**(3): 235-239.

Vazquez, R. F. and J. Feyen (2003). "Effect of potential evapotranspiration estimates on effective parameters and performance of the MIKE SHE-code applied to a medium-size catchment." Journal of Hydrology **270**(3-4): 309-327.

Wallace, J. S. (1995). "Calculating Evaporation: resistance to factors." Agriculture for Meterology **73**: 353-366.

Wight, J. R. and R. J. Hanks (1981). "A water -balance climate model for range herbage production." Journal of Range Management **34**: 307-311.

Wight, J. R., C. L. Hanson and K. R. Cooley (1985). "Modeling Evapotranspiration from Sagebrush-Grass Rangeland." Journal of Range Management **39**(1).

Wright, J. L. (1982). "New Evapotranspiration Crop Coefficients." Journal of the Irrigation and Drainage Division, ASCE **108**(1): 57-73.

Wright, J. L. and M. E. Jensen (1972). "Peak water requirements of crops in southern Idaho." Journal of Irrigation and Drainage ASCE **98**(IR2): 193-201.

Xevi, E., K. Christiaens, A. Espino, W. Sewnandan, D. Mallants, H. Sørensen and J. Feyen (1997). "Calibration, Validation and Sensitivity Analysis of the MIKE-SHE Model Using the Neuenkirchen Catchment as Case Study " Water Resources Management **11**(3): 219-242.

APPENDIX

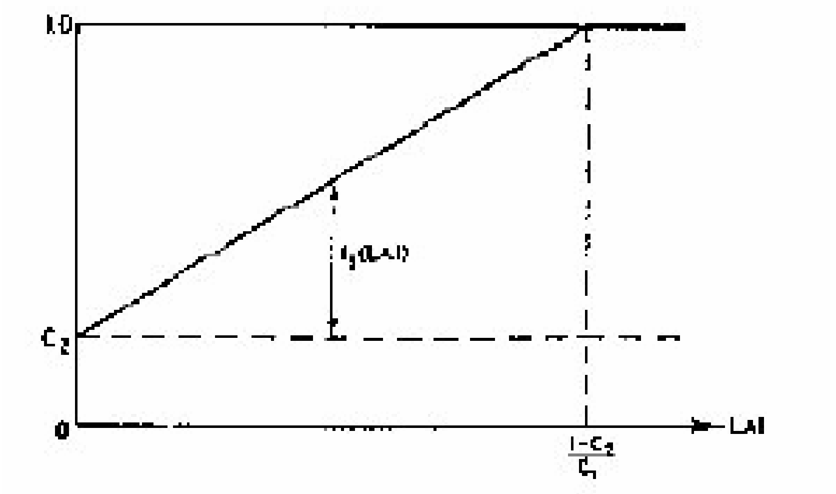
Appendix I

The Kristensen and Jensen evapotranspiration method uses f(1) as a linear function of *LAI*. It uses empirical parameters C1 and C2, such as

$$f_1(LAI) = C_2 + C_1 LAI$$

The graph below is from the DHI MIKE SHE manual, borrowed from Kristensen and Jensen (1975). The function is the ratio of actual *ET* to potential *ET*, *EA/EP* is a function of vegetative growth, here considered as *LAI*. The original text says that it can be any growth property such as height, development stage, age or vegetation and so on, but the slope of the line C1 should be changed accordingly.

Here it shows that value of $f_1(LAI)$ lies between 0 and 1. The $f_1(LAI)$ is exactly 1 when $LAI = (1-C_2)/C_1$. When *LAI* is greater, then $f_1(LAI)$ is considered as a constant $(1-C_2)$.



Appendix II

HCPC, DECA18-CANE2 Plant Species Composition

	Grass/ Grasslike			Annual Production in Pounds Per Acre	
Group	**Group Name**	**Common Name**	**Scientific Name**	**Low**	**High**
1 - Dominant deep rooted perennial grasses				1250	1625
		tufted hairgrass	Deschampsia caespitosa	1250	1625
2 - Sub-dominant deep rooted perennial grasses				450	575
		reedgrass	Calamagrostis	75	125
		Nebraska sedge	Carex nebrascensis	125	200
		small floating mannagrass	Glyceria borealis	75	125
			Juncus balticus (Syn)	75	125
5 - Other perennial grasses				50	500
		American sloughgrass	Beckmannia syzigachne	0	5
		sedge	Carex	0	5
		oatgrass	Danthonia	0	5
		slender wheatgrass	Elymus trachycaulus	0	5
		meadow barley	Hordeum brachyantherum	0	5
		prairie Junegrass	Koeleria macrantha	0	5
		beardless wildrye	Leymus triticoides	0	5
		Sandberg bluegrass	Poa secunda	0	5

Forb				**Annual Production in Pounds Per Acre**	
Group	**Group Name**	**Common Name**	**Scientific Name**	**Low**	**High**
7 - Dominant perennial forbs				75	150
		buttercup	Ranunculus	25	50
		western aster	Symphyotrichum ascendens	25	50
		clover	Trifolium	25	50
9 - Other perennial forbs				25	200
		common yarrow	Achillea millefolium	0	5
		rosy pussytoes	Antennaria rosea	0	5
		foothill arnica	Arnica fulgens	0	5
		strawberry	Fragaria	0	5
		threepetal bedstraw	Galium trifidum	0	5
		iris	Iris	0	5
		primrose monkeyflower	Mimulus primuloides	0	5
		cinquefoil	Potentilla	0	5
		ragwort	Senecio	0	5

Shrub/Vine				**Annual Production in Pounds Per Acre**	
Group	**Group Name**	**Common Name**	**Scientific Name**	**Low**	**High**
15 - Other shrubs				50	125
		silver sagebrush	Artemisia cana	0	5
		wax currant	Ribes cereum	0	5

Tree				**Annual Production in Pounds Per Acre**	
Group	**Group Name**	**Common Name**	**Scientific Name**	**Low**	**High**
18 - Dominant deciduous trees				50	150
		quaking aspen	Populus tremuloides	25	75
		willow	Salix	25	75

Plant Type	Low	Representative Value	High
Forb	100	225	350
Grass/Grasslike	1650	2175	2700
Shrub/Vine	50	88	125
Tree	50	100	150
Total:	**1850**	**2588**	**3325**

Percent Production by Month

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0	0	0	0	10	30	40	15	5	0	0	0

Appendix III

AgriMet Weather Station Equipment and Sensors

Equipment	Manufacturer
Data Logger Model CR10X	Campbell Scientific, Inc.
GOES Transmitter Model TX312	Campbell Scientific, Inc.
Yagi Antenna, Model 5000-0080	Sutron, Inc.
10 Watt Solar Panel Model MSX-10	Solarex, Inc.
31-PHD Workaholic Battery	Interstate Batteries, Inc.
Station Tripod	U.S. Bureau of Reclamation
NEMA 4-E Enclosure Model A-24 H20 CLP	Hoffman, Inc.

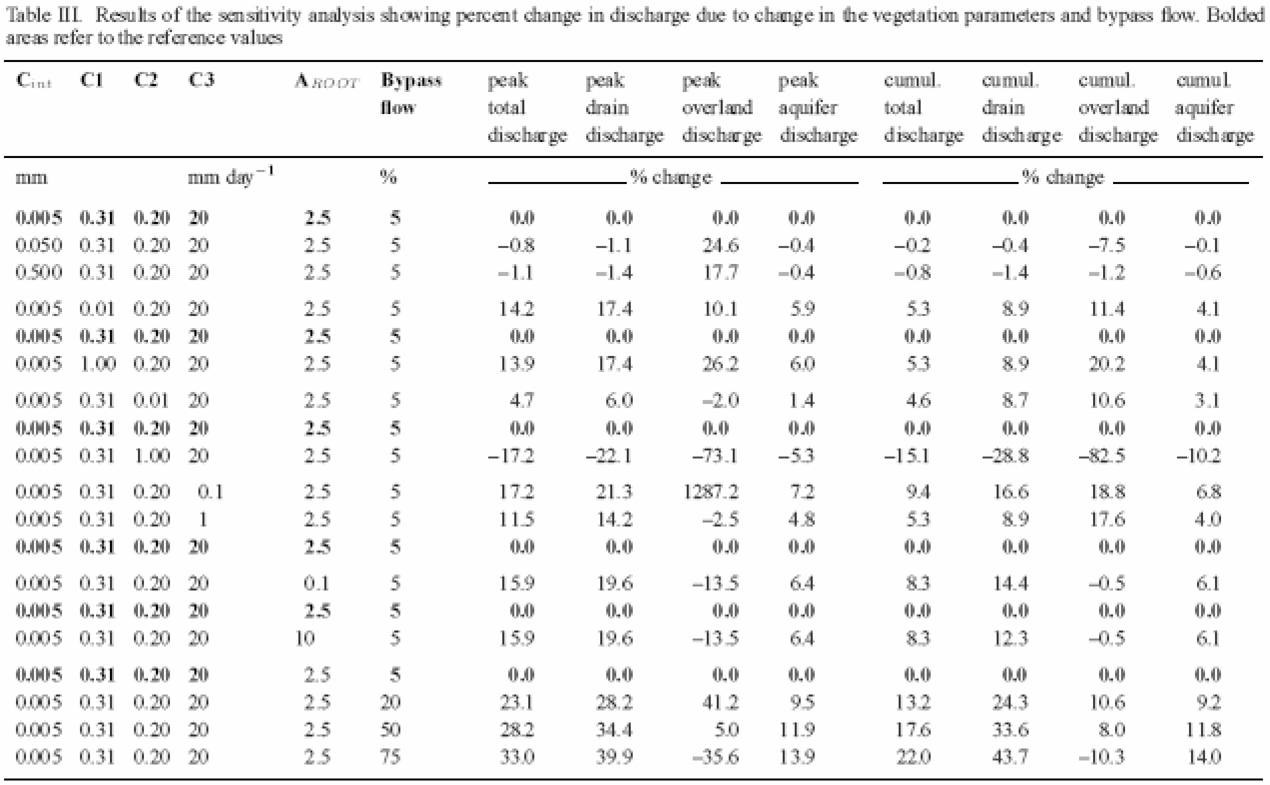
Sensors	Manufacturer	Sensor Height
Pyranometer Model LI-200	Licor, Inc.	3 meters
Wind Monitor Model 05103	RM Young, Inc.	2 meters
Air Temperature Thermistor Model 44030	YSI, Inc.	2 meters
Relative Humidity Sensor Model HMP 35A/45D	Vaisala, Inc.	2 meters
Temperature/RH Radiation Shield Model 41002P	RM Young, Inc.	2 meters
Tipping Bucket Precipitation Gage Model 6011A/6010	All Weather, Inc.	2 meters
Tipping Bucket Precipitation Gage Model TB3	Hydrological Services, Ltd.	2 meters
Universal Storage Precipitation Gage	Belfort Instruments, Inc.	2 meters

Soil Temperature Thermistor Model 44030	YSI, Inc.	1,2,4,8,20,40 inches
Leaf Wetness Sensor Model 237	Campbell Scientific, Inc.	Variable
Barometer Model PTB 101B	Vaisala, Inc.	2 meters
Evaporation Pan	Novalynx, Inc.	12 inches

Source:
http://www.usbr.gov/pn/agrimet/aginfo/sensors.html

Appendix IV

Table III. Results of the sensitivity analysis showing percent change in discharge due to change in the vegetation parameters and bypass flow. Bolded areas refer to the reference values



C$_{int}$	**C1**	**C2**	**C3**	**A**$_{ROOT}$	**Bypass flow**	peak total discharge	peak drain discharge	peak overland discharge	peak aquifer discharge	cumul. total discharge	cumul. drain discharge	cumul. overland discharge	cumul. aquifer discharge
mm			mm day^{-1}		%	% change				% change			
0.005	**0.31**	**0.20**	**20**	**2.5**	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
0.050	0.31	0.20	20	2.5	5	−0.8	−1.1	24.6	−0.4	−0.2	−0.4	−7.5	−0.1
0.500	0.31	0.20	20	2.5	5	−1.1	−1.4	17.7	−0.4	−0.8	−1.4	−1.2	−0.6
0.005	0.01	0.20	20	2.5	5	14.2	17.4	10.1	5.9	5.3	8.9	11.4	4.1
0.005	**0.31**	**0.20**	**20**	**2.5**	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
0.005	1.00	0.20	20	2.5	5	13.9	17.4	26.2	6.0	5.3	8.9	20.2	4.1
0.005	0.31	0.01	20	2.5	5	4.7	6.0	−2.0	1.4	4.6	8.7	10.6	3.1
0.005	**0.31**	**0.20**	**20**	**2.5**	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
0.005	0.31	1.00	20	2.5	5	−17.2	−22.1	−73.1	−5.3	−15.1	−28.8	−82.5	−10.2
0.005	0.31	0.20	0.1	2.5	5	17.2	21.3	1287.2	7.2	9.4	16.6	18.8	6.8
0.005	0.31	0.20	1	2.5	5	11.5	14.2	−2.5	4.8	5.3	8.9	17.6	4.0
0.005	**0.31**	**0.20**	**20**	**2.5**	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
0.005	0.31	0.20	20	0.1	5	15.9	19.6	−13.5	6.4	8.3	14.4	−0.5	6.1
0.005	**0.31**	**0.20**	**20**	**2.5**	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
0.005	0.31	0.20	20	10	5	15.9	19.6	−13.5	6.4	8.3	12.3	−0.5	6.1
0.005	**0.31**	**0.20**	**20**	2.5	**5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
0.005	0.31	0.20	20	2.5	20	23.1	28.2	41.2	9.5	13.2	24.3	10.6	9.2
0.005	0.31	0.20	20	2.5	50	28.2	34.4	5.0	11.9	17.6	33.6	8.0	11.8
0.005	0.31	0.20	20	2.5	75	33.0	39.9	−35.6	13.9	22.0	43.7	−10.3	14.0

Appendix V

Softwares used for the preparation of this thesis are as follows:

1. MS word 2007 for the body text and layouts
2. MS Excel 2007 for the graphs
3. MS OneNote 2007 for screen prints and figures, organizing and planning
4. MS Powerpoint 2007 for presentation slides
5. MS Equation Editor ver. 3.1 for equations
6. EndNote X1.0.1 for bibliography
7. Matlab ver. 2006 for calculations
8. Arc GIS ver 9.1 for mapping
9. DHI MIKE SHE ver. 2005 and ver. 2007 for running the simulation
10. Freemind ver 0.8.0 for flowcharts and throwing ideas
11. Notepad ver 5.1 for collecting ascii data
12. Toshiba machine, A105-S2716, 1024MB ram, 100GB hard drive, Intel Centrino Mobile Technology processor