AN ABSTRACT OF THE THESIS OF

Joshua M. Owens for the degree of Master of Science in Water Resources Engineering presented on June 10, 2010.

Title: Basin-wide Distributed Modeling of Hydrologic Responses to Irrigation Management in the Wood River Basin, Klamath County, OR

Abstract approved:

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The Wood River Basin lies upstream of Upper Klamath Lake, the main reservoir of the USBR Klamath Irrigation Project that provides irrigation water to 210,000 acres of downstream land. Water allocation became a contentious issue in 2001 when drought led to curtailment of irrigation deliveries to the Klamath Irrigation Project in order to maintain minimum lake levels and river flows for endangered species. After lengthy negotiations the Klamath Basin Restoration Agreement was signed in February 2010, and calls for flow increases of 30,000 ac-ft/yr into Upper Klamath Lake from voluntary upstream sources. The Wood River Basin is a potential source of this water, but poorly understood hydrology makes estimates of water gains in response to conservation strategies uncertain.

To better understand the hydrology of the Wood River Basin a fully distributed, physically based model was set up using the MIKE SHE hydrology model and MIKE 11 hydraulic model by DHI, Inc. The model was developed by recreating the actual management of the basin from 2002 to 2009, a period when tracts of land in the basin were enrolled in land idling programs for water conservation. Calibration and validation was evaluated against shallow groundwater observations. Overall the

model described the average conditions of the basin well. Locations that were simulated inaccurately were limited to those in close proximity to the model boundary or to the Wood River, the result of using average values to describe these heterogeneous features. The model was used to simulate two end-member scenarios to determine the limits of water conservation strategies, basin-wide full irrigation and non-irrigation. Two reduced irrigation scenarios were also simulated, the first reduced the irrigation season to June and July, the second eliminated every other irrigation application.

The simulation that recreated the actual management showed that non-irrigated tracts did not substantially reduce the consumptive use because water from the surrounding irrigated tracts was able to flow in via the shallow aquifer and provide sub-irrigation. For the full irrigation scenario the average annual consumptive use was 126,000 ac-ft/yr. For the non-irrigated scenario it was 96,000 ac-ft/yr, a reduction of 24%. For the two reduced irrigation scenarios the consumptive use was decreased by 14% and 12%. When compared to the irrigated scenario the total increase of flow to Upper Klamath Lake during the growing season was 60,000 ac-ft/yr for the non-irrigated scenario; and 36,000 ac-ft/yr and 31,000 ac-ft/yr for the two reduced irrigation scenarios respectively. Irrigation in the basin was found to transfer stream flow from the summer time to the winter time due to saturated winter conditions from late season irrigations resulting in increased runoff.

There is potential for water conservation strategies in the Wood River Basin to substantially increase water flow into Upper Klamath Lake, but these strategies would have to be implemented extensively throughout the basin to reduce sub-irrigation.

Basin-wide Distributed Modeling of Hydrologic Responses to Irrigation Management in the Wood River Basin, Klamath County, OR

by

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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.

Joshua M. Owens, Author

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

<u>Figure</u> <u>Page</u>

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

Figure | Page

LIST OF FIGURES (Continued)

<u>Figure</u> <u>Page</u>

LIST OF TABLES

Table | Page

Basin-wide Distributed Modeling of Hydrologic Responses to Irrigation Management in the Wood River Basin, Klamath County, OR

1 Introduction

Drought water shortages in the Upper Klamath Basin (Figure 1) in 2001 brought water allocation issues to the national attention. Legal requirements from the Endangered Species Act (ESA) required water to be kept in-lake and in-stream. This led to curtailment of water deliveries to the US Bureau of Reclamation (USBR) Klamath Irrigation Project (Klamath Project), resulting in economic losses estimated to be between $27 million to $47 million (Jaeger, 2003). Major water users in the Upper Klamath Basin include Klamath Project Irrigators served by the USBR, private non-Klamath Project Irrigators, the US Fish and Wildlife Service (USFWS) for maintaining National Wildlife Refuges, Pacificorp as an operator of some dams in the Klamath Project, and the Klamath Tribes who have water rights to maintain traditional hunting, fishing, trapping, and gathering activities.

The Klamath Project had received uninterrupted water deliveries for over 100 years, but recent water rights confirmed for the Klamath Tribes and given to endangered species meant that the Klamath Project irrigators would be the first to have water deliveries cut off. The tribal water rights have a priority date of time immemorial and are senior to the Klamath Project rights. Water for in-lake and in-stream uses are also given priority over the Klamath Project because of ESA legal requirements. The water rights priority of the tribes and the ESA has been confirmed in *Klamath Water Users Association v. Patterson* and *Kandra v. United States*. Most of the conflict arose because the water requirements for the Klamath Tribes and endangered species were never quantified and the amount of water needed for these uses was under dispute.

Upper Klamath Lake is the main reservoir of the Klamath Project, which delivers water to irrigation districts downstream in Oregon and California. To secure water for deliveries to the Klamath Project the USBR created a water bank in 2003 that paid

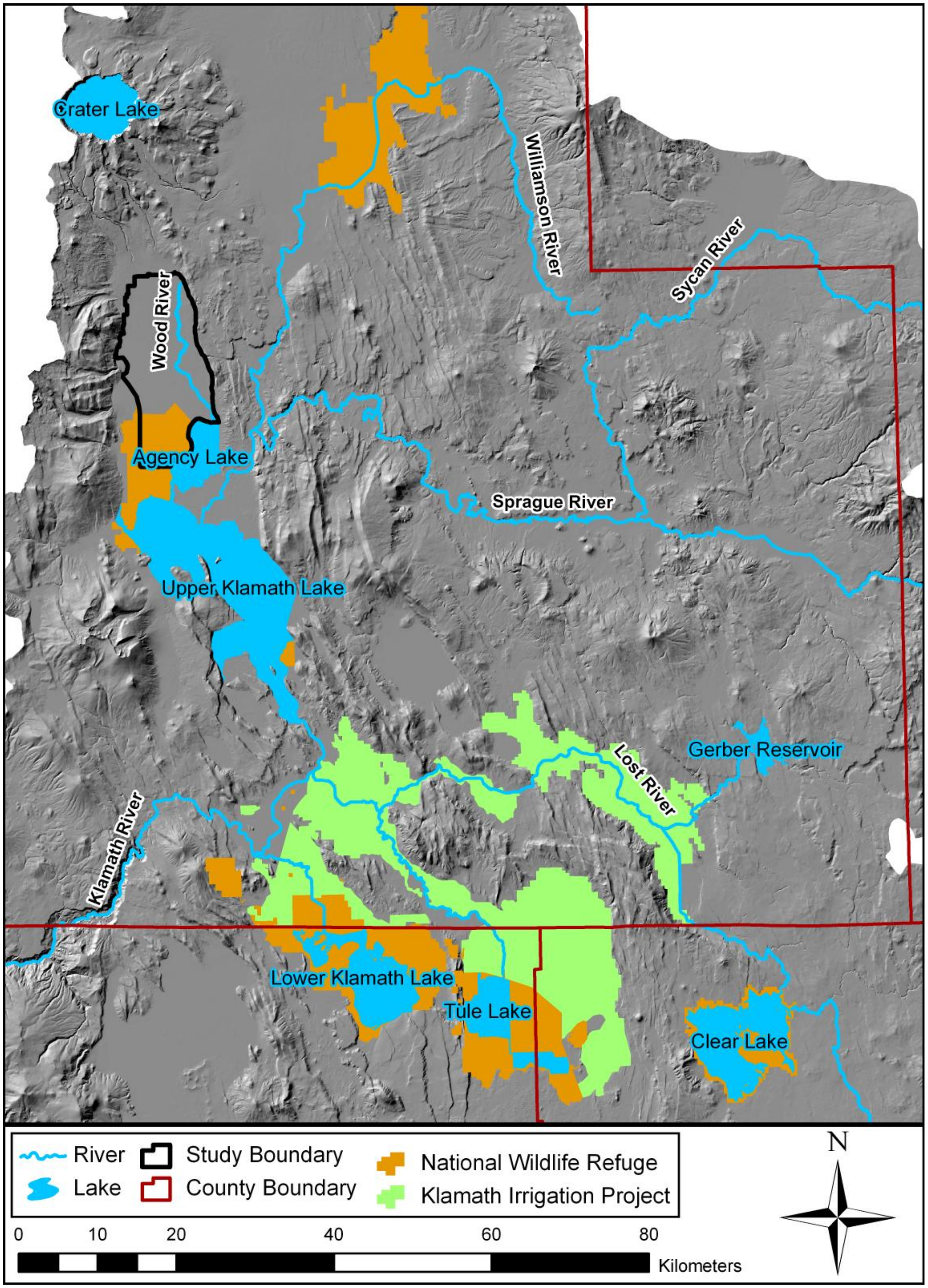

Figure 1: Upper Klamath Basin.

Klamath Project irrigators for land idling and using groundwater in lieu of receiving surface water deliveries, thereby decreasing water demand. To reduce the costs of operating the water bank and reduce the overall economic impacts of water shortages Jaeger (2004a) suggested that the additional water for the Klamath Project would best be obtained by transferring it from low value uses to high value uses. Non-Klamath Project lands are upstream of Upper Klamath Lake and have a lower land capability than Klamath Project lands, meaning that agricultural activities are limited and the land is less productive. Presumably these lands have less economic return per volume of water applied than the more capable lands in the Klamath Project, and would be the best source for additional water.

Water rights transfers cannot currently be done in the basin because the adjudication process for confirming water rights is not complete, however if irrigators upstream of the Klamath Project are paid for irrigation forbearance then the conserved water will be available for use downstream. A water rights transfer is not required in this case because the downstream users are only interested in ensuring that adequate flows are available to use their current water right, and not in enlarging it. Irrigated lands outside of the Klamath Project are in the Wood River, Williamson River, and Sprague River basins. In 2004 the USBR extended participation in the water bank to these basins, however it is difficult to get an accurate measurement of water savings due uncertain hydrology and unmetered irrigation applications (USGS, 2005). This research focuses on the hydrology of Wood River Basin which has many irrigators participating in irrigation and grazing forbearance programs with the assistance of the Klamath Basin Rangeland Trust (KBRT) and the Natural Resources Conservation Service (NRCS).

The Wood River Basin lies in Klamath County, OR sloping from the North at Mt. Mazama to the South at Agency Lake (Figure 2). Wood River originates from a

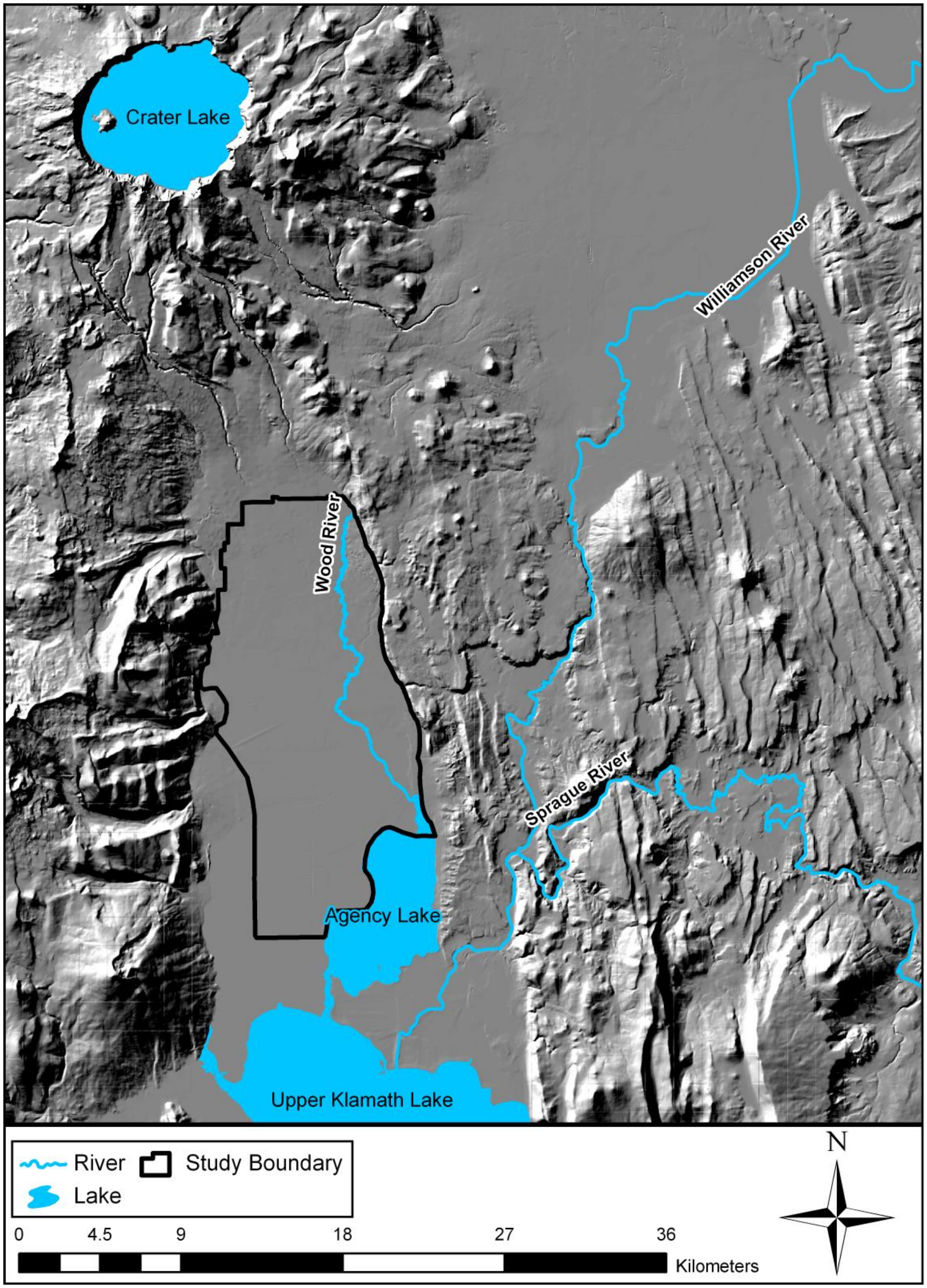

Figure 2: Wood River Basin Study Site. Crater Lake, OR is about 18 km north of the study site. The Sprague, Williamson, and Wood Rivers are the main inflows to Upper Klamath Lake.

spring at Jackson F. Kimball State Recreation Site and flows south for about 30.5 km before emptying into Agency Lake. Agency Lake then flows into Upper Klamath Lake through a small channel. Major tributaries include Annie Creek, Sun Creek, Crooked Creek, Fort Creek, and Sevenmile Creek. The Wood River watershed contains forest, agricultural pasture, and wetlands that are owned and managed by The Bureau of Land Management (BLM), The US Forest Service (USFS), The National Park Service (NPS) and private entities. The study site is the valley bottom which is mostly private land used for pasturing cattle in the summer and fall. Flood irrigation through diversion of surface water is used to maintain pasture productivity.

In 2006 the NRCS initiated a Conservation Effects Assessment Project (CEAP) study in the Wood River Basin to determine the effects of USBR water conservation programs and NRCS grazing forbearance programs on forage production and animal unit carrying capacity (NRCS, 2006). Findings from a field-scale two year vegetation study (Stringham and Quistberg, 2008) and subsequent hydrological and crop growth modeling (Owens et al., 2009) concluded that pasture in non-irrigated tracts was about 20% less productive then in irrigated tracts, although the difference is not significant due to variability within treatments. This indicated that water is available throughout the late summer and fall growing season to sustain pastures. If this is the case then the decrease in water consumptive use in non-irrigated fields may not be as much as the USBR anticipated in the water bank contracts, resulting in less water being available downstream. Possible sources of water include soil water storage, which is high in the porous andisols soils; and sub-irrigation, the upward flux of water to the root zone from the subsoil or shallow aquifer.

The hydrology of the Wood River Basin is poorly understood and the interactions between surface water, groundwater, and irrigation are uncertain. It is possible that inefficient surface irrigations recharge the aquifer during the growing season, elevating the water table across the entire basin and making it available for sub-irrigation in productive non-irrigated tracts. If this is the case then wide scale adoption of the land idling programs may lead to lower non-irrigated pasture productivity than was indicated in the CEAP study. A flux of water from irrigated fields to non-irrigated fields has been recognized at the local field scale by USGS (2005) and Pacific Groundwater Group (2003), but the extent of this flux is unknown.

This uncertainty makes it difficult for the ranchers in the Wood River Basin to make informed decisions about their future water management and the feasibility of adopting long term dryland operations with options to either receive payments for land idling or water rights transfers. To address this question a basin wide hydrologic model was constructed using DHI, Inc's MIKE SHE and MIKE 11 models. MIKE SHE is a versatile model that handles all major processes in the land phase of the hydrologic cycle. MIKE SHE is uniquely suited for this study because it includes a land use and irrigation module that can simulate the basin-wide impacts of irrigation management. Irrigation models are generally written for field-scale studies, while regional hydrology models generally don't contain detailed irrigation capabilities.

The purpose of this study is to evaluate the effects of basin wide irrigation management. More specifically this study will:

- Use MIKE SHE and MIKE 11 to create a basin wide hydrology and irrigation model. This model will be calibrated by simulating the actual management that occurred in the Wood River Basin from 2002 to 2009.
- Simulate the same period with a full irrigation scenario, where all of the pasture in the basin is fully irrigated, with a non-irrigated scenario, where no irrigation occurs in the basin.

- Determine possible reduced irrigation water conservation strategies and simulate their impacts on consumptive use and inflows to Agency Lake.
- The results from these scenarios will be used to assess groundwater, surface water, and consumptive use dynamics in response to irrigation management.

This information will allow irrigators within the Wood River Basin to make informed decisions about their future operations regarding water management. It will also allow the NRCS and USBR to evaluate the effectiveness and value of land idling and grazing forbearance programs.

2 Literature Review

2.1 The Klamath Project

Upper Klamath Lake is the principle reservoir for the US Bureau of Reclamation (USBR) Klamath Project, an irrigation project that was authorized in 1905 and now provides water to about 85,000 ha (210,000 ac) of cropland downstream of the lake in Klamath County, OR; Siskiyou County, CA; and Modoc Co, CA (USBR, 2009). Irrigators in the Wood River basin are not part of the Klamath Project, but since the Wood River is an inflow of Upper Klamath Lake they do impact water availability of the Klamath Project.

Upper Klamath Lake and Agency Lake levels are controlled by the Link Dam, on the Link River near the outlet of Upper Klamath Lake. The Link Dam is operated by PacifiCorp under agreement with the USBR. The water in the lake has important ecological and agricultural uses for the area and management of the water and dam has been a very contentious issue (Owens et al., 2009). During the summer months when agricultural demand is high, the water quality in the lakes is at its worst. The Upper Klamath Lake has historically been eutrophic during the summer, but over the past decades it has become hyper-eutrophic with blue-green algal blooms leading to low dissolved oxygen levels (USFWS, 1993). Both lakes are designated impaired water bodies for chlorophyll a, dissolved oxygen, nutrients, pH, and sedimentation with Upper Klamath Lake is also being impaired for temperature (ODEQ, 2009). Nutrient loading, especially phosphorus, from agricultural sources where poor riparian management has occurred is believed to the greatest contributor to poor water quality.

The Lost River Sucker and Shortnose Sucker are endemic to the Klamath Basin and declining populations since the 1960’s led them to be listed as endangered in 1988.

During the summer, when lake quality is at its worst, the fish take refuge in the north part of the lakes, inflowing rivers, and marshes at the lake edges; including the Wood River and the Wood River Wetland (USFWS, 1993). Maintaining flow and water quality in these streams is an important component of restoring habitat for these species. The BLM has been working on improvements in the Lower Wood River Basin. In 1994 the BLM acquired the Wood River Ranch, a 1,295 ha (3,200 ac) cattle ranch on the north shore of Agency Lake, to restore the Wood River Wetland (USGS, 2009).

In 2001 the total precipitation falling between October 1, 2000 and April 1, 2001 was only 7.6 cm (3 in), about 32 percent of normal levels. The snow pack was also low and water shortages were anticipated (Braunworth et al., 2003). Due to the presence of endangered suckers in Upper Klamath Lake, the USFWS specified minimum lake levels that the USBR had to maintain. To protect salmon the National Marine Fisheries Service (NMFS) issued a biological opinion that required minimum flows at the Iron Gate Dam, a dam on the Klamath River in California (NMFS, 2001). To meet these lake level and flow requirements the USBR severely limited water deliveries to Klamath Project irrigators, resulting in net losses of between $27 and $47 million (Jaeger, 2003), as well as social strife.

In early 2002 the National Research Council (NRC) released an interim report reviewing the biological opinions of the NMFS and USFWS. They found that the scientific evidence linking lake level and flow level to sucker and salmon health respectively was inconclusive. This gave Klamath Project irrigators a sense of vindication because it appeared that perhaps they were unfairly singled out as the cause for the environmental impacts in the basin (Keppen, 2004). In 2002, Klamath Project irrigators received the full allotment of water. In September 2002 the first recorded major adult salmonid mortality occurred in the Klamath River downstream of the confluence of the Klamath and Trinity rivers. The total kill was estimated at 34,000 fish and attributed to a disease epizootic, exacerbated by lower than normal flows and higher than normal runs resulting in a high population density (CADFG, 2004). Under current water allocation practices there was not enough water in 2001 or 2002 to meet all of the demands.

In 2002 the USBR proposed the establishment of a water bank so that willing buyers and sellers could provide additional water for fish and wildlife (USBR, 2002). The water bank was anticipated to grow up to 1.23×10^8 m^3 (100,000 ac-ft) by 2005. A four step operation was proposed with the goal of continuing future operation in a manner consistent with the historic operation defined as the ten-year period from 1990 to 1999. These steps were:

- Determination of water year type (above average, below average, dry, or critical dry) from data available through April 1.
- Preliminary calculation of Klamath Project water supply based on reservoir levels no lower than historic minimum end-of-month elevations, and Klamath River flows based on daily averages no lower than observed historic ten-year minimums.
- Proposed calculation of Klamath Project water supply based on reservoir levels no lower than historic average end-of-month elevations, and Klamath River flows based on daily averages no lower than observed historic ten-year averages, plus a release of 1.23×10^7 m^3 (10,000 ac-ft) in April for downstream smelt migration. This option requires more water to be kept in the lake because it is based on monthly average lake levels, not monthly minimum lake levels.
- Determine water bank requirements based on the difference between the proposed and preliminary calculations above.

The goal of USBR operations is to operate the Klamath Project so that minimum reservoir levels and Klamath River flow based on average ten-year historical levels would be met through the use of a water bank to make up the difference in dry and critical dry years.

In February 2010 the Klamath Basin Restoration Agreement (KBRA) and the Klamath Hydroelectric Settlement Agreement (KHSA) were signed in Salem, OR (Learn, 2010) by over 40 parties. The KHSA calls for the potential removal of four dams on the Klamath River downstream of the Keno Dam pending detailed environmental review, studies, and planning (KBRA, 2010). These are the Iron Gate, J.C. Boyle, Copco 1, and Copco 2 dams. Dam removal is expected to open up 483 km (300 mi) of river habitat for fish.

The KBRA includes actions to increase in-stream flows and Upper Klamath Lake elevations for fisheries (KBRA, 2010). The increase in water supply for these areas may lead to a deficit of up to $1.23x10^8$ m^3 (100,000 ac-ft) in the driest years for the Klamath Project. Water conservation, increased lake storage via levee breaching, and increasing flows from the tributaries of Upper Klamath Lake will be used to enhance water supply. To increase flows into Upper Klamath Lake the Water Use Retirement Program (WURP) will be established to secure $3.70x10^7$ m^3 (30,000 ac-ft) from the Wood, Sprague, Sycan, and Williamson Rivers on a voluntary basis. The WURP will be lead by a team consisting of the Klamath Tribes and the Upper Klamath Water Users Association. Section 16.2.2.E.i of the KBRA lists options securing the additional water as quoted below:

> "Measures that may be used to fulfill the WURP purpose will be described in the WURP. These measures may include, but shall not be required to include or be limited to, sale of valid surface water rights for irrigation, retirement of valid surface water use for irrigation, forbearance agreements, short-term water leasing, split season irrigation, effects of upland management and

> juniper removal, instream flow increases deriving from water efficiency projects, dryland crop alternatives in lieu of irrigation, effects of natural storage such as wetland or improved riparian area performance, and other similar measures."

Accurate determination of flow increases to Upper Klamath Lake in response to the management options listed above will require a better understanding of the complex hydrology within these basins. For the Wood River Basin this research will help determine the quantity of water flow increases and help determine the viability of dryland operations for irrigators within the basin that may choose to take part in the WURP.

2.2 Water Banks and Water Valuation

The purpose of water banks is to provide a means for water to be traded based on market values. A freely operating water bank will transfer water from sellers of low value uses to buyers of high value uses. In the case were water is to be obtained for environmental benefit, such as the Klamath Basin Wildlife Refuge Complex, public funds are used to purchase the water. California has developed four programs to secure water for environmental uses; these are the Environmental Water Account, the Environmental Water Program, the Water Acquisition Program, and the Drought Water Bank. Of these the Water Acquisitions Program is jointly run by the USBR and USFWS, the price paid per acre-foot of water has ranged from $15 to $150 (Burke et al., 2004) from 1993 to 2001. The USBR also operated water banks in the Yakima Basin Project in Washington. The Yakima water bank was spurred by drought in 2001 (Roundtable Associates, n.d.), and was able to transfer water to high value orchards in the region (Meiners and Kosnik, 2003) where a single year drought could have led to serious setbacks in production over a long period. Water banks face considerable challenges to affecting transfers. In general these are establishing the correct price for the water, determining the hydrology and amount of water that will actually be transferred, and operating within the legal and social framework that has been established over water rights and water uses (Burke et al., 2004).

For the Klamath Pilot Water Bank, currently known as the Water Supply Enhancement Study (WSES), there are four options for depositing water. These are land idling, groundwater substitution, groundwater pumping, and off-stream storage. In land idling, or irrigation forbearance, growers are paid per acre to not irrigate. Idling lands within the Klamath Project reduces demand for water delivery whereas idling lands upstream of the Klamath Project increases water supply for water delivery. The uncertain hydrology in the basin makes estimates of water savings per acre of idled land difficult, and the timing of excess available water cannot be controlled. Groundwater substitution uses groundwater in lieu of water from surface reservoirs to reduce demand for water deliveries, and can only be used with a subsurface water right. Groundwater pumping involves delivering groundwater to the Klamath Project canals for use by other growers. Groundwater can be easily metered and scheduled so it is easier for the USBR to account for. However, increased pumping over multi-year periods has led to water table declines and questions as to whether ground water use is sustainable (USGS, 2005). Off-stream storage involves storage of water on lands that are, or formerly have been, natural water bodies. Like groundwater this option can be easily metered and scheduled, but it also entails growers removing land from production and building the infrastructure necessary to make water deliveries at specified times. There is also no guarantee that excess winter flows will be available for storage.

In 2003, the first year of the water bank, USBR offered fixed payments of \$0.06 per m^3 \$75 per ac-ft) for groundwater substitution and \$463 per ha (\$187.50 per ac) to Klamath Project lands for land idling for a total cost of \$4.4 million (USBR, n.d.). From 2004 to 2007 USBR operated the water bank based on a bidding process for land idling and groundwater substitution that included non-Klamath Project lands. There was no water bank in 2008. In 2009 the USBR used groundwater substitution and storage to meet the water bank needs. The cumulative cost of operating the water bank until 2011 could exceed $65 million though 2011 (GAO, 2005).

Burke et al. (2004) estimates the value of water to farmers as the value they would receive from growing crops plus an added amount as incentive to sell. They also note that using fixed prices for water banks can be tricky since the value is not always easily determined. In 1991 the Drought Water Bank in California offered $0.10 per m^3 ($125 per ac-ft) and received offers for $1.01x10^9$ m^3 (820,000 ac-ft) when they wanted only $4.93x10^8$ m^3 (400,000 ac-ft). Using a bidding process has the advantage that farmers are allowed to determine the value of their own water and USBR has an easy criteria for ranking the bids and lowering their costs.

Land value has been used as a surrogate for water value since the land value is tied to agricultural productivity based on the NRCS land capability class where class I lands are the most productive and class V lands are the least productive (Jaeger, 2004a; 2004b). Land prices in the Upper Klamath Basin range from $494 per ha ($200 per ac) for non-irrigated class V lands, to $6425 per ha ($2600 per ac) for irrigated class II lands. The spatial distribution of land capability class is such that most of the higher value lands are within the Klamath Project. The Klamath Project also contains less than half of the irrigated acres in the Upper Klamath Lake Basin (Figure 3). This analysis approach concludes that the USBR can lower their water bank costs by targeting lower value non-Klamath Project lands for increased water supply.

Using land value as a surrogate for water value is simplistic and there are many compounding factors such as external impacts, owner/lessee contracts, and water delivery efficiency (Keppen, 2004). For cattle ranches on class IV or V lands the land costs may have to be low because operating costs are high. Keppen (2004) states that

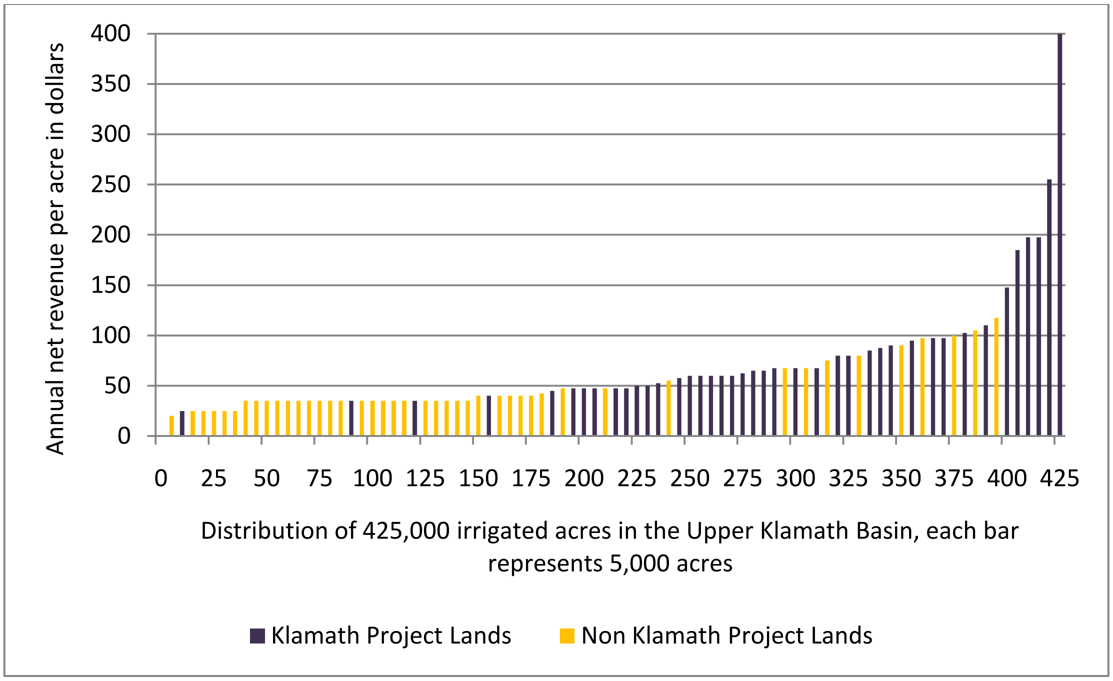

Figure 3: Annual net revenue per acre for all irrigated lands in the Upper Klamath Basin. Non-Klamath Project lands, such as in the Wood River Basin, do not generate as much revenue as Klamath Project lands. (After Jaeger, 2004b)

while water value is highly variable within the Upper Klamath Basin it should be up to the water users to determine the value. This is allowed in the water bank bidding process, but water users who have little experience with land idling or dryland operations may not be able to accurately and easily determine the value of their water.

In the Wood River Basin, where pasture is used from April to September to rear cattle, the land value may be low but it may also be a critical piece of a profitable and valuable operation. It is difficult for water users to convert to dryland operations when the long-term feasibility is uncertain. To help determine the feasibility of converting to dryland operations involving land idling and possibly grazing forbearance, and to assess the water value, the NRCS initiated a Conservation Effects Assessment Project in the Wood River Basin.

2.3 Conservation Effects Assessment Project (CEAP)

Ranchers in the Wood River Basin participated in the USBR water bank once it was opened to non-Klamath Project lands. Many were concerned about the viability of dryland grazing since they did not have much experience with it. To help address these concerns the NRCS also used their Environmental Quality Incentives Program to pay ranchers for grazing forbearance. With program participants who operated both irrigated and non-irrigated pastures the NRCS began a CEAP in 2006 to study the effects of irrigation forbearance on pasture production, and hence stocking rates. The CEAP collected vegetation data in 2007 and 2008 for irrigated and non-irrigated tracts. In addition, the Klamath Basin Rangeland Trust (KBRT) collected water table elevation data during this time. These data were then combined to produce a hydrologic and crop growth model to assess the relationship between irrigation levels and pasture production. The ultimate result of the CEAP was to communicate to the ranchers if they could make it under dryland operations, which would open up an opportunity for them to lease or transfer their water rights once the adjudication process in the basin is complete.

The CEAP study selected 12 tracts, 6 irrigated and 6 non-irrigated, distributed throughout the Wood River Basin. All irrigated tracts were fully irrigated, there were no tracts with reduced irrigation levels. The vegetation study was conducted by Stringham and Quistberg (2008). Three vegetation transects and one vegetation exclosure were established at each site. Transects were approximately 45.7 m (150 ft) long and oriented north-south. Clippings were done within a 0.180 m^2 (1.92 ft^2) hoop. Samples were collected about every 0.61 m (2 ft) along the transects once a month from April to October with exclosure samples taken concurrently. For each sampling location the following data/observations were taken:

- Monthly productions via clippings and re-clippings

- Distance between rooted plants
- Species composition by percent cover
- Presence of invasive species, especially bull thistle

In reclipping the same plants are reclipped monthly to mimic regrowth after grazing. In 2007 there was no significant difference for annual dry weight production between the irrigated and non-irrigated treatments with high variation within the treatments. The average annual dry weight productions for these treatments were 151.8 g (0.3347 lbs) and 128.6 g (0.1784 lbs) respectively. There is a difference in the treatments at the p=0.12 level. The results from this portion of the CEAP indicated that dryland grazing operations would not be considerably less productive than irrigated pasture.

Owens et al. (2009) used the vegetation data to calibrate a 1-D soil-plant-atmosphere model called Daisy (http://code.google.com/p/daisy-model), which was then used in conjunction with the hydrologic model MIKE SHE (http://www.dhigroup.com/Software/WaterResources/MIKESHE.aspx) to determine pasture production as a function of irrigation level and grazing management. Eight irrigation levels where simulated as described in Table 1. The bi-weekly (Lv 2) irrigation was considered to be the standard practice for irrigated tracts and no rrigation (Lv6) is considered to be the standard practice for non-irrigated sites. Two grazing management practices were also simulated. The first grazing management simulation approximated the typical continuous grazing practice in the Wood River Basin. At typical stocking levels this is a 10 day rest period (time between clippings) with a base height of 10 cm (4 in). The second grazing management simulation used a 30 day rest period with a base height of 10 cm (4 in), which allows for plants to stay in the optimal growth development stage for a longer period of time, increasing productivity. The results of these simulations are shown in Figure 4 and Figure 5.

Table 1: Irrigation frequency scenarios simulated for the CEAP study in the Wood River Basin. The irrigation season is assumed to occur from May 1 to Sept 30 in each year. (After Owens et al., 2009)

Irrigation Level	Irrigation Frequency
Lv1	Weekly
Lv2	Bi-Weekly
Lv3	Monthly
Lv4	Bi-Monthly
Lv5J	Once on Jun 1
Lv5A	Once on Aug 1
Lv5S	Once on Sep 1
Lv6	None

The variation in productivity is greater between years than it is between irrigation levels for the 10 day rest period (Figure 4), whereas the 30 day rest period reduces the variation between years. (Figure 5). Using this management, ranchers can consistently achieve higher productivity between years and mitigate the effect of what would be poor years under traditional management, such as 2007 in Figure 4.

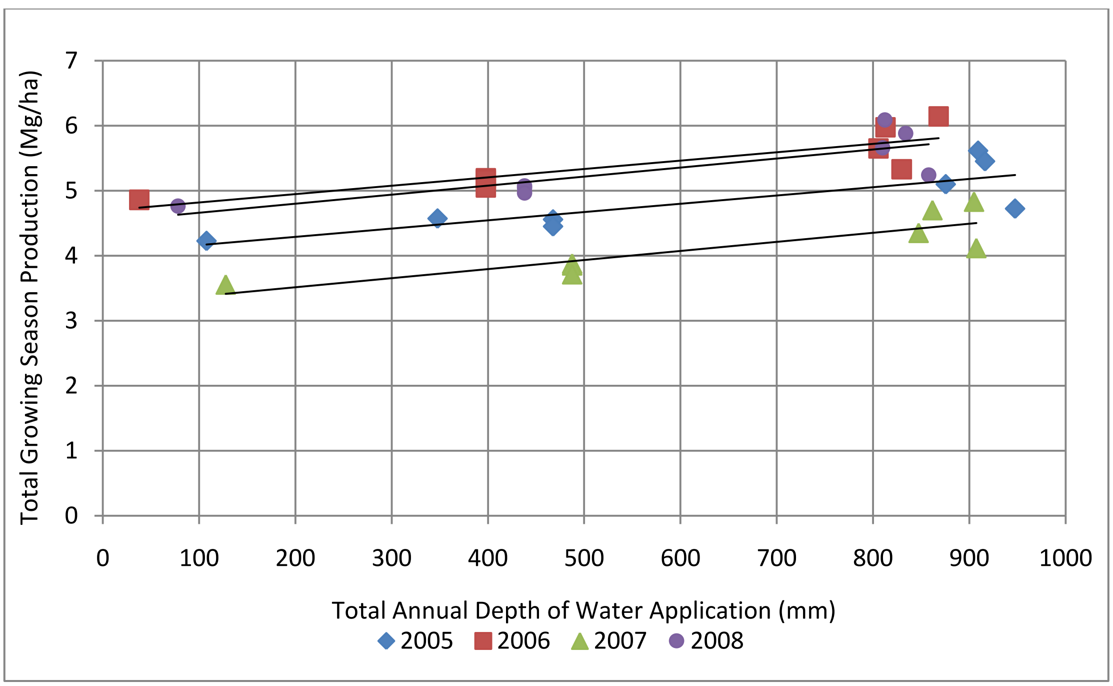

Figure 4: Annual pasture production with a 10 day rest period as a function of total growing season depth of water application over a four year period from 2005 to 2008. (After Owens et al., 2009)

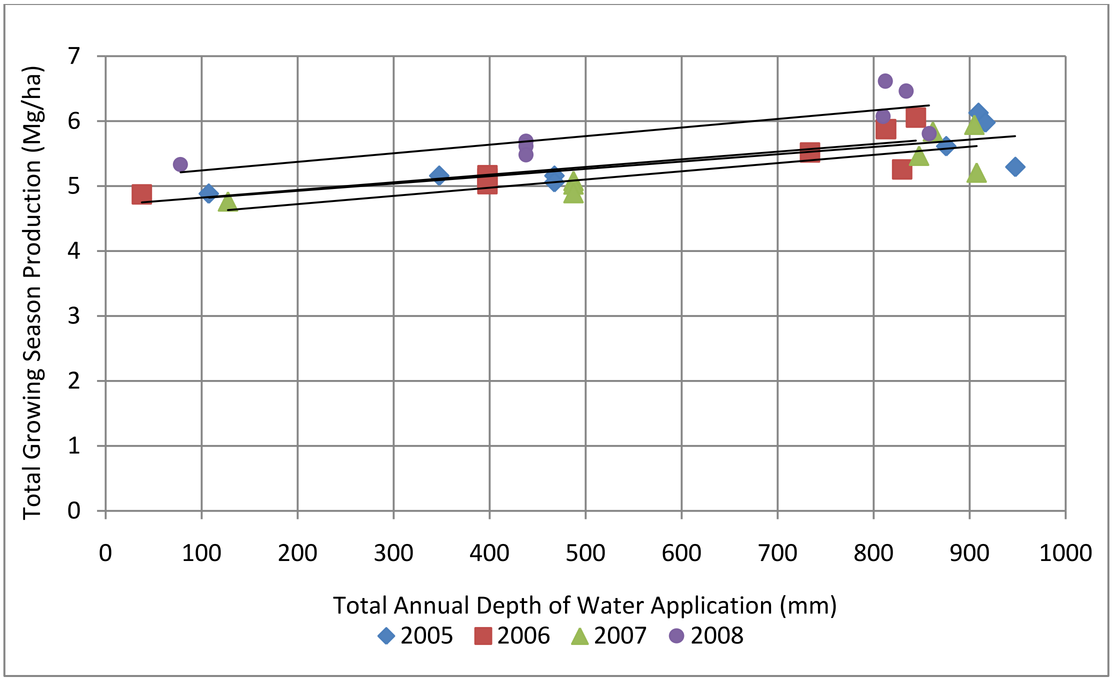

Figure 5: Annual pasture production with a 30 day rest period as a function of total growing season depth of water application over a four year period from 2005 to 2008. (After Owens et al., 2009)

There has been a measured difference between irrigated and non-irrigated pasture productivity and consumptive use, however the difference is much smaller than might be expected given that the typical practice in the Wood River Basin is to flood irrigate every couple of weeks. Peterson and Cuenca (2006) used Bowen Ratio Stations to measure and compare evapotranspiration (ET) in Wood River Basin irrigated and non-irrigated tracts. They found that in the growing season from April 23, 2004 to October 15, 2004 the total ET for irrigated sites was 798 mm (31.4 in) and for non-irrigated sites it was 541 mm (21.3 in), a percent difference of 38.4. This shows that consumptive use in non-irrigated sites is still fairly high. A possible explanation for continued consumptive use and pasture productivity in non-irrigated tracts is that water is being transported in from irrigated tracts via a highly transmissive shallow aquifer. This water would have to be shallow enough to be brought up the soil profile and into the root zone. This process is termed sub-irrigation.

2.4 Sub-Irrigation

Most studies of sub-irrigation have focused on water table management where increasing the groundwater table elevation provides water for plants and reduces the irrigation requirement. Kruse et al. (1993) studied the use of water from a shallow water table in Colorado where local geology and inefficient surface irrigation created high water tables. They found that in the presence of a high water table surface irrigations can be reduced without affecting crop productivity, but also note that a long term effect of this may be a lowering of the water table.

A review of the potential of shallow groundwater as an irrigation resource is provided by Ayars et al. (2005). The important measurement when discussing root uptake of shallow groundwater is not the depth of the water table, but the distance between the bottom of the root zone and the saturated or near-saturated zone because this is the distance that water has to travel to become available to plants. The upward flux of water from the saturated zone to the root zone is determined by this distance, the matric potential gradient and the unsaturated hydraulic conductivity of the soil. The matric potential gradient is created because plants use the water in the root zone so that it has lower moisture content and a more negative matric potential. This difference in matric potential drives the flux of water into the root zone.

Soil texture is important because finer texture soils will be able to establish a greater matric potential gradient and support higher capillary rise due to smaller pores, but will also have lower unsaturated hydraulic conductivity so that water cannot be transported fast enough to replenish the root zone. Data from Grismer and Gates (1988) suggest that coarse textured loams with higher hydraulic conductivity will be able to get more water from the shallow water table than fine textured loams or heavy clay soils. Doorenbos and Pruitt (1977) report upward flow of groundwater versus groundwater depth below a moist root zone for nine soil textures. For very fine sandy loam the upward flow rate ranged from 2 mm/day (0.08 in/day) to 6 mm/day (0.24 in/day) for groundwater depths below root zone from 4 m (13 ft) to 2 m (6.5 ft) respectively. For sticky clay the upward flow rate ranged from 0.2 mm/day (0.01 in/day) to 6 mm/day (0.24 in/day) for groundwater depth below root zone from 0.8 m (2.5 ft) to 0.2 m (0.5 ft) respectively. This shows that substantial soil moisture can be available for plants even though it is stored below the root zone.

As the root zone dries out the upward flux of groundwater for crop use will increase. Crop water contributions from groundwater were studied for alfalfa (Benz et al., 1984; 1983), and corn and sugar beets (Benz et al., 1981). Alfalfa is a perennial crop with a deep root zone and so is the most similar to pasture grasses of the Wood River Basin. Results for alfalfa are shown in Figure 6, where in some cases depth to water table exerts more control on crop yield than irrigation rate. For example, in the 155 cm (6.1 in) water table depth case the yields do not differ much despite irrigation

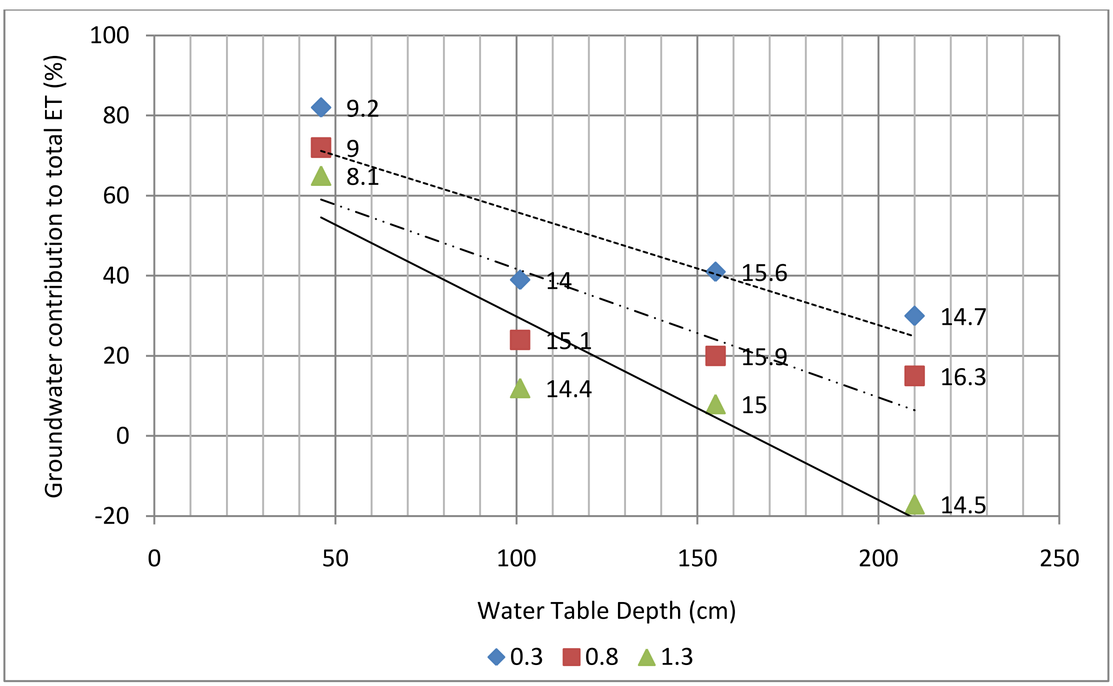

Figure 6: Percent contribution of groundwater to total alfalfa evapotranspiration (ET) as a function of water table depth. Values are reported for irrigation levels of 0.3, 0.8, and 1.3 where *irrigation level* = *(surface applied irrigation + rainfall)/(calculated ET)*. Points are labeled with annual yield in t/ha. Negative values indicate drainage losses. (After Benz et al, 1984)

levels ranging from 0.3 to 1.3 times the calculated ET, showing that as surface water application decreases more groundwater is used. The lowest yields generally occur at the highest irrigation level.

The Wood River Basin is almost entirely covered by a single soil map unit, the Kirk-Chock Association (Soil Survey Staff, n.d.). Both soils are very deep medial loams with low bulk densities and high saturated hydraulic conductivies, ideal for sub-irrigation. Considering that they overlay a highly transmissive shallow aquifer, there is potential for substantial sub-irrigation. Water table observations in 2002 and 2003 (Pacific Groundwater Group, 2003) showed that water table depths in non-irrigated sites are highly variable, generally 0.9m (3 ft) to 1.5 m (5 ft) below ground surface in 2002 and 0.9 m (3 ft) to 2.4 m (8 ft) in 2003. Throughout the Wood River Basin the maximum water table depth observed was 3 m (10 ft). Roots have been observed to be most active from 0.6 m (2 ft) to 0.76 m (2.5 ft) and extend to 1.2 m (4 ft) below the ground surface (Pacific Groundwater Group, 2003). Therefore, in non-irrigated sites the distance from the bottom of the root zone to the water table would generally range from -0.3 m (-1 ft, overlapping) to 1.2 m (4 ft) and the maximum distance between the bottom of the root zone and the groundwater table is 1.8 m (6 ft).

Under irrigated conditions the water table depth ranged from 0 m (0 ft) to 1.15 m (3.8 ft) resulting in a local mounding of the water table. The mounding was observed to extend laterally up to 365 m (1200 ft) (Pacific Groundwater Group, 2003) into non-irrigated pasture, demonstrating groundwater flowing from irrigated sites to non-irrigated sites. This is consistent with hydrologic modeling done by Owens et al. (2009) where water flux into the non-irrigated tracts was necessary to simulate water table depths. USGS (2005) also recognized that sub-irrigation is an issue for quantifying water savings due to land idling in the Wood River Basin and state that idled fields not adjacent to irrigated fields should be given preference because of reduced sub-irrigation potential.

Vegetation and evapotranspiration studies show that pastures continue to be productive and use water through the summer and fall (section 2.3) in the current patchwork of irrigated and non-irrigated fields in the Wood River Basin. The likeliest water source for this growth is sub-irrigation from shallow groundwater. The water can move upward in the direction of the matric potential gradient caused by drying in the root zone. This movement is limited by the texture and hydraulic conductivity soil. Soils in the Wood River Basin have a fine texture and a high hydraulic conductivity, which is ideal for sub-irrigation. This indicates that water table depth exerts control over pasture productivity in the Wood River Basin.

While it has been recognized that water flows from irrigated fields to adjacent non-irrigated fields, irrigation may have a basin-wide affect, not just a local one. Inefficient surface irrigation will recharge the shallow groundwater, which in turn may elevate the water table across the entire basin. If more ranchers choose to adopt land idling because of the good pasture productivity of non-irrigated fields that can be optimized through grazing management (section 2.3) then the source of shallow groundwater recharge will diminish and the water table elevation may decline to where sub-irrigation in quantities necessary to maintain pasture productivity is no longer possible. Ranchers may face declines in productivity beyond what was expected from current field scale studies. Basin wide affects of increased land idling need to be examined for ranchers and water managers to make the best decisions for future operations.

2.5 MIKE SHE

The European Hydrological System (SHE) hydrologic model was developed in the 1980's as a joint effort by the Institute of Hydrology, Societe Grenobloise d'Etudes et d'Applications Hydrauliques, and the Danish Hydraulics Institute (now called DHI, Inc. globally, and DHI Water & Environment within the United States) (Abbot et al., 1986a). These three have since developed SHE independently, and MIKE SHE is the DHI version of the model. MIKE SHE is one of many models that DHI has developed that are included in their MIKE Zero modeling package. MIKE SHE simulates the land phase of the hydrological cycle including ground water, soil moisture, overland (non-channelized) flow, precipitation, irrigation, and evapotranspiration.

MIKE SHE is a fully distributed, physically-based model that uses finite difference numerical techniques to solve equations base on first principles or empirical equations from experimental research (Abbot et al., 1986a). Prior to the development of distributed models, lumped models were used that simplified entire catchments into a few parameters. These required long periods of data to calibrate and the parameters did not have any real physical interpretation, therefore the affect of hydrologic changes in response to catchment changes could not be evaluated and the use of the models for scenario testing or prediction was limited. MIKE SHE is versatile with a modular structure built around a central control element called the FRAME (Abbot et al., 1986b). The FRAME allows for parallel running of the modules and also allowed for modules to be developed independently. MIKE SHE has been used to model scales from a single grid cell (Shakya, 2007) up to the 80,000 km^2 (31,000 mi^2) Senegal Basin (Andersen et al., 2001). More information on MIKE SHE can be found in Graham and Butts (2005), and Refsgaard and Storm (1995).

The modules in MIKE SHE allow it to be tailored to project needs that use as much or as little data as is available. The modules include Overland Flow, Rivers and Lakes (requires MIKE 11), Unsaturated Flow, Evapotranspiration, Saturated Flow, and Advection-Dispersion for Water Quality. Each module is flexible, giving the user control over how the model is run. For example, the unsaturated flow module can be run using Richards Equation, gravity flow, or a two-layer model method (DHI, 2009). The method is selected based on the user's requirements for accuracy and computational efficiency. Furthermore, MIKE SHE allows selection from two soil moisture retention curve functions, and three hydraulic conductivity functions. It is possible to set up very complex models but computational resources and time requirements become major factors in using MIKE SHE, especially when running 3-dimensional models over large areas or at fine spatial resolutions.

Demetriou and Punthakey (1999) applied MIKE SHE to the 220,000 ha (544,000 ac) Wakool Irrigation District in New South Wales, Australia to assess scenarios for mitigating soil salt increases from shallow saline aquifers that have been rising due to inefficient irrigation. From 1960 to 1970 the area affected by shallow water table grew from 7,200 ha (17,800 ac) to 47,500 ha (117,300 ac). To combat this problem a large scale groundwater pumping plant was implemented in the 1980's. The plant pumps about 14,600,000 m^3 (11,800 ac-ft) of saline water per year to 2,100 ha (5,200 ac) of evaporating ponds (Murray Irrigation Limited, 2006). At the time of the study the land affected by shallow water table was 26,100 ha (64,500 ac), and continued to increase. The scenarios tested, either individually or in combination, included: 1) Recycling ponds and land forming to reduce infiltration of excess surface water and collect it at the farm scale, 2) Deep rooted perennials to increase ET and lower the water table, 3) Tree planting to increase ET and lower the water table, 4) Shallow pumping to remove salty groundwater to evaporation ponds, and 5) Deep pumping to reverse the flow of saline water from the deep aquifer to the shallow aquifer. The model was run for 25 years and it predicted that without further intervention the amount of land affected by shallow water table would increase by 22% by 2020. The most effective scenarios were recycling ponds and land forming, and shallow pumping, which led to the amount of land affected by shallow water table to increase by 7% and 10% respectively.

The study above demonstrates the ability of MIKE SHE to combine irrigation with basin-wide hydrology and surface water and groundwater exchange to predict long term affects of management decisions. There have been other studies that have used MIKE SHE to model irrigation scenarios and management. Singh et al. (1997) used MIKE SHE/MIKE 11 to model the Mahanadi main canal command area consisting of 197,500 ha (488,000 ac) within the Mahanadi Reservoir Irrigation Scheme in Madhya Pradesh, India. The irrigation project services 374,000 ha (924,000 ac) during the monsoon growing season from July to October (kharif) and 131,000 ha (324,000 ac) during the winter season from November to February (rabi). Simulations showed that significant wastage during kharif severely limited production during rabi. When combined with an irrigation optimization system (Singh et al., 1999) for decision support on a multi-week scale the model could be used to reduce waste and increase productivity.

Singh et al. (1999) did a similar analysis for a 694 ha (1715 ac) catchment in West Bengal, India through kharif and rabi. To reach potential yield, 490 mm (19.3 in) and 340 mm (13.4 in) of irrigation had to be applied on the upstream and downstream ends of the catchment during kharif. Stored water from kharif could be used during rabi to reach potential yield. Lohani et al. (1993) used SHE (prior to the development of MIKE SHE) to model 1-dimensional plot scale, field scale, and irrigation command scale (5 fields) in the Barna Project in Madhya Pradesh, India. The model was used to evaluate irrigation distribution at the field scale and water release strategies (e.g. fixed release vs. soil moisture response release) at the command scale.

Jaber and Shukla (2004) used MIKE SHE/MIKE 11 in a 265.5 ha (656 ac) citrus grove in Florida to model the efficacy of farm impoundments to reduce excess flows into the Caloosahatchee estuary and store water for irrigation. Jayatilaka et al. (1998) modeled a 9 ha (22 ac) irrigation plot in the Tragowel Plain, Australia which also faced with problems of rising water tables and salinity. MIKE SHE was used to evaluate processes that affect surface drainage and shallow water table elevations. Shallow water tables increase the groundwater exfiltration and baseflow components to surface drain flows, transporting salt to the drains. A shallow water table also increased saturation excess overland flow, another process that is effective at transporting salts to the surface drains.

MIKE SHE is a versatile and complete hydrologic model that captures all of the major processes in the land phase of the hydrologic cycle, including irrigation. It can also be coupled with MIKE 11, a river and lake hydraulic model (Havnø et al., 1995), to simulate channel flow, flooding, and water conveyance. These capabilities make MIKE SHE/MIKE 11 uniquely capable of handling basin wide irrigation scenarios for water resources management.

3 Materials and Methods

The Wood River Basin has been the subject of multiple investigations since 2002, including studies of surface water, groundwater, evapotranspiration, and vegetation. This effort has been coordinated primarily by the Klamath Basin Rangeland Trust and the NRCS with the purpose of better understanding the hydrology of the basin and to inform ranchers of management options for water conservation and improved water quality. The availability of data from previous investigation in the basin made accurate basin-wide modeling possible.

The basin-wide model was built and calibrated based on the actual management within the basin that occurred from 2002 to 2009 using observed data collected during this period. This scenario is referred to as "WRBActual" and includes both irrigated and non-irrigated tracts. Once calibrated, a full irrigation scenario was simulated, referred to as "WRBIrrigated", where all of the pasture was considered to be under full irrigation management, non-pasture areas in the model were not irrigation in this scenario. A non-irrigated scenario "WRBNonIrrigated" was also simulated were no irrigation occurs in the basin. Two reduced irrigation scenarios called "Red1" and "Red2" were also simulated. For all of these simulations the irrigation management prior to 2002 is considered to be full irrigation because it water conservation programs were not in effect during this time. The term tract is used to refer to management areas within the model, mostly to differentiate non-irrigated fields from irrigated fields in the WRBActual scenario. The term site is used to refer to specific locations of sampling or monitoring activities.

Each module used in MIKE SHE will be discussed in this section. The many parameters available for use in MIKE SHE, and the length of time required to run a simulation, make calibration and sensitivity analysis for each parameter impractical. To reduce the calibration burden the model parameters need to be tightly constrained, and then key parameters can be chosen for calibration within predefined reasonable ranges. This approach has been used for MIKE SHE by Refsgaard (1997) and Refsgaard and Storm (1995) because it reduces the number of "free" parameters, greatly simplifying the overall model. MIKE SHE will automatically populate default parameters, these were used if there were no data or literature that suggested a more appropriate value.

3.1 Model Domain and Grid

The model domain is the Wood River flood plain defined in Figure 2. Fault scarps delineate the east and west boundaries. Portions of the western boundary were drawn to exclude alluvial fans because they cause discontinuities in the geologic layers that are difficult to account for due to lack of information regarding size and material. These alluvial fans are also not managed as pasture. The north boundary is defined where the management changes from pasture to forestry, which also corresponds to a break in slope. The south boundary is Agency Lake or the marshes to the southwest that are connected to Agency Lake. Most of the south boundary is along a dike built to reclaim land in the basin.

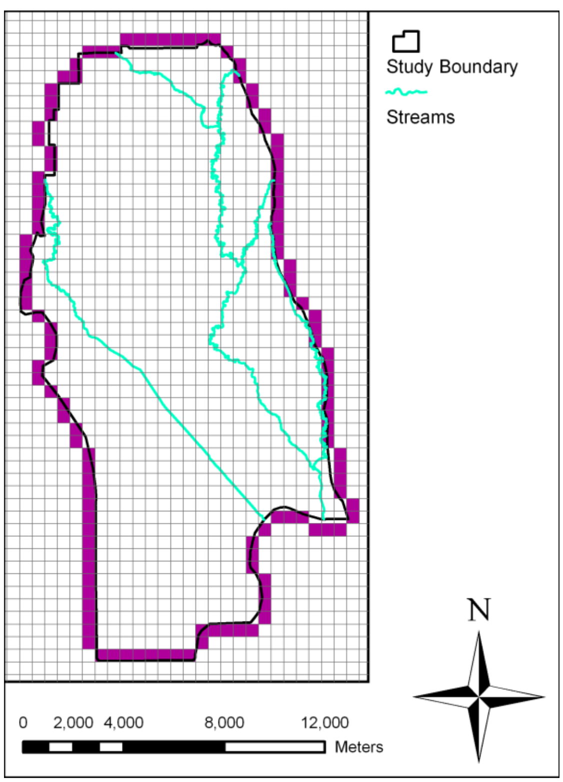

Figure 7: Model domain and grid with 500 m cells. The boundary cells are colored, and correspond to the delineation of the study boundary.

MIKE SHE automatically classifies the model domain into a grid with a user specified grid cell size. 500 m x 500 m

(1640 ft x 1640 ft) grid cells were used (Figure 7) because the flat topography in the Wood River Basin does not require fine grid resolution to be represented accurately, and computation time is decreased. This resulted in a total of 811 internal calculation cells (20,275 ha, 50,100 ac), 763 (19,075 ha, 47,100 ac) of which are managed as pasture.

3.2 Topography

A grid-based digital elevation model (DEM) is used to define the topography in MIKE SHE (Figure 8). MIKE SHE assigns each grid cell a unique elevation based on an input DEM or other elevation data. The input DEM used came from the one arc-second (approximately 30 m, 98.4 ft) National Elevation Dataset (NED30) (USGS, 2006), downloaded from http://datagateway.nrcs.usda.gov/ for Klamath County. The NED30 data is in the North American Vertical Datum of 1988 (NAVD88). The input DEM was clipped to the study boundary and converted to a MIKE SHE file type.

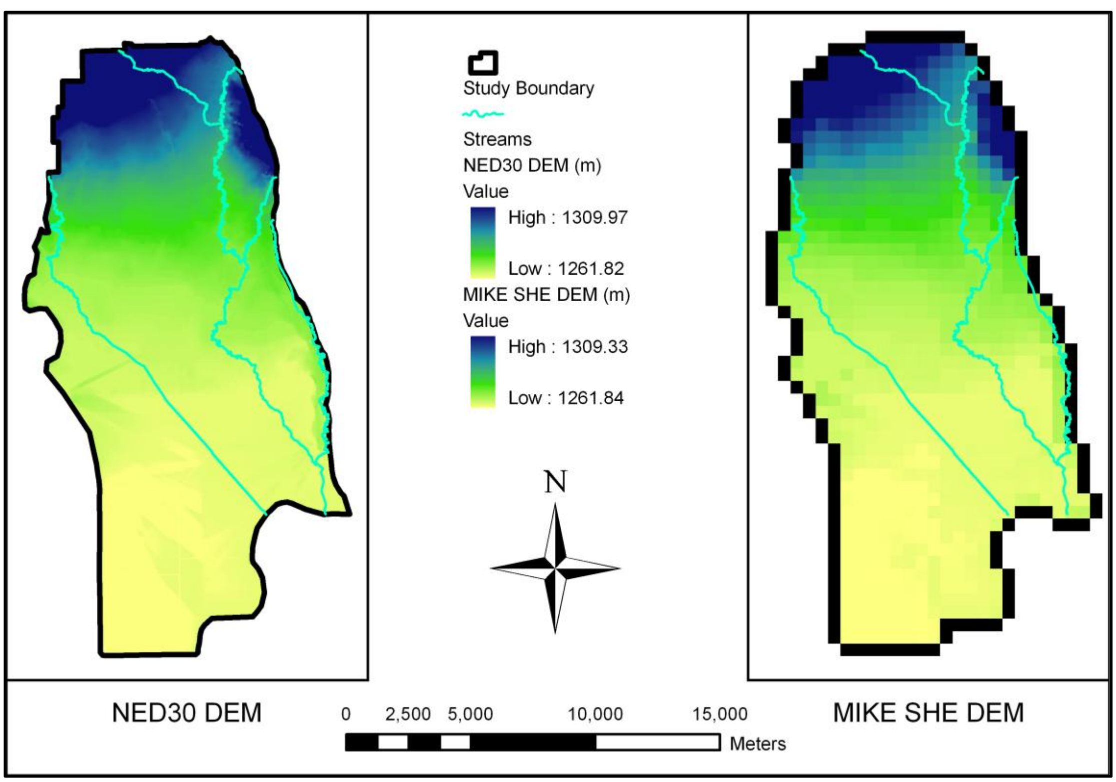

Figure 8: NED30 DEM (left) was coarsened to the MIKE SHE grid (right).

Converting a DEM with 30 m (98.4 ft) grid cells to the model grid of 500 m (1640 ft) grid cells coarsened the resolution substantially. This is why input DEM's with finer resolutions were not used such as the NED10 (approximately 10 m (32.8 ft) grid cells) or an available Light Detection and Ranging (LiDAR) based DEM (1 m (3.3 ft) grid cells).

3.3 Climate

Mean daily air temperature, precipitation, and alfalfa-based reference evapotranspiration ($ET_{r\ alf}$) were obtained for the period from January 1, 2001 to December 31, 2009 from the USBR Agency Lake AgriMet Station (http://www.usbr.gov/pn/agrimet/agrimetmap/agkoda.html). The AgriMet stations use the Kimberly-Penman model for calculating $ET_{r\ alf}$ (USBR, 2008), although a grass-based ET_r is used throughout most of the world (Allen et al., 1998). The $ET_{r\ alf}$ was multiplied by 0.833 to convert it to the grass-based ET_r (Jensen et al., 1990). ET_r in this document will refer to the grass-based ET_r. The average annual precipitation is 353 mm (13.9 in), and the average annual ET_r is 1055 mm (41.5 in). During the growing season from April 1 to September 30 the average precipitation is 74 mm (2.9 in) and the average ET_r is 864 mm (34.0 in). 82% of the total annual ET_r occurs during the growing season. The highest ET_r occurs in July and averages 6.5 mm/day (0.26 in/day), but daily values of about 7.5 mm/day (0.30 in/day) are common. In the first and last months of the growing season typical ET_r values range from 2 mm/day (0.08 in/day) to 4 mm/day (0.16 in/day) (Figure 9).

AgriMet data is typically high quality, but there are occasional gaps in the record. Within this record the largest data gap was 14 days. There was also an eight day gap, and occasional one or two day gaps. The gaps in the precipitation and temperature record were filled using data from the National Climate Data Center Chiloquin 12 NW station (Coop ID 3515740), (http://www4.ncdc.noaa.gov/cgiwin/wwcgi.dll?wwDI~StnSrch~StnID~20015803). Gaps in the ET_r record were filled by calculating the average ET_r for the given day of year from the remaining records.

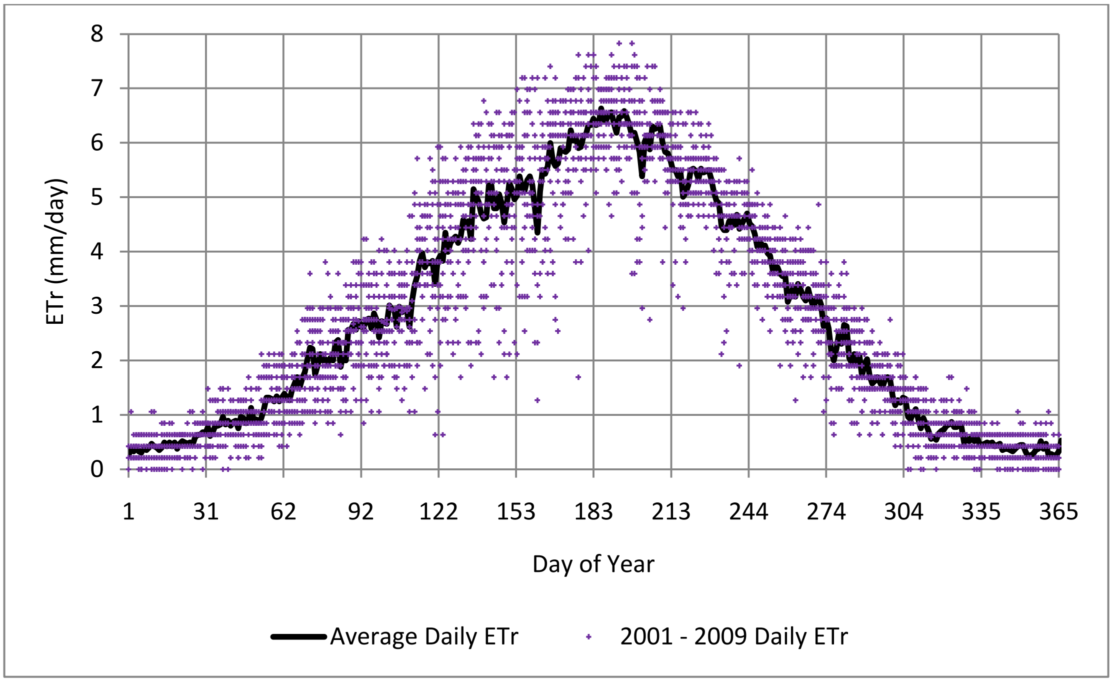

Figure 9: Daily Reference Evapotranspiration (ETr) for the 9 year period from 2001 to 2009.

The average temperature was required in the model for snow accumulation and melt, which MIKE SHE simulates using the melting degree day method (DHI, 2009). If the average temperature is below the freezing temperature precipitation will fall as snow and accumulate. If the temperature increases above the freezing temperature then snow will melt of at a rate determined by the melting/freezing degree-day coefficient, the MIKE SHE default is 2 mm/°C/day (0.04 in/°F/day). MIKE SHE defaults were used for all snow melt parameters.

3.4 Land Use

3.4.1 Vegetation and Evapotranspiration

Vegetation and irrigation properties are controlled in the land use module. Vegetation properties include leaf area index (LAI) and root depth. MIKE SHE allows for spatial distribution and temporal variations of vegetation properties, but these must be entered and cannot be simulated. Since most of the Wood River Basin is pasture, the vegetation is considered to be uniform within the model. The LAI and root depth are considered to be constant because the typical management practice is for open grazing at a stocking rate that allows for about a 10 day rest period between grazings that keeps the grass within a narrow range of development stage over the entire growing season. Using constant vegetation rates that are typical of the growing season would overestimate ET during the non-growing season. However, during the non-growing season ET_r is low and this discrepancy will minimally impact the overall water balance. Although grazing and subsequent recovery of grass will cause fluctuations in the LAI, a value of 1 was used based on calibration (see below). The root depth was set to 1220 mm (48 in) from observations (Pacific Groundwater Group, 2003).

Evapotranspiration is also termed consumptive use because this water is exported from the basin and is no longer available for downstream users. Water applied in excess of the consumptive use is generally available for downstream use and can make up parts of downstream water rights, though the timing of availability and water quality may be affected. Evapotranspiration is an important part of the water balance and globally accounts for about 60% to 65% of precipitation, with the remainder becoming runoff (Brutsaert, 2005). ET_r is calculated based on a reference surface that is disease free, well fertilized, and grown in large fields under optimum soil conditions (Allen et al., 1998). In other words there are no stresses on the plants and they transpire at the maximum rate, thus it is also sometimes referred to as the potential ET. To convert from the reference surface to different crop or surfaces, a crop coefficient (K_c) is used in the following equation.

$$ET_C = ET_R \times K_C$$

Where ET_c is the resulting evapotranspiration for the unstressed crop. This approach can also be used for non-crop surfaces. K_c is variable through the growing season based on plant development stage, and can be input into MIKE SHE as part of a vegetation parameter input file for different plants. The crop surface of the Wood River Basin is pasture grasses that behave the same as the grass reference crop, therefore K_c is constant at 1 and ET_r can be entered directly.

MIKE SHE uses the Kristensen and Jensen method (Kristensen and Jensen, 1975) for calculating the actual ET from the ET_r in response to the soil moisture deficit. The method is based on three empirical ET parameters that describe the soil and plant properties, C_1, C_2, and C_3; and a plant development metric. The plant development metric used was LAI because it was built into MIKE SHE. Other plant metrics could be used, such as height, biomass, or development stage.

Ideally, soil moisture in the unsaturated zone would be used to calibrate the ET parameters, but this data was not available. LAI, C_2, and C_3 were calibrated using ET and water table depth observations (unpublished) to evaluate the model fit. These observations were collected within a non-irrigated tract near 2N WT (Figure 10) by Yutaka Hagimoto and Shannon Peterson. The model grid cell where the observations were taken was isolated and the ET, unsaturated zone, and saturated zone were simulated 1-dimensionally with depth. The model parameters were the same as the basin-wide model except that a water flux into the deep aquifer was adjusted to calibrate the water table depth to observed depths in conjunction with the ET

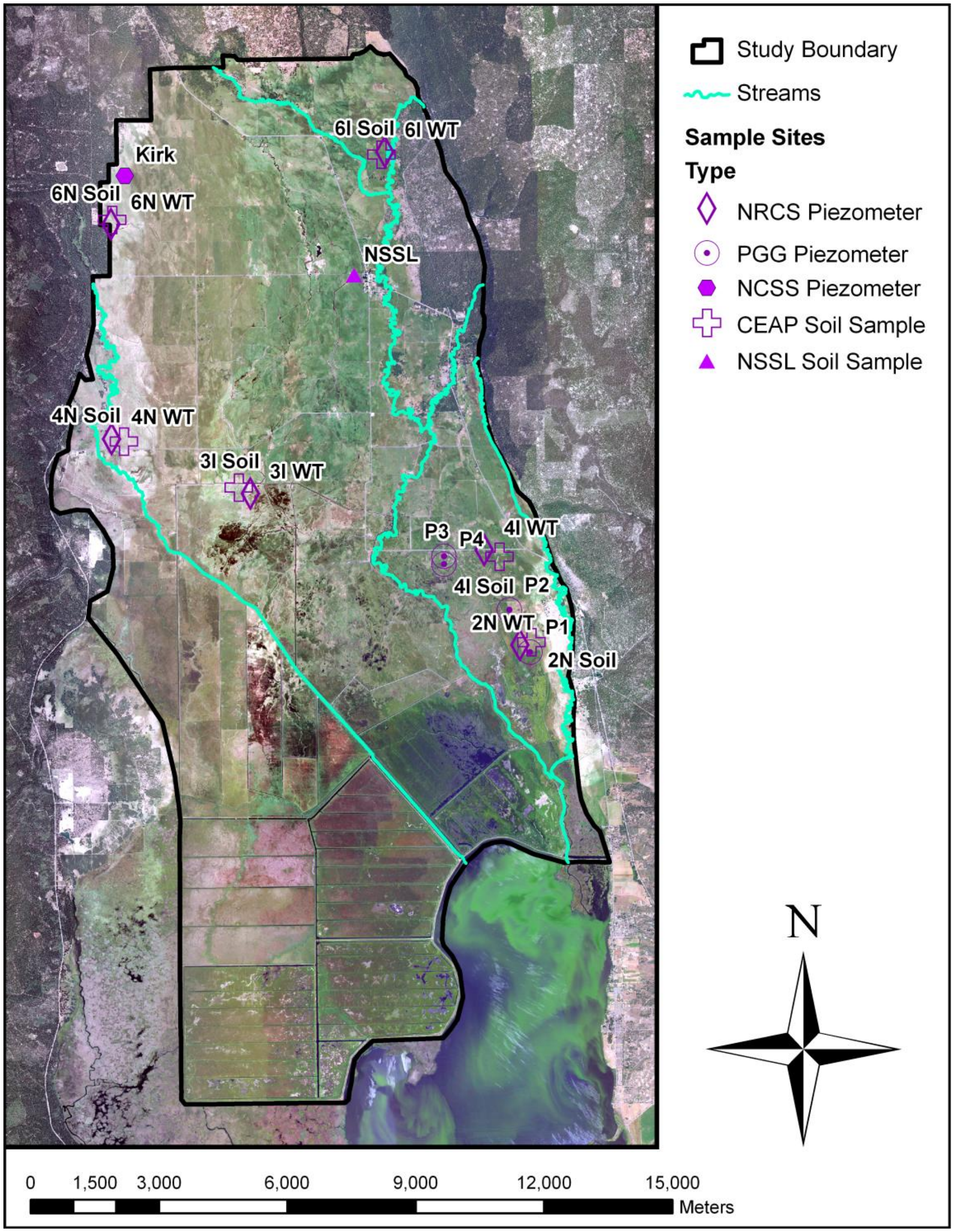

Figure 10: Locations of soil sampling and water table monitoring sites. 2009 imagery is from the Farm Service Agency National Agriculture Imagery Program.

parameters. The soil moisture is simulated by the model within the unsaturated column using the water table as the lower boundary condition and the soil surface as the upper boundary condition. This allowed for the use of water table observations to perform the calibration of ET parameters.

The observed ET (*ETobs*) data was taken from May 1, 2004 to October 1, 2004. It is typically greater than ET_r until mid-June, then lower than ET_r until the end of the growing season. The anomalously high *ETobs* value of >12mm/day (Figure 11) is incorrect because there is not enough daily radiation input to drive that magnitude of ET, and was probably caused by instrumentation errors due to either low power supply or maintenance. This value does not affect the calibration because it was replaced by the ET_r value as described below. In the model the simulated ET (*ETsim*) cannot be greater than ET_r, therefore if the period from May 1 to mid-June is used to evaluate the fit then the ET parameters would be adjusted to maximize *ETsim* during this period, which would result in an over estimation of *ETsim* from mid-June to October 1. Prior to mid-June there is enough soil moisture for the plants to be unstressed and transpire at the maximum rate. Mid-June to October 1 is the period of greatest interest for accurate determination of ET because it describes how ET responds to decreasing soil moisture. A new ET series, called *ETfit* (Figure 11), was created by setting *ETobs* equal to ET_r if *ETobs* was greater than ET_r for that given time. *ETfit* was used to evaluate the calibration because it weights the calibration for the period of interest from mid-June to October 1 and accounts for the inability of the model to simulate ET values greater than ET_r. This inability is a limitation of the input data and not of the model. If the actual ET is different from the ET_r under unstressed conditions then development of a K_c for the modeled crop surface would better describe the ET.

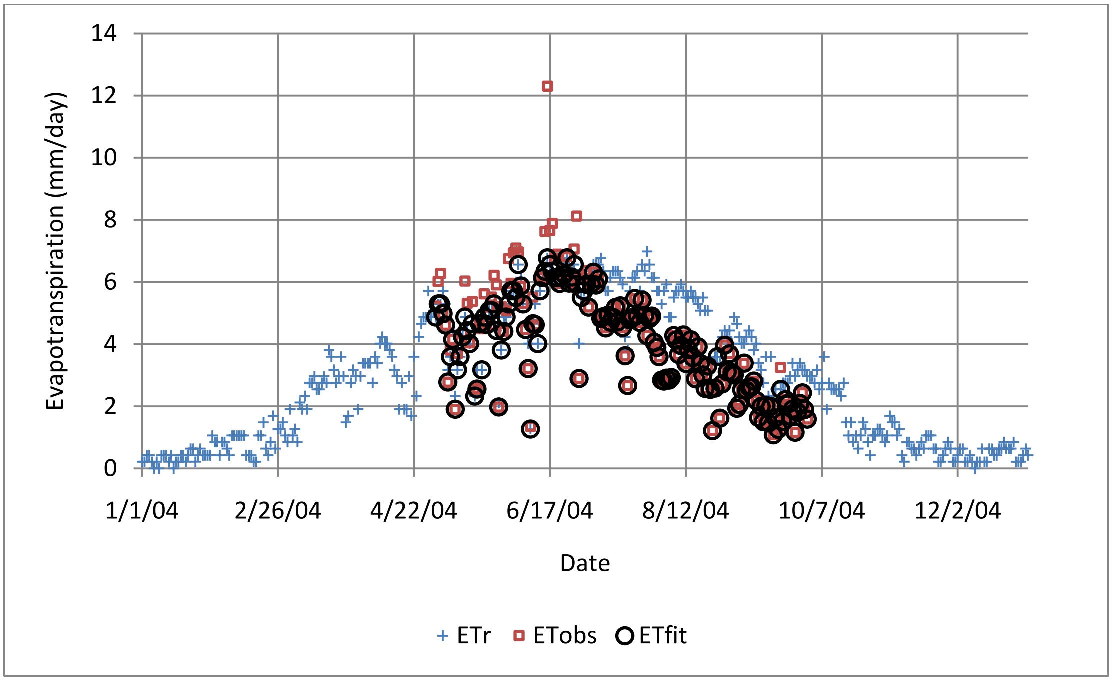

Figure 11: Reference ET (ET_r), observed ET (ETobs), and the resulting time series (ETfit) used to calibrate ET parameters.

Calibration was done by trial and error using a simulation period from January 1, 2001 to December 31, 2004 to allow for a model "spin up" period prior to the May 1, 2004 to October 1, 2004 evaluation period. The model simulation performed well when evaluated against ETfit resulting in a Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) of 0.818 (Figure 13). The Nash-Sutcliffe efficiency evaluates the fit between simulated and observed values relative to the mean of the observed data. A value of one indicates a perfect model fit, a value of 0 indicates that the model performed the same as using the mean of the observed data, a negative value indicates the model performed worse than the mean of the observed data. The percent difference of the cumulative *ETsim* and *ETfit* over the evaluation period is 3.4% (Figure 12). The observed and simulated water table depths fit well resulting in a Nash-Sutcliffe efficiency of 0.882 (Figure 14). Observed water table depth was only available for about a two month portion of the evaluation period because the water table dropped below the sensor depth.

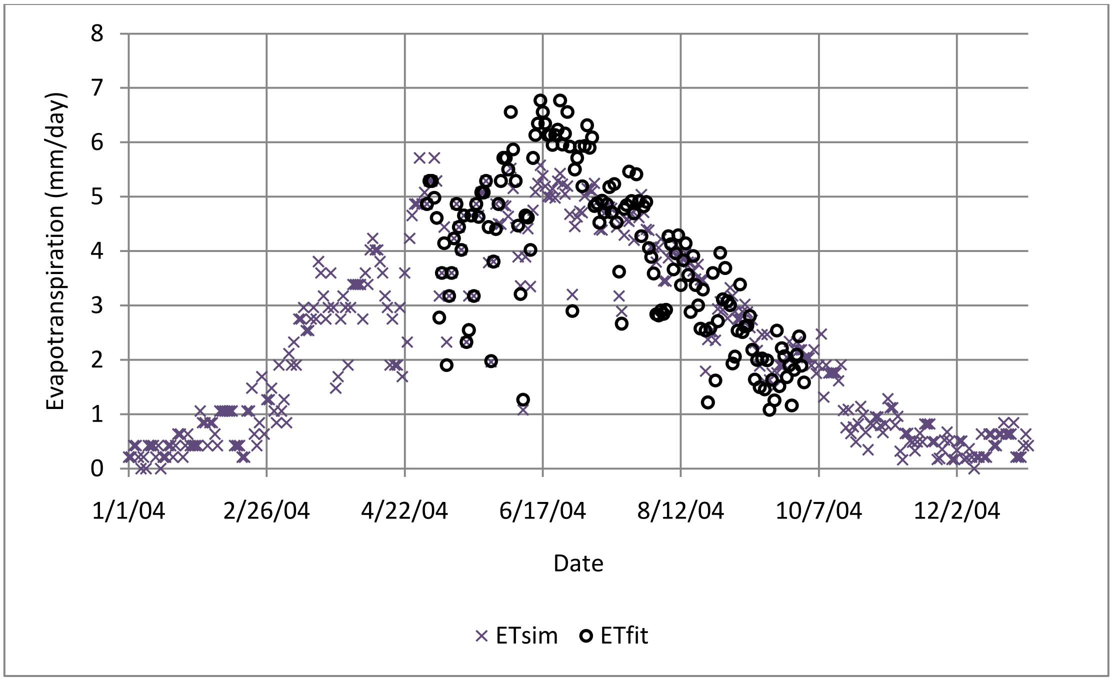

Figure 13: Daily values of the simulated ET (ETsim) and the time series used to evaluate the fit (ETfit). Nash-Sutcliffe efficiency = 0.818, R^2 = 0.929.

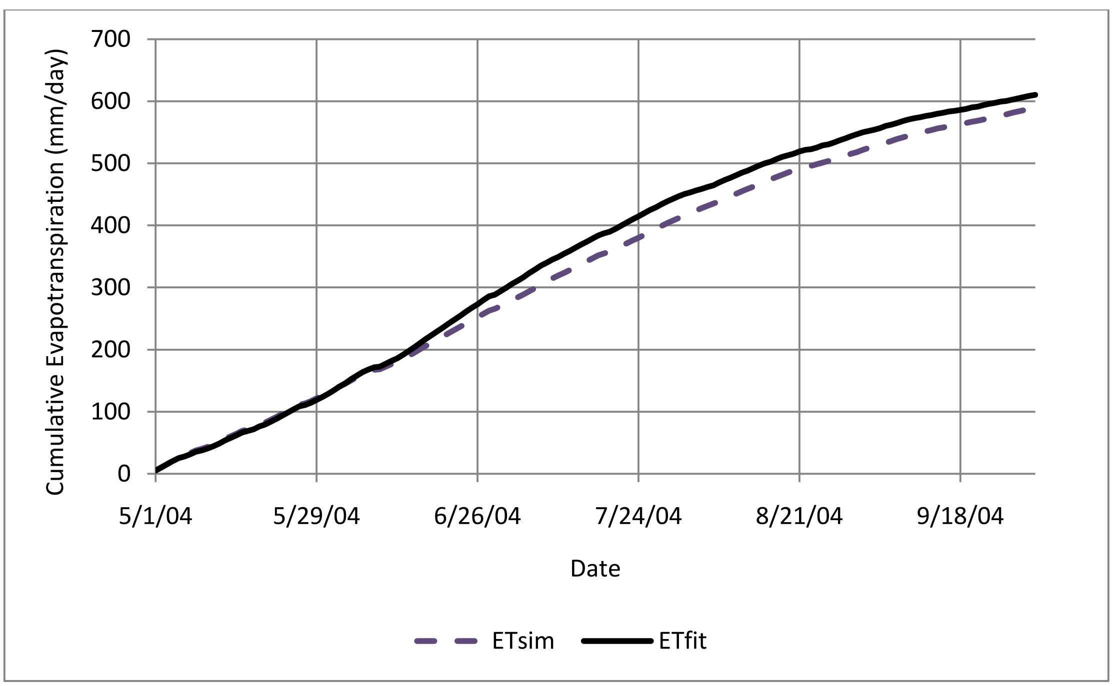

Figure 12: Cumulative values of the simulated ET (ETsim) and the time series used to evaluate the fit (ETfit). Percent difference = 3.4%.

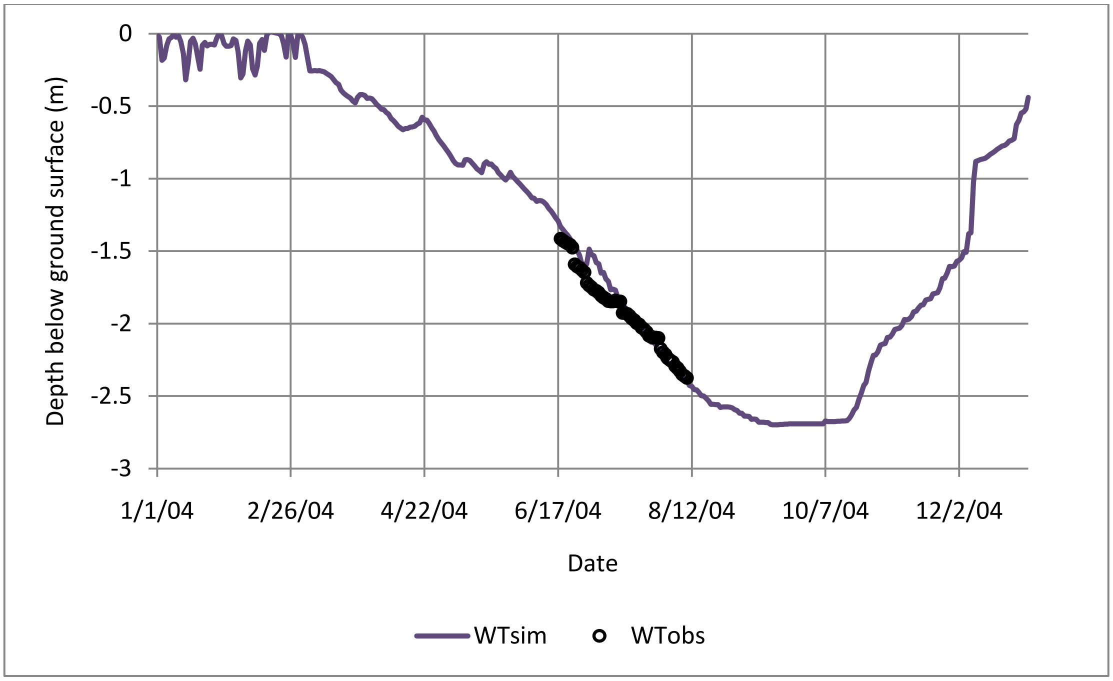

Figure 14: Simulated (WTsim) and observed (WTobs) water table depths for calibrating the ET parameters. Nash-Sutcliffe efficiency = 0.882, R^2 = 0.98.

The calibration resulted in the following ET parameters describing the observed data best: LAI = 1, C_2 = 0.2, and C_3 = 10 mm/day (0.39 mm/day). The MIKE SHE default for C_2 and C_3 is 0.2 and 20 mm/day (0.79 in/day) respectively. Kristensen and Jensen (1975) used C_3 = 10 mm/day (0.39 mm/day) as a typical value. Generally C_3 is higher if more water is released at low matric potentials or if the root density is high. These parameters were not calibrated within the basin-wide model.

3.4.2 Irrigation

Irrigation is described in MIKE SHE by specifying irrigation command areas and irrigation demand. Each irrigation command area (Figure 15) can be assigned a unique irrigation source and application type. For this research, river sources were used with sheet application (i.e. flood irrigation) to model the diversion and land application of water that occurs in the basin. The irrigation demand is specified as an application rate (mm/hr) occurring over a given time period. The Wood River Basin

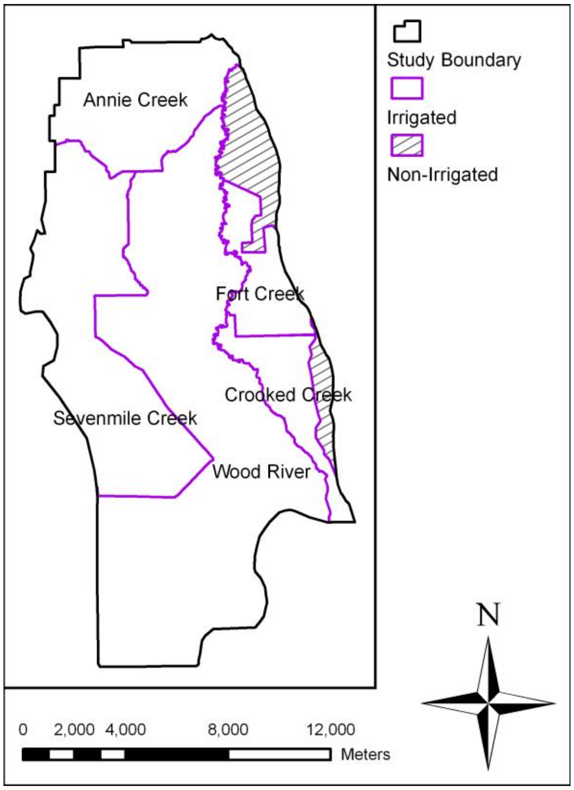

Figure 15: Irrigation command areas.

has an informal irrigation management system with few records regarding timing or intensity of irrigation. Irrigation is generally applied every 10 days to 14 days over a 24 hr to 48 hr period (Ciotti, 2005). Figure 16 shows water table depths in response to irrigation events for three irrigated sites in 2007. Early season irrigation events occur approximately on a 14 day rotation for the 3I and 6I sites, but less frequently in the 4I site. The water table in the 4I site also recedes much more slowly. The final irrigation events occurred in early September.

A sample of water rights in the Wood River Basin (OWRD, n.d.) were examined. Many irrigation water rights were established in the late 1800's to early 1900's, although some were not established until the mid 1900's. Irrigation water rights that designate a duty amount are either 0.9 m (3 ft) or 1.5 m (5 ft) of water. The rate is generally $1.39x10^{3}$ $m^3/s/ha$ (1/50th cfs/ac) for the irrigation season before July 20th and 8.7 $x10^{4}$ $m^3/s/ha$ (1/80th cfs/ac) after July 20th; or 8.7 $x10^{4}$ $m^3/s/ha$ (1/80th cfs/ac) for the entire season. The largest water right sampled (permit no. 42581) lists a rate of 8.7 $x10^{4}$ $m^3/s/ha$ (1/80th cfs/acre) for 15,962.6 ac (6460 ha). No duty is specified, but if 8.7 $x10^{4}$ $m^3/s/ha$ (1/80th cfs/ac) were applied continuously over a 180 day irrigation season then the total depth of application would be 1.37 m (4.5 ft). If 8.7 $x10^{4}$ $m^3/s/ha$ (1/80th cfs/ac) were applied on a 14 day rotation the application rate for any given rotation would be 0.175 cfs/acre ($1.2x10^{2}$ $m^3/s/ha$) which is equivalent to 4.4 mm/hr (0.17 in/hr).

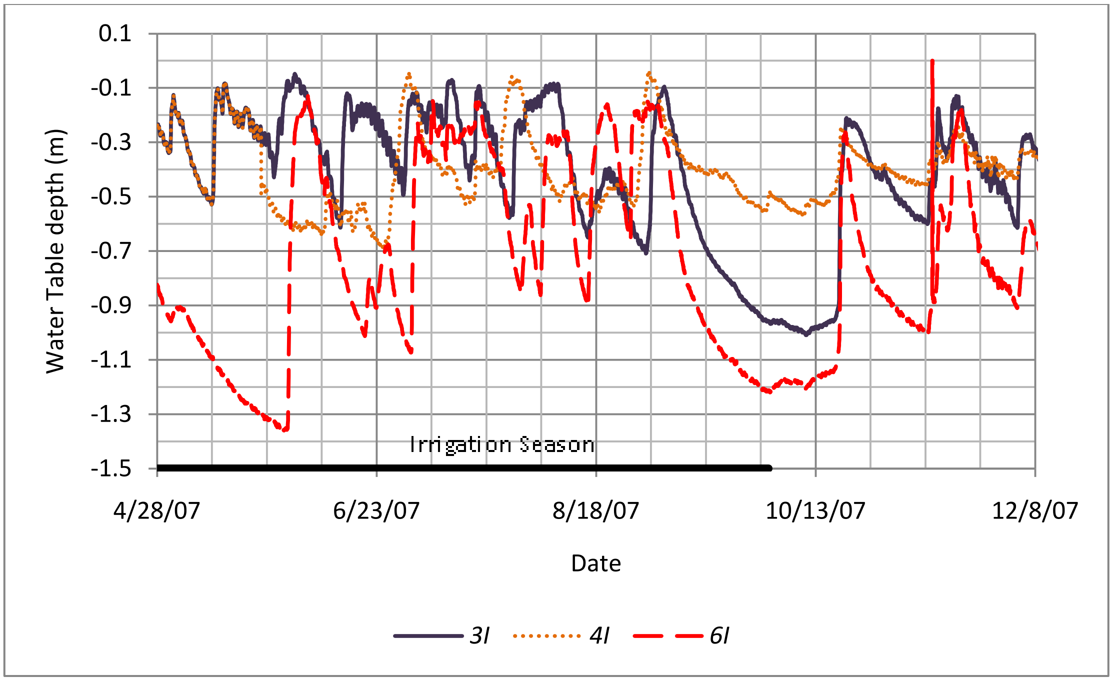

Figure 16: Water table depths in three different irrigated sites during the 2007 growing season. Vertical gridlines are spaced every 14 days. Peaks correspond to irrigation events that occur irregularly. The final irrigation event for these fields occurred in early September.

This rate applied over 24 hours results in a total application of 106 mm (4.17 in) per rotation.

Under real flood irrigation conditions irregularities in small-scale surface topography leads to poor irrigation efficiencies and large amounts of tailwater. For this research irrigation efficiency is considered to be the fraction of applied water that infiltrated into the soil. Land leveling is used in row crop systems to increase flood irrigation efficiency, but is not used for pasture because it is costly and requires bare ground. Small-scale topography cannot be simulated directly in this model set-up, each grid cell is considered as a large level surface. Flood irrigation in MIKE SHE is applied uniformly over the grid cell leading to high irrigation efficiencies within the model. In flood irrigation overland flow transports water across the field within individual tracts, but due to the high soil permeability and infiltration capacity, it is not likely a process that transports water over grid cell size scales during the growing season. Irrigation in the Wood River Basin occurs at a scale that is smaller than the model grid cell. To represent this system, the application rate was adjusted so that the amount of infiltration in the model is the same as in real conditions. The modeled application rate was calculated based in assumed irrigation efficiencies and then adjusted through calibration. This rate was used for all irrigation applications in the basin.

In 2003 Ciotti (2005) measured irrigation efficiency for two irrigation events on a 2 ha (4.9 ac) plot in the Wood River Basin that resulted in calculated efficiencies of <34%. Typical irrigation efficiency for average flood systems with no improvements is about 50% (Woods, n.d.). Irrigation tailwater managed through an extensive ditch network make up an important source of water for downstream irrigators in the basin and the reuse of tailwater will increase the irrigation efficiency over larger scales. If an efficiency of 50% is applied to the 4.4 mm/hr (0.17 in/hr) application rate then the equivalent application rate for a 100% efficient system would be 2.2 mm/hr (0.09 in/hr).

Irrigation applications are modeled as occurring once every 14 days over a 24 hr period from late April to early September, resulting in 10 irrigation events per season. The application rate was calibrated to account for uncertainties in the irrigation application rates and efficiencies. The rate was adjusted to match water table patterns that are typically seen under irrigated conditions, namely that the water table is elevated to near the surface for most irrigation events. Reduced irrigation scenarios used the same application rate and duration, but changed the rotation timing.

Early in the season the adjusted modeled application rates may still be greater than the total available soil storage leading to saturated conditions and overland flow. In the Wood River Basin this excess flow would quickly be removed by the surface drainage network and routed to downstream users or returned to streams. To model this, and eliminate inaccurate ponding in DEM sinks, shallow subsurface drainage is use to route excess water from the saturated zone (section 3.8) directly to MIKE 11 channels. A drain level of 0.1 m (0.33 ft) below ground level was used and is consistent with water table depths shown in Figure 16.

Irrigation demand is distributed in MIKE SHE based on grid codes. A different irrigation demand can be assigned for each unique grid code and grid codes can be assigned to one or more grid cells. Each irrigated grid cell was assigned a random grid code from 1 to 14 corresponding to the daily irrigation rotation. All cells with a grid code of 1 were irrigated on the first day of the rotation; all the cells with a grid code of 2 were irrigated on the second day of the rotation, etc. For the WRBActual scenario various non-irrigated tracts were enrolled in water conservation programs, a map of these lands for the 2003 and 2006 irrigation seasons is shown in Figure 17.

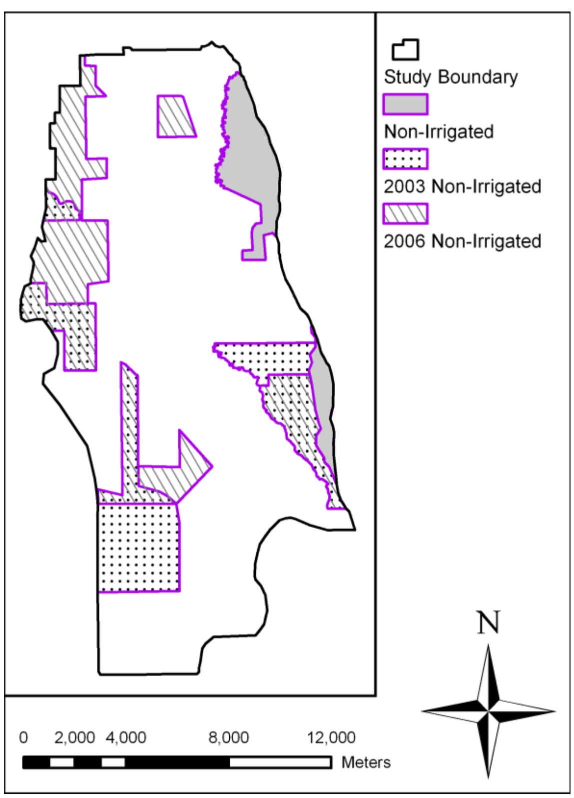

Figure 17: Non-irrigated land in the Wood River Basin.

2003 non-irrigated lands (after Pacific Groundwater Group (2003)) are considered to be non-irrigated for the years 2002, 2003, 2004, and 2005, termed the 03 period. 2006 non-irrigated lands (after Peterson (2006)) are considered to be non-irrigated for the years 2006, 2007, 2008, and 2009, termed the 06 period. This results in five different irrigation management scenarios from 2001 to 2009, summarized in Table 2, each one requiring a unique set of grid codes.

Table 2: Irrigation management scenarios occurring from 2001 to 2009 with corresponding grid code assignments where xx is a random integer from 01 to 14.

Irrigation Management	Grid Code
Permanently Non-Irrigated	100
Full Irrigation	1xx
2003 Non-Irrigated	2xx
2006 Non-Irrigated	3xx
2003 & 2006 Non-Irrigated	4xx

3.5 MIKE 11 Rivers and Lakes

The Wood River is the main source of irrigation water, but most water sources in the basin have been developed for irrigation, including numerous springs on the eastern and western edges. Water is conveyed through a complex series of canals, making a detailed simulation of irrigation management impractical. Most of the water diverted from the Wood River eventually flows into Agency Lake through Sevenmile Canal (Graham Mathews and Associates, 2007). The water sources in the basin were considered to be the natural flowing creeks that eventually flow into Agency Lake, including Wood River, Sevenmile Creek, Crooked Creek, Fort Creek, and Annie Creek.

MIKE 11 simulates flow rate and water depth. The river is placed along grid cell edges in MIKE SHE, but cross sections are used to calculate the rating curves, slopes and distances (chainage) independently of MIKE SHE. To interact with MIKE SHE the elevation of the banks at the grid cell is interpolated from the specified cross section elevation and chainage. If the bank elevation and grid cell elevation do not match then river and overland flow interactions may be prevented. This research is primarily interested in flow rate, and not near-stream flood plain interactions in response to stream water level. Therefore, numerous cross sections to accurately describe the stream profile and rating curves are not necessary. Cross section data for Wood River was taken from Campbell and Ehinger (1993), locations are shown in

Figure 18. Cross section data was not available for the other streams, therefore rectangular cross sections were assumed using a depth of 1.5 m (4.9 ft) and a width as measured from georeferenced imagery. The vertical datum for each cross section was taken from the NED30 DEM.

Boundary conditions for each open end of the stream network must be defined, these include the upstream ends where the streams enter the study area or at the stream origin, and the downstream end where the streams flow into Agency Lake. These streams are largely fed by groundwater springs and seeps resulting in consistent flow rates throughout the year, therefore a constant inflow rate was used as an approximation even though the streams to respond to rainfall events and snow melt over the larger catchment area. This means that total simulated stream flow into Agency Lake was not accurate. However, relative gains or losses in stream flow can be quantified for the various simulated scenarios

Determining inflows is difficult because no records exist before irrigation development and records that are available do not include diversions and return flows. USBR (2004) does report average annual flows for streams in the Wood River Basin that were calculated from available flow records. According to the report the average annual flow at Wood River Spring was 8.30 m^3/s (293 cfs). Wood River flow near Fort Klamath increased by 1.59 m^3/s (56 cfs) from the source. This is considered to be the flow of Annie Creek, the main tributary of the Wood River between the origin and Fort Klamath. The flow of Fort Creek was 2.55 m^3/s (90 cfs) and the flow of Crooked Creek was 2.66 m^3/s (94 cfs). Crooked Creek flows at the very eastern edge of the basin and accrues flow from numerous springs and seeps along its length. The flow from the streams and springs along the west side of the basin was reported as 118,000 ac-ft/yr, or 4.62 m^3/s (163 cfs). This lumped source is considered to be the

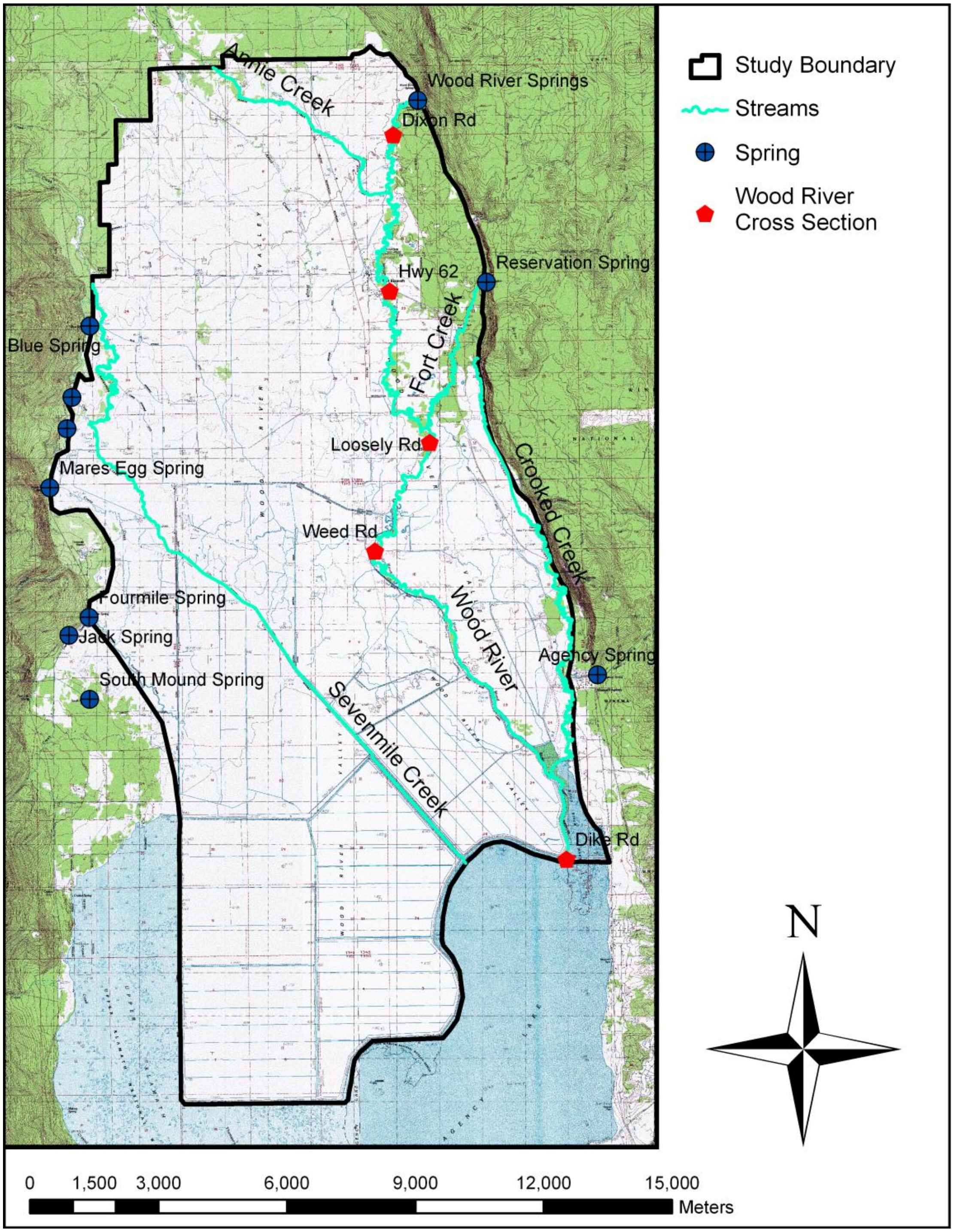

Figure 18: Wood River Basin streams used for irrigation. Most springs have also been developed for irrigation.

Sevenmile Creek flow because in the model it is the only source available for irrigation water in this part of the basin, and the tailwater from these sources will ultimately drain through Sevenmile Creek. The sum of average annual flows into Agency Lake is 19.72 m^3/s (696 cfs). The boundary condition for the outflow of Wood River and Sevenmile Creek is the water elevation of Agency Lake (see section 3.8.2)

3.6 Overland Flow

Overland flow is the flow of water across the land surface and is simulated in MIKE SHE by specifying two parameters. These parameters are the Manning's M value describing the surface roughness, and detention storage which is the minimum water depth required for flow to initiate. A Manning's M value of 33 (Manning's n = 0.03) was used because it is a typical value for short grass pasture flood plains with no brush (Chow, 1959) . Based in field observations a detention storage depth of 25 mm was used to account for the micro-topography, caused by the presence of livestock which created depressions. This module is required when using MIKE 11 because it is a potential mechanism for generating runoff.

3.7 Unsaturated Zone

The unsaturated zone is dynamically defined by MIKE SHE depending on the depth to the water table; therefore the unsaturated zone must be characterized to the lowest water table depth that will be encountered during the simulations. Vertical water movement within the unsaturated zone is controlled by the unsaturated hydraulic conductivity and soil moisture retention that are described using van-Genuchten parameters (van Genuchten, 1980) and solved by applying the Richards equation (Richards, 1931).

The soil in the Wood River Basin is volcanic in origin and mapped as the Kirk-Chock association soil, except in the southeast portion between Agency Lake and Sevenmile Creek where drained marshes were mapped as a Lather soil (Soil Survey Staff, n.d.). In the Kirk-Chock association the Kirk soil makes up about 70% of the map unit and the Chock soil makes up about 20% of the map unit. From the official series descriptions (Soil Survey Staff n.d.) the Kirk soil is *Ashy-pumiceous, glassy, nonacid Typic Cryaquands*, the Chock soil is *Ashy. glassy, nonacid Typic Cryaquands*, and the Lather soil is *Diatomaceous, euic, frigid Limnic Haplohemists*. Kirk and Chock soils are very similar; with Kirk soils having more pumice materials in them. The Lather soils are mostly made of organic matter and will have different hydrologic properties than the Kirk and Chock soils. There is no sampling or monitoring data available for the Lather soils, therefore these soils cannot be simulated or evaluated separately from the Kirk and Chock soils. Therefore the soils within the Wood River Basin were considered to be uniform.

The Wood River Basin soils are deep to very deep, poorly drained, and moderately permeable, these classifications are discussed in Schoeneberger et al. (2002). The depth class designation means that they extend below a 1.52 m (60 in) depth, therefore the C horizon of the soil is likely the same material that makes up the shallow aquifer discussed in section 3.8. The drainage class designation indicates that the soils are wet at shallow depths for prolonged period of time and requires drainage for most crops. The shallow water table in poorly drained soils is typically caused by either a restrictive layer with low hydraulic conductivity, or persistent rainfall. Since neither of these conditions exists in the Wood River Basin the drainage class is interpreted to be the result of the aquifer hydrology. The permeability class is a qualitative estimate of a soils ability to transmit water that is roughly based on bulk density and soil texture. Moderate permeability is estimated to be within the range of 4.2×10^{-6} m/s (0.6 in/hr) to 1.4×10^{-5} m/s (2.0 in/hr).

Volcanic soils have unique physical and chemical properties due to the formation of non crystalline materials and the accumulation of organic carbon (Dahlgen et al., 2004). These properties include low bulk density, high porosity, large specific surface area, and stable structural voids that affect both the moisture retention properties and the hydraulic conductivity. Typical values based on soil texture for these parameters are not appropriate for these soils due to their unique properties. Soil samples were taken near NRCS piezometer sites (Figure 10) to characterize moisture retention properties. Additionally data from one soil sample site for a Kirk Soil near Fort Klamath is available from the National Soil Survey Laboratory (NSSL) (National Cooperative Soil Characterization Data, 2009), Pedon ID: 67OR035013.

Soil samples were analyzed in the laboratory for soil moisture content at a matric potential of -33kPa (-4.8 psi), bulk density (ρ_b), and fraction of sand, silt, and clay. These data were then input into the Rosetta pedotransfer model (ARS, n.d.; Schaap & Leij, 2000) which predicts van Genuchten parameters used to describe the soil moisture retention and the unsaturated hydraulic conductivity as a function of soil moisture. If the soil moisture content at a matric potential of -1500 kPa (-218 psi) is known then that can also be entered for a more accurate prediction. Soil moisture as a function of matric potential is:

$$\theta(\Psi) = \theta_r + \frac{(\theta_s - \theta_s)}{[1 + (\alpha\Psi)^n]^m}$$

Where Ψ is the absolute value of the matric potential in cm H_2O, θ_r is the residual moisture content, θ_s is the saturated moisture content, α and n are empirical parameters that relate to the inverse of air entry pressure and pore size distribution respectively, and $m = 1-1/n$. Unsaturated hydraulic conductivity as a function of matric potential is:

$$K(\Psi) = K_s \frac{[(1 + |\alpha\Psi|^n)^m - |\alpha\Psi|^{n-1}]^2}{(1 + |\alpha\Psi|^n)^{m(L+2)}}$$

Where K_s is the saturated hydraulic conductivity and L is an empirical parameter that relates to the tortuosity and connectivity of pores.

Soil physical characteristics and the predicted van Genuchten parameters are summarized in Table 3 and Table 4. Field capacity is defined as the water content at a matic potential of -10kPa, which is the MIKE SHE default, but is also recommended for use with soils with high sand contents (NRCS, 1995).

Examination of the resulting soil moisture retention curves showed that samples in Table 4 marked (1) are similar and occur at a depth of 0 cm (0 ft) to 20 cm (0.79 ft),

Table 3: Physical characterization of soil samples

Sample Site	Horizon	Depth* (cm)	ρ_b (g/cm^3)	Sand %	Silt %	Clay %	θ -33kPa	θ -1500kPa
3I	A	9-12	0.88	67	28	5	0.45	--
4N	B	11-14	0.68	58	30	11	0.44	--
4I	B	17-20	0.75	68	17	15	0.52	--
3I	B	25-28	0.81	72	17	11	0.30	--
6N	B	36-39	0.73	81	14	5	0.32	--
2N	BC	34-37	0.71	67	23	9	0.36	--
4N	BC	51-54	0.48[1]	63	29	8	0.27	--
6N	BC	67-70	0.87	71	23	6	0.34	--
3I	C	47-50	0.68	56	17	28	0.59	--
2N	C	67-70	0.71	62	24	14	0.39	--
NSSL	A1	0-5	0.59	55.5	28.5	16.0	0.54	0.16
NSSL	A2	5-10	1.13	57.9	28.0	14.1	0.45	0.15
NSSL	A3	10-23	1.20	65.5	23.9	10.6	0.41	0.11
NSSL	A/C	23-38	1.32	72.9	19.6	7.5	0.31	0.09
NSSL	C	38-63	1.33	86.2	10.4	3.4	0.30	0.04

*For the NSSL data the depth describes the upper and lower boundaries for the horizon that the sample was taken from, for the other samples the depth refers to the actual depth of sampling.

[1]The minimum value for ρb in Rosetta is 0.5, which was entered for this sample

Table 4: Estimated van Genuchten soil parameters to describe the soil hydrology based on the values in Table 3.

Sample Site	Horizon	Depth* (cm)	ϑ_r	ϑ_s	*L*	α	*n*	K_s
3I (1)	A	9-12	0.06	0.53	1.14	0.0029	1.62	8.7e-6
4N (1)	B	11-14	0.06	0.60	0.46	0.0075	1.39	2.2e-5
4I (1)	B	17-20	0.08	0.61	0.59	0.0042	1.50	2.8e-6
3I (2)	B	25-28	0.05	0.57	-2.48	0.0413	1.22	6.9e-5
6N (2)	B	36-39	0.04	0.59	-2.87	0.0373	1.20	5.2e-5
2N (2)	BC	34-37	0.05	0.58	-1.41	0.0020	1.23	4.7e-5
4N (2)	BC	51-54	0.04	0.63	-4.45	0.0866	1.20	1.4e-4
6N (2)	BC	67-70	0.04	0.533	-0.43	0.0152	1.27	3.3e-5
3I (4)	C	47-50	0.11	0.66	-1.29	0.0197	1.46	3.4e-6
2N (2)	C	67-70	0.05	0.60	-0.06	0.0056	1.46	3.4e-6
NSSL (1)	A1	0-5	0.08	0.62	0.53	0.0027	1.76	9.6e-6
NSSL (4)	A2	5-10	0.08	0.49	0.88	0.0015	1.99	3.1e-6
NSSL (4)	A3	10-23	0.06	0.46	1.04	0.0016	1.98	3.0e-6
NSSL(3)	A/C	23-38	0.03	0.42	0.86	0.0041	1.59	4.1e-6
NSSL (3)	C	38-63	0.03	0.4	1.06	0.0031	1.69	3.9e-6

*For the NSSL data the depth describes the upper and lower boundaries for the horizon that the sample was taken from, for the other samples the depth refers to the actual depth of sampling.
(1) samples used for characterizing the A horizon (top soil)
(2) samples used for characterizing the B or BC horizon (sub soil)
(3) samples used for characterizing the C horizon (soil parent material)
(4) samples not used for soil characterization

their parameters were averaged to characterize the soil A horizon from 0 cm (0 ft) to 20 cm (0.79 ft) (Figure 19). The samples marked (2) are similar and occur at a depth from 20 cm (0.79 ft) to 70 cm (2.76 ft), their parameters were averaged to characterize the BC horizon from 20 cm (0.79 ft) to 1 m (3.3 ft) in depth (Figure 20). The official soil series description has the BC horizon extending to a depth of 1.52 m (60 in), but field sampling revealed that the C horizon can often occur at much shallower depths. The two samples marked (3) were both from the NSSL and occurred at shallow depths, but were used to represent the soil below 1 m (3.3 ft) (Figure 21). The NSSL profile was described with a horizon sequence of A1-A2-A3-A/C-C, the lack of a B horizon means that there has been very little soil morphology and profile

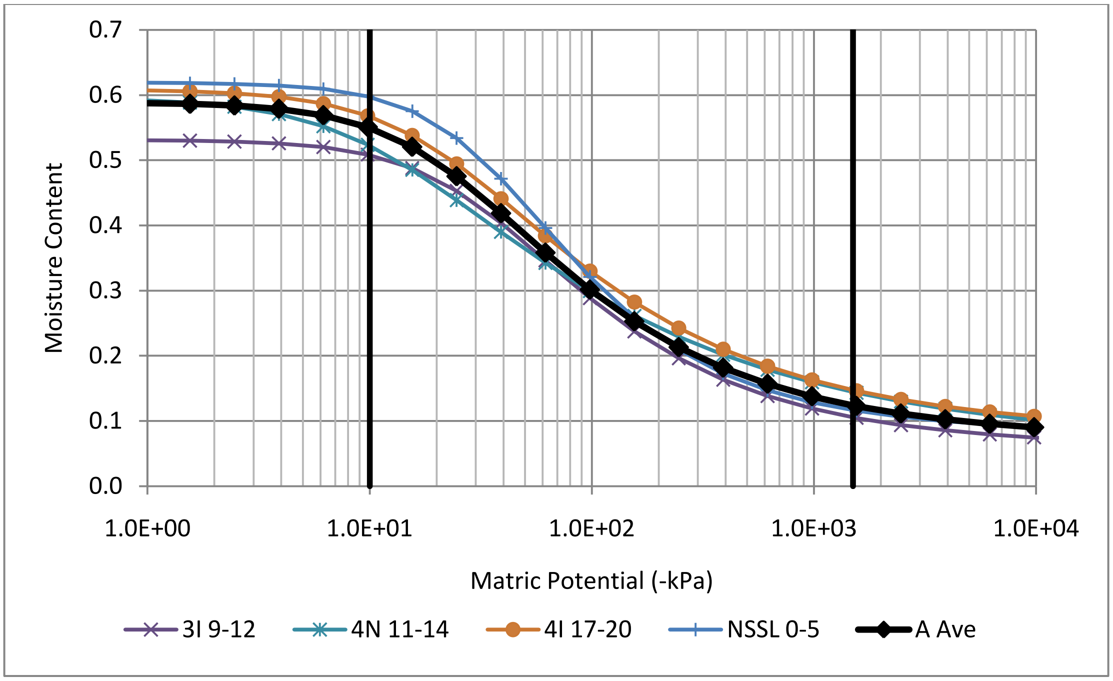

Figure 19: Soil moisture retention curves for samples representing the top 20 cm of soil. The dark vertical lines represent field capacity (-10kPa) and permanent wilting point (-1500kPa). A Ave is the curve resulting from averaging parameters of the other curves.

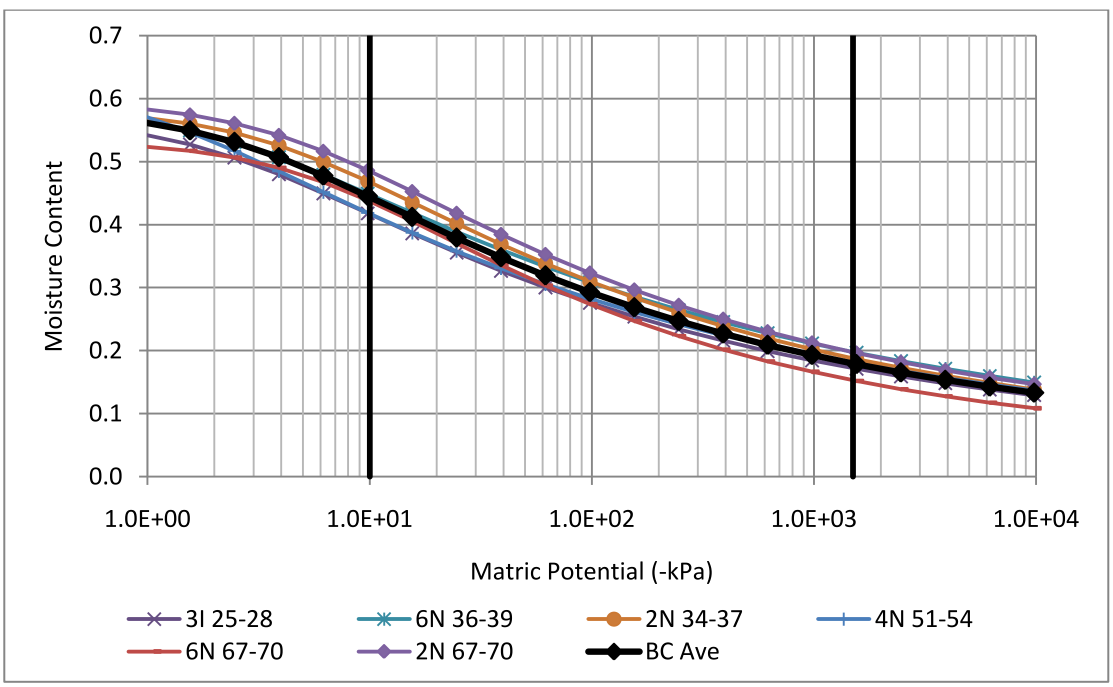

Figure 20: Soil moisture retention curves for samples representing the soil from 20 cm to 1.0 m depth. The dark vertical lines represent field capacity (-10kPa) and permanent wilting point(-1500kPa). BC Ave is the curve resulting from averaging parameters of the other curves.

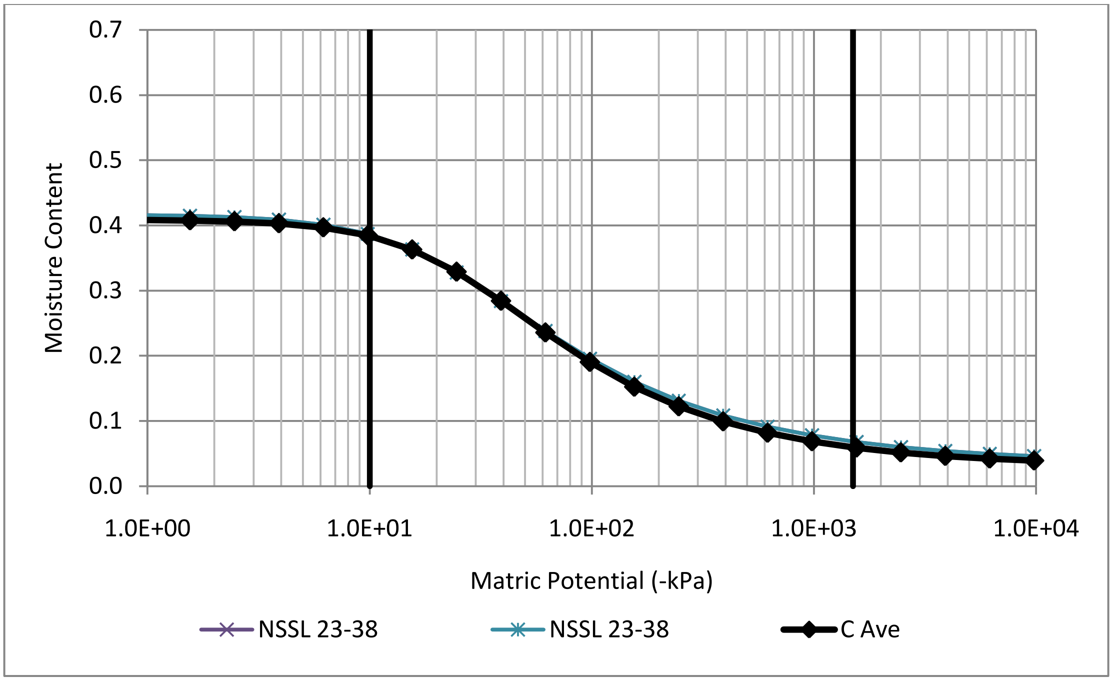

Figure 21: Soil moisture retention curves for samples representing the soil below 1.0 m depth. The dark vertical lines represent field capacity (-10kPa) and permanent wilting point (-1500kPa). C Ave is the curve resulting from averaging parameters of the other curves.

development. The bulk density of this soil is also inconsistent with the other samples, and the higher bulk density can indicate that the material lacks structure and therefore is well representative of the C horizon. This is interpreted to mean that the samples from the A/C and C horizons are representative of the unconsolidated basin-fill parent material that also makes up the shallow aquifer below the soil, and therefore these samples are used to characterize the unsaturated zone below 1.0 m. Samples marked (4) were inconsistent with the other samples and were not used. The resulting moisture retention curves representing the A, BC, and C horizons are shown in Figure 22.

K_s is a difficult parameter because it varies by orders of magnitude over small distances (DHI, 2009) and the size of the sample volume can influence the measurement. The Rosetta model does predict K_s, but those predictions can be inaccurate and are for samples whose physical properties where measured over a

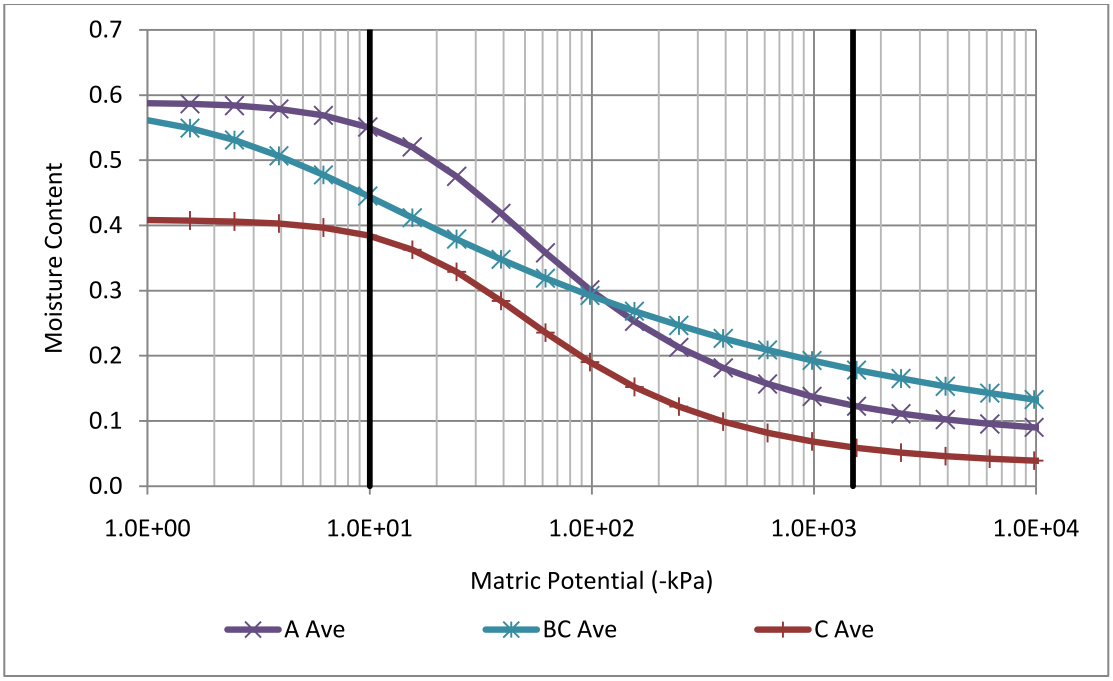

Figure 22: Resulting average soil moisture retention curves for the A, BC, and C horizons. The dark vertical lines represent field capacity (-10kPa) and permanent wilting point (-1500kPa).

small scale (~70 cm^3, 4.27 in^3). K_s data for a Kirk soil located on a near shore relict lake terrace near the Williamson River was available from Schoeneberger (2007). Five replicates were measured in situ, results are summarized in the Table 5. The K_s values for the A and 2Eg horizons were in the "high" hydraulic conductivity class which corresponds to a range of 1×10^{-6} m/s (0.142 in/hr) to 1×10^{-5} m/s (1.417in/hr). The 2BC horizon is anomalously low, especially since it was originally estimated to be in the same permeability and K_s class as the A and 2EG horizons. It was noted that a densified 2BC layer was common along the relict lake shore and this value is probably not representative of similar layers in the Wood River Basin. General K_s and

Table 5: In situ K_s measurements for a Kirk soil, after Schoeneberger (2007).

Horizon	Depth (cm)	Average K_s (m/s)	Standard Deviation (m/s)	Field Texture
A	16	1.9×10^{-5}	8.7×10^{-6}	medial fine sandy loam
2Eg	50	2.8×10^{-5}	2.7×10^{-5}	very paragravelly ashy loamy coarse sand
2BC	72	9.7×10^{-7}	2.7×10^{-7}	very paragravelly ashy loamy coarse sand

bulk density (ρ_b) data was also available from the soil survey for each of the soil types (Table 6).

Table 6: Soil physical properties from the Klamath County, OR, Southern Part Soil Survey (Soil Survey Staff, n.d.).

Soil Name	Depth (cm)	K_s (m/s)	ρ_b (g/cm^3)
Kirk	0-22.5	$4\times10^{-6} - 1.4\times10^{-5}$	0.85-0.95
	22.5-37.5	$4\times10^{-6} - 1.4\times10^{-5}$	0.85-0.95
	37.5-150	$4.2\times10^{-5} - 1.4\times10^{-4}$	0.85-0.95
Chock	0-17.5	$4\times10^{-6} - 1.4\times10^{-5}$	0.4-0.6
	17.5-150	$4\times10^{-6} - 1.4\times10^{-5}$	0.4-0.6

For the A horizon the in situ measured K_s was 1.9×10^{-5} m/s, slightly above the range reported for the 0-22.5 cm depth in Table 6; and the average predicted K_s from Rosetta was 9.1×10^{-6} m/s (1.29 in/hr), within the range reported for the 0-22.5 cm depth in Table 6. For the B horizon depth (corresponding to the 2Eg horizon in Table 5) the in situ measured K_s was 2.8×10^{-5} m/s (4.0 in/hr), and the predicted K_s from Rosetta was 5.5×10^{-5} m/s (7.8 in/hr); both of these values are slightly above the range reported for the 37.5cm to 150 cm depth in Table 6. For the C horizon the in situ measured K_s is not applicable due to special soil characteristics at the measuring site. The average K_s from Rosetta was 2.0×10^{-7} m/s (0.03 in/hr), well below the range reported in Table 6. The C horizon was considered to be the same material that makes up the shallow aquifer and was assigned a K_s value based on the characterization of the saturated zone, which resulted in a range of K_s from 1.0×10^{-4} m/s (14.2 in/hr) to 8.0×10^{-4} m/s (113.4 in/hr) (section 3.8). Parameters used to characterize the unsaturated zone are summarized in Table 7. The only calibration parameters for the unsaturated zone are the K_s for each soil layer. The K_s for the C horizon is further constrained to be equal to the K_s for the shallow aquifer.

Table 7: Unsaturated zone parameters, values and calibration ranges, parameters that do not list a range of values are not subject to calibration.

Soil Hoizon	Depth (cm)	Parameter	Unit	Low Value	High Value
A	0-20	K_s	(m/s)	2.5×10^{-6}	3.0×10^{-5}
		ρ_b	(g/cm3)	0.77	-
		ϑ_r	(cm/cm)	0.072	-
		ϑ_s	(cm/cm)	0.59	-
		L	()	0.680	-
		α	()	0.0040	-
		n	()	1.16	-
BC	20-100	K_s	(m/s)	3.5×10^{-6}	1.5×10^{-5}
		ρ_b	(g/cm3)	0.77	-
		ϑ_r	(cm/cm)	0.045	-
		ϑ_s	(cm/cm)	0.58	-
		L	()	-2.154	
		α	()	0.0309	-
		n	()	1.225	-
C	100+	K_s	(m/s)	1×10^{-4}	8×10^{-4}
		ρ_b	(g/cm3)	1.35	-
		ϑ_r	(cm/cm)	0.030	-
		ϑ_s	(cm/cm)	0.41	-
		L	()	0.960	-
		α	()	0.0036	-
		n	()	1.64	-

3.8 Saturated Zone

The saturated zone represents the groundwater component of the hydrologic cycle where water can move laterally between grid cells, exchange with surface water, or be withdrawn through groundwater pumping. Groundwater pumping was not simulated because there is very little groundwater pumping in the Wood River Basin, for water year 2000 it was estimated that 1,100 ac-ft ($1.36\text{x}10^6$ m^3) was pumped to irrigate 360 ac (146 ha) (USGS, 2007). This saturated zone module is divided into geologic layers and lenses, and computational layers. The geologic layers and lenses describe the physical characteristics of the geologic material. Layers are continuous throughout the model whereas lenses are not. The computational layers specify the initial and boundary conditions, the boundary conditions represent important physical processes.

3.8.1 Geologic Layers and Lenses

Conceptual geologic models are difficult to develop because information about the subsurface is scarce. For the Wood River Basin the geologic model is based on previous groundwater and geology studies (Pacific Groundwater Group, 2003; USGS, 2007) and drillers' well logs available from the Oregon Water Resource Department at http://apps2.wrd.state.or.us/apps/gw/well_log/Default.aspx

USGS (2007) studied groundwater hydrology in the entire Upper Klamath Basin and found that ground water typically responds to decadal scale climate patterns. Their conceptual model of the ground water system is shown in Figure 23, which includes recharge and discharge mechanisms from the local to inter-basin scale. The Wood

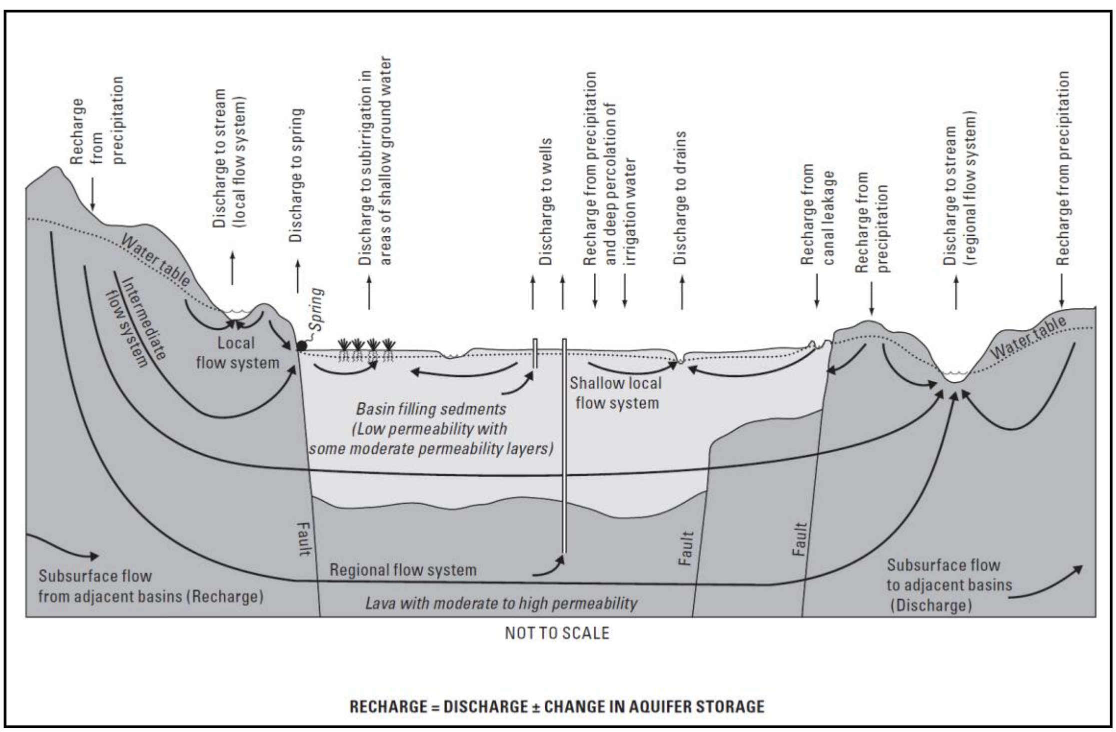

Figure 23: Conceptualization of groundwater flow processes in the Upper Klamath Basin, Oregon and California. Copied from USGS (2007).

River Basin was describe as having an aquifer in the upper 30.5 m (100 ft) to 91.4 m (300 ft) of sand and pumice fill deposits, confined by a clay layer. Hydraulic heads in this deep aquifer are typically higher than the surface elevation, resulting in artesian conditions; most wells in the area are developed in this aquifer. Overlying the clay confining layer is a shallow aquifer which can be a combination of surficial pumice soils and deeper sand and gravel layers, both of which are highly permeable.

A more detailed study was done by Pacific Groundwater Group (2003) and examinined OWRD well logs and supplementary data from shallow soil borings, cone penetrometer borings, and a well drilled on the southeastern side of the basin just north of where the Wood River flows into Agency Lake. They found that a surface pumice layer covers the entire surface of the basin and varies in thickness from 16.5 m (54 ft) near Fort Klamath (Well Logs KLAM 50938, KLAM 11812) to 4.6 m (15 ft) in the south of the basin (KLAM 11528). The pumice materials overlay either clay layers or sand and gravel layers, indicating that the clay layers are not laterally continuous in the basin and would be best describe as geologic lenses. The middle of the basin has a single thick clay layer, but in the northern and southern portions the clay occurred in several distinct layers between sand and gravel deposits.

For the model set-up, well logs were used to characterize the depths geologic layers and lenses (Figure 24). These logs were mapped by placing them in the middle of the smallest cadastral division reported, typically quarter section or quarter-quarter section. No verification of well location was done. Depths to the upper and lower levels of the clay lenses were recorded. Typical well log descriptions for the clay lenses included clay, brown clay, grey clay, yellow clay, blue clay, fine sandy clay, sandy clay, and sand and clay. Four different clay lenses were defined, correlating roughly to depth intervals of 0 m (0 ft) to 15.2 m (50 ft), 15.2 m (50 ft) to 30.5 m (100 ft), 30.5 m (100 ft) to 45.7 m (150 ft) and 45.7 m (150 ft) to 61 m (200 ft) in depth. Clay lenses that extended through two of more of these depths were divided into these depth classes. The thickness was calculated for each lens; in well logs where the lens was not present a thickness value of 0 m (0 ft) was used. An inverse distance weighting routine in ArcGIS was then used to interpolate the thickness and the upper level depth for each lens. Areas where the lenses were less than 3 m (9.8 ft) thick were considered to be discontinuities and removed. The lower level of each lens was then calculated by adding the thickness to the upper level. The levels of overlapping lenses were adjusted to the average value. Figure 24 shows the total thickness for all of the clay lenses. The thickest clay deposits occur in the middle of the basin, consistent with the geologic transects reported by Pacific Groundwater Group (2003). Wells under artesian conditions generally occur in areas with thick clay deposits.

The levels for the geologic layers and lenses were defined relative to ground surface, which is a negative value in MIKE SHE. MIKE SHE can also define the levels by elevation. When referring to the MIKE SHE parameters negative values will be used to denote depth relative to ground surface, otherwise positive values are used. Two geologic layers were defined, referred to as the shallow aquifer and the deep aquifer. The lower level of the shallow aquifer was taken to be -15 m (-49.2 ft) because that is the largest depth recorded for the surficial pumice materials. Shallower depths of these surficial materials were accounted for by defining the clay lenses. The deepest well (KLAM 10189), in the northern part of the basin, hit hard grey rock at a depth of 124 m (406 ft). It is the only well to report hitting rock, which may or may not be extensive at this depth in the basin. Another deep well (KLAM 56456), in the middle of the basin, was drilled to a depth of 122 m (400 ft) without hitting rock. The lower level for the deep aquifer cannot be determined because the wells do not penetrate to the bottom of the basin fill deposits. Due to uncertainty in the total aquifer depth (lower level) it will be used as a calibration parameter with an upper limit of -120 m (-394 ft), consistent to the deepest report of bedrock material. This has the potential to

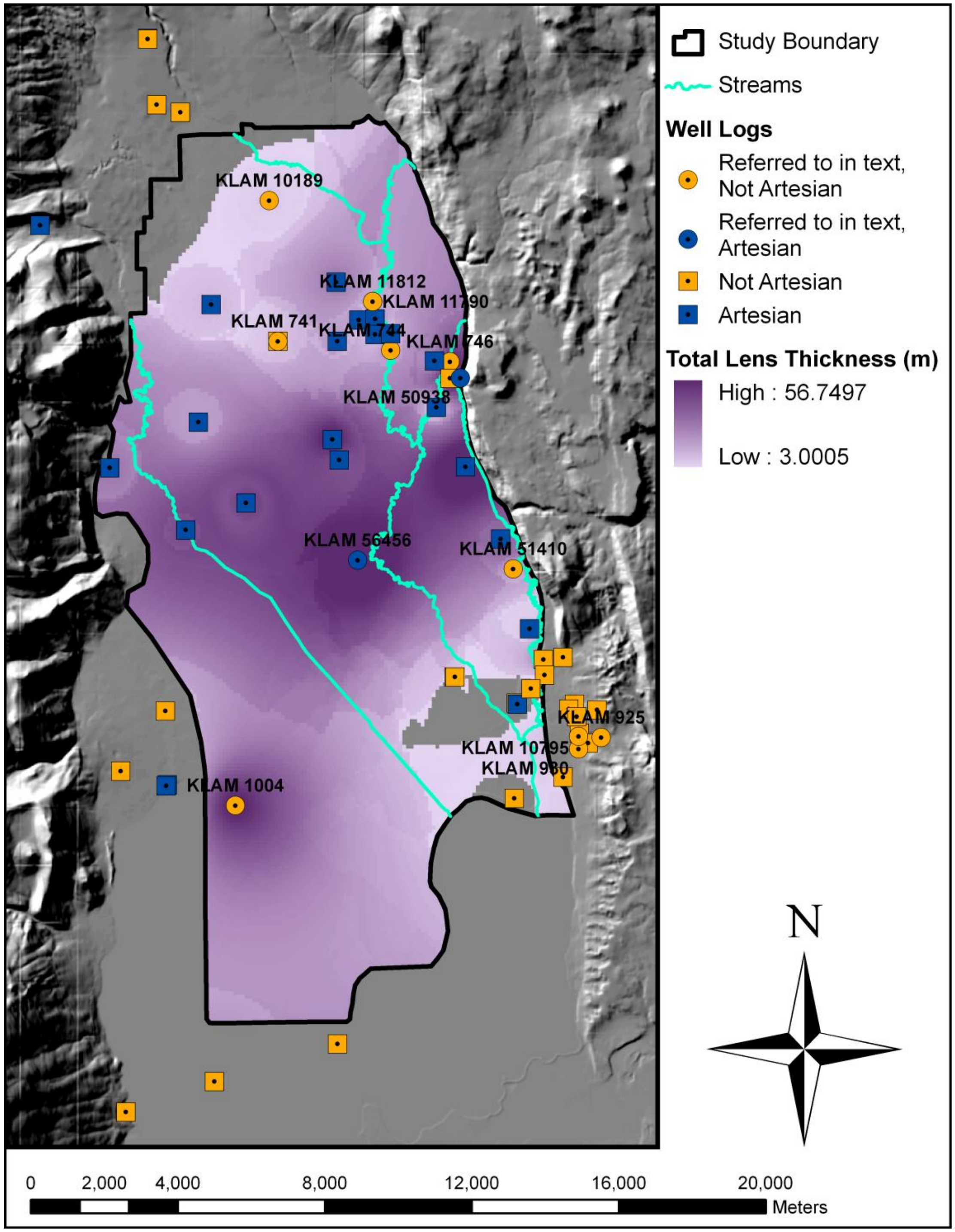

Figure 24: Well logs used to characterize the geologic layers and lenses. Well logs referred to in the text are labeled. The total thickness of the clay lenses is shown. Note that artesian wells generally occur in areas with large total lens thickness.

be a very important parameter because the thickness of the deep aquifer multiplied by the hydraulic conductivity of the material determines the total aquifer transmissivity.

Both horizontal and vertical K_s are specified in MIKE SHE. The vertical K_s is typically lower than the horizontal K_s, especially in alluvial deposits (Todd and Mays, 2004), but since there are no data to suggest a difference between them the same value will be used for both. K_s for the shallow aquifer was calculated from well test data provided in well logs, using an empirical equation from Driscoll (1986) for an unconfined aquifer:

$$T = 1500 \times \frac{Q}{s}$$

Where T is transmissivity in gpd/ft, Q is flow rate in gpm, and s is drawdown in ft. Hydraulic conductivity can then be calculated using:

$$K_s = \frac{T}{h}$$

Where K_s is in gpd/ft^2 and h is the aquifer thickness in ft. Most of the wells in the area were developed in the deep aquifer, but there was some well test data available for the shallow aquifer, summarized in the Table 8. These values compare well with the typical value of 5.2×10^{-4} m/s (73.7 in/hr) reported by Todd and Mays (2004) for coarse sand, which is the commonly reported material for the shallow and deep aquifers.

Table 8: K_s calculated from shallow aquifer pump tests reported in well logs.

Report No	Q (gpm)	s (ft)	h (ft)	K_s (gpd/ft^2)	K_s (m/s)
Klam 11790	10	3	11	455	2.1×10^{-4}
Klam 11790	20	11.5	11	237	1.1×10^{-4}
Klam 925	50	9	10	833	3.9×10^{-4}
Klam 11812	40	7	30	286	1.4×10^{-4}
Klam 51410	60	14	20	225	1.1×10^{-4}

One of the advantages of using well tests to estimate K_s is that the sample volume is large and therefore more likely to reflect the overall aquifer K_s than a small scale sample. The empirical equation is based on average well and aquifer properties and provides only an estimation of K_s.

The same approach was used for the deep aquifer, which is considered to be confined. The Driscoll (1986) equation for a confined aquifer is:

$$T = 2000 \times \frac{Q}{s}$$

The units are the same as above. The resulting K_s values are summarized in Table 9, and range from 1.0x10^{-5} m/s (1.4 in/hr) to 2.4x10^{-4} m/s (34.0 in/hr).

Table 9: K_s calculated from deep aquifer pump tests reported in well logs.

Report No	*Q* (gpm)	*s* (ft)	*h* (ft)	K_s (gpd/ft^2)	K_s (m/s)
Klam 741	30	5	24	500	2.4×10^{-4}
Klam 744	20	10	9	444	2.1×10^{-4}
Klam 746	30	22	104	26	1.0×10^{-5}
Klam 930	40	5	89	180	8.0×10^{-5}
Klam 1004	1200	92	120	217	1.0×10^{-4}
Klam 10189	750	200	140	54	3.0×10^{-5}
Klam 10795	30	29	38	54	3.0×10^{-5}
Klam 11790	20	11.5	16	217	1.0×10^{-4}
Klam 11790	10	3	16	417	2.0×10^{-4}

In reviewing the well logs, Pacific Groundwater Group (2003) noted that clay is commonly used to describe all materials finer than sand. The clay lenses were often referred to as sandy clay or fine sandy clay indicating that the sand and the clay materials were of similar size due to their concurrent deposition. Clays would not be deposited with sand, because of their small particle size they would remain in suspension and be transported further downstream. Furthermore the surficial deposit materials have very little clay; the fine fraction is dominated by fine sands and silts. I interpreted this to mean that the clay lenses are likely made up of silt materials. A typical K_s value for silt of 1.0×10^{-6} m/s (0.14 in/hr) (Todd and Mays, 2004) was used for the horizontal and vertical hydraulic conductivities in the lenses.

Two other parameters used to characterize the geology are specific storage and specific yield. For the specific storage the MIKE SHE default of 0.0001 was used. Specific yield was calibrated within the measured range of 0.1 to 0.24 (Pacific Groundwater Group, 2003).

Parametrization for the saturated zone physical properties are summarized in Table 10. The parameters that are subject to calibration include the K_s for the shallow and deep aquifers and the specific yield for both aquifers and the lenses. To further constrain the calibration the Horizontal K_s was considered to be equal to the vertical K_s and the specific yield will be considered equal for all of the layers and lenses.

Table 10: Parametrization for geologic layers and lenses in the saturated zone.

	Parameter	Unit	Low Value	High Value
Shallow Aquifer	Lower Level	(m)	-15	--
	Horizontal K_s	(m/s)	1×10^{-4}	8×10^{-4}
	Vertical K_s	(m/s)	1×10^{-4}	8×10^{-4}
	Specific Yield	()	0.10	0.24
	Specific Storage	(m^{-1})	1×10^{-4}	--
Deep Aquifer	Lower Level	(m)	-120	-250
	Horizontal K_s	(m/s)	1×10^{-5}	3×10^{-4}
	Vertical K_s	(m/s)	1×10^{-5}	3×10^{-4}
	Specific Yield	()	0.10	0.24
	Specific Storage	(m^{-1})	1×10^{-4}	--
Lenses	Lower Level	(m)	*	--
	Horizontal K_s	(m/s)	1×10^{-6}	--
	Vertical K_s	(m/s)	1×10^{-6}	--
	Specific Yield	()	0.10	0.24
	Specific Storage	(m^{-1})	1×10^{-4}	--

* The lower and upper levels of the lenses are from well logs and not subject to calibration

3.8.2 Computational Layers

In the unsaturated zone water moves vertically and the boundary conditions are the soil surface, simulated in the land use module, and the water table, simulated in the saturated zone module. In the saturated zone water can move laterally and boundary conditions must be specified for the model domain. The types of boundary conditions include zero flux, fixed head, flux, and gradient. Boundary conditions in this study were separated into the north, east, south and west boundaries, which are specified for the shallow and deep aquifer.

From the conceptual model of the hydrogeology (Figure 23) most of the influx of water is from the regional flow system through the deep aquifer. Estimations of groundwater head gradients are based on data available from this aquifer. USGS (2007) describes the groundwater head gradient in the Wood River Basin as going from north to south and being 0.057 (300ft/mi) to 0.019 (100 ft/mi) from Crater Lake to the northern basin edge, 0.0076 (40 ft/mi) from the northern basin edge to Fort Klamath, and 0.001 (5 ft/mi) from Fort Klamath to Agency Lake. The northern boundary condition is defined as a gradient flux boundary within these ranges.

The groundwater head in the mountains to the west also causes groundwater flux into the Wood River Basin, and is also defined as a gradient flux. In the mountains the groundwater gradient is approximately 0.0045 (24 ft/mi) (USGS, 2007), however the gradient at the boundary may be lower. Groundwater to the east of the study site primarily flows south and the eastern boundary condition is defined as zero flux. Agency Lake makes up the southern boundary and the boundary condition is defined as time-variable fixed head using the Upper Klamath Lake elevation record available from waterdata.usgs.gov (Station 11507001), and correcting it to the NAVD88 vertical datum used for the NED30 DEM. The southern boundary of the shallow aquifer is also defined as time-variable fixed head using the Upper Klamath

Lake data record. All other boundaries in the shallow aquifer are considered to be zero flux.

The boundary condition fluxes are extremely important because they control how much water is flowing into the deep aquifer. Considering that the Wood River and many of the creeks in the basin are spring fed the amount of groundwater flux into the basin may be considerable. The parametrization of the saturated zone boundary conditions are summarized in Table 11, the only calibration parameters are the groundwater head gradients for the northern and western deep aquifer boundary.

Table 11: Saturated zone boundary conditions.

Aquifer	Boundary	Flux Type	Low Value	High Value
Shallow	North	Zero	--	--
	East	Zero	--	--
	South	Fixed Head	*	--
	West	Zero	--	--
Deep	North	Gradient	0.001	0.02
	East	Zero	--	--
	South	Fixed Head	*	--
	West	Gradient	0.00	0.0045

*Head elevation for this boundary is taken from the Upper Klamath Lake water elevation record, see text.

3.8.3 Drainage

Drains remove water from the saturated zone once the water table rises to the level of the drains; they do not intercept infiltrating water. MIKE SHE can simulate drainage in a number of different configurations, for this model the drainage is routed to the nearest river, ignoring topography. In the Wood River Basin water from excess surface applications are channeled to downstream users or canals with an extensive surface drainage network. In the model excess surface water applications infiltrate to the saturated zone where it is removed if the water table rises to a depth of 0.1 m or above (see section 0). A drainage time constant determines how quickly drainage occurs, typical values range from 1.0×10^{-6} 1/s to 1.0×10^{-7} 1/s (DHI, 2009). A value of 1.0×10^{-6} 1/s was used to reflect the high permeability soils.

3.9 Initial Conditions

Initial conditions for the model are specified within the individual modules and include the water table depth (saturated zone), the soil moisture content (unsaturated zone), and the initial water depth (overland flow). The model was started on January 1 when the basin is fairly saturated, therefore initial water table depth was set at 0.5 m (1.6 ft) below ground surface, initial soil moisture content was set using a matric potential of -10 m H_20 (-98 kPa, -14.2 psi), and the initial water depth was set at 0 mm. Initial conditions can have a considerable affect over the early simulation time, but as the simulation progresses the initial condition affect decreases as long as they were within a reasonable range and did not cause model instability. To reduce the effect of inaccurate initial conditions a five year “spin up” period was used to lead into the time period of interest. Complete data records were available for the period from January 1, 2001 to December 31, 2009. The four year period from January 1, 2005 to December 31, 2008 was redefined as January 1, 1997 to December 31, 2000 and used for the model spin up period. For all scenarios the basin was considered to be under full irrigation from January 1, 1997 to December 31, 2001. Results are summarized for the time period from January 1, 2002 to December 31, 2009 because the simulations had different irrigation management scenarios over this period.

4 Results and Discussion

4.1 Calibration and Validation

The WRBActual simulation was used for model development and calibration because it recreates the management that actually occurred during the simulation period and therefore the data observed over this period can be used to evaluate the model. Calibration was done using trial and error because MIKE SHE simulations can take considerable time, making automatic calibration of multiple parameters impractical. Model calibration and validation were developed based on the model's ability to recreate water table observations collected from non-irrigated tracts around the basin (Figure 25). The local irrigation management within individual irrigated tracts is unknown and was modeled as a basin average, making direct comparison of the simulated and actual water table levels in irrigated sites impossible. The irrigated sites can be used for general comparisons and a few will be presented here. Water table observations made in 2002 and 2003 (P1, P2, P3 Figure 25) were used for calibration. Validation was then done with water table observations made in 2007 and 2008 (2N, 4N, 6N Figure 25). P1, P2, P3, and 2N are in a single non-irrigated tract in the southeastern part of the basin. 4N is in the west central basin and 6N is in the northwestern basin. Due to the lack of non-irrigated sites in the northern basin the irrigated sites 3I and 6I were also used to qualitatively assess model performance. Calibration results for sites P1 (Figure 26) and P2 (Figure 27) are in good agreement with the observed data showing Nash-Sutcliffe (Nash and Sutcliffe, 1970) efficiencies of 0.812 and 0.806 respectively. These sites are near each other and the observed water table data was consistent between them. Therefore, it is not surprising that the model performs similarly for both. The results for site P3 (Figure 28) are less promising with a Nash-Sutcliffe efficiency of -39.08 due to the simulated water table dropping to depths of about 4 m when the observed water table stays within a depth

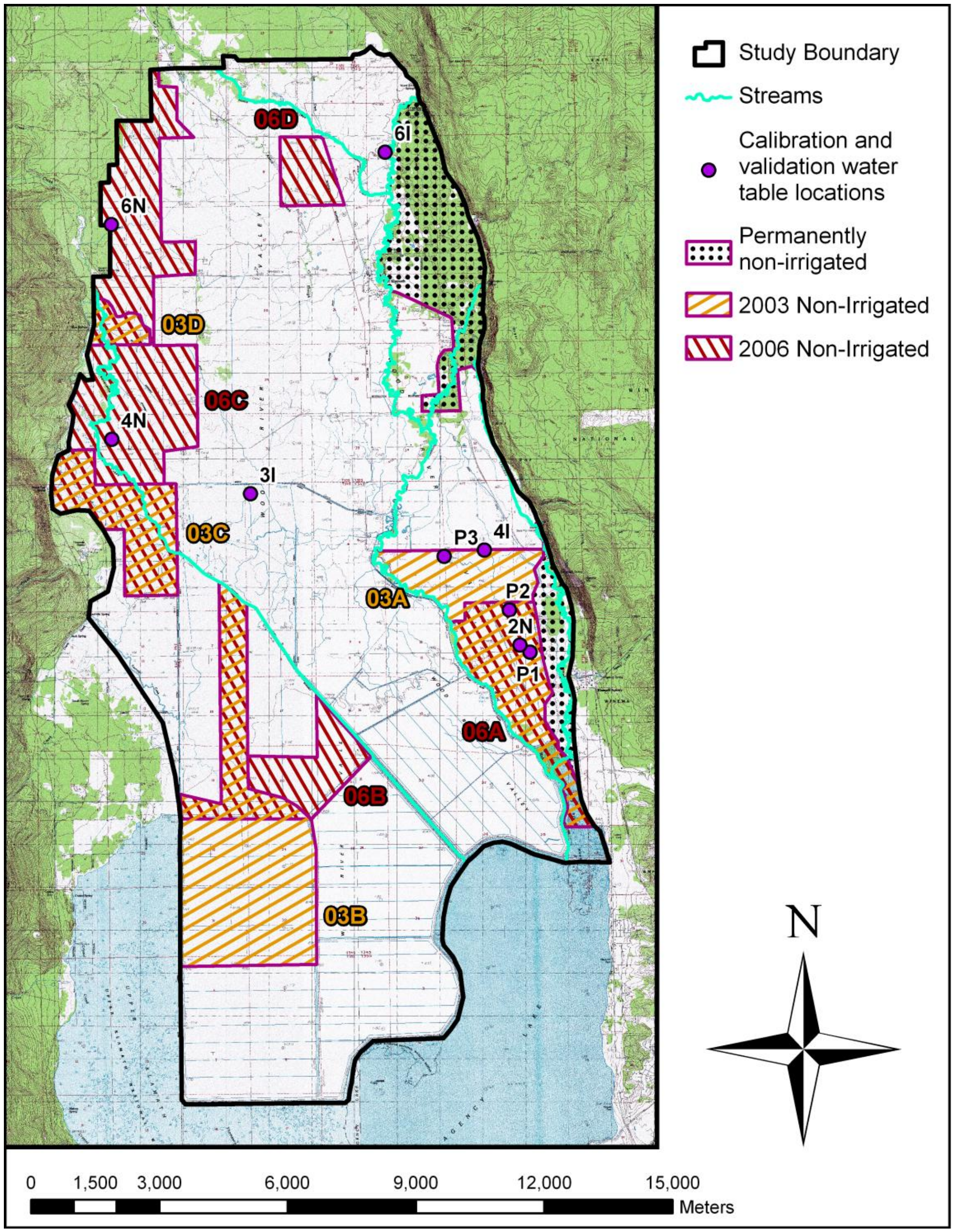

Figure 25: Piezometer sites used for model calibration and non-irrigated tracts used in the WRBActual scenario. 2003 non-irrigated tracts were considered to not be irrigated for the 4 years of 2002, 2003, 2004, and 2005. 2006 Non-irrigates tracts were considered to not be irrigated in 2006, 2007, 2008, and 2009.

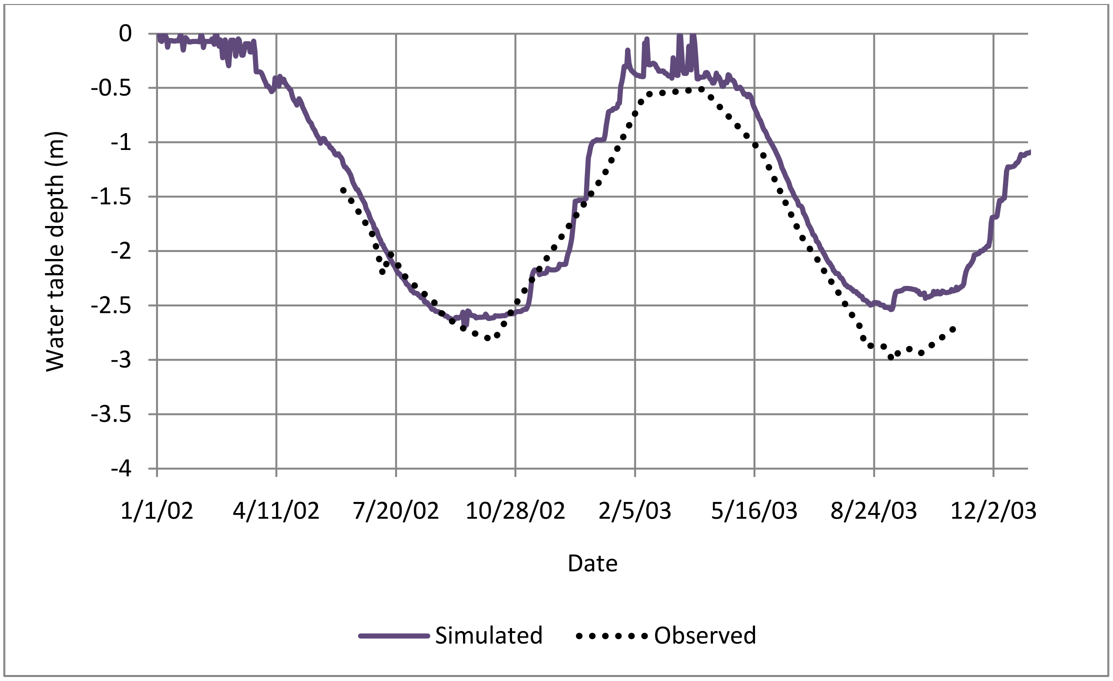

Figure 26: Calibration results for site P1. Nash-Sutcliffe efficiency = 0.812.

of 2 m (6.6 ft). P3 is about 800 m (2625 ft) from the Wood River on the border of a naturally wet area that occurs between P3 and Wood River. This likely caused the shallow depths of the observed water table. This level of detail is not rendered in the model, leading to the difference between the modeled and simulated water table depths at this site. P4 behaved similarly to P3 and will not be discussed further.

The validation shows that the observed and simulated water tables for 4N (Figure 29) are in fair agreement, resulting in a Nash-Sutcliffe efficiency of 0.713. Examining the water table recession curve reveals that the observed recession starts to slow before the simulated recession. Unfortunately, the observed data is truncated during mid-summer when the water table dropped below the sensor depth. If this data were available the simulated and observed values may be in poorer agreement.

The simulated and observed values for the 2N site (Figure 30) and the 6N site (Figure 31) are in poor agreement with Nash-Sutcliffe efficiencies of -0.665 and -28.34 respectively. The poor performance for 2N is surprising given its proximity to P1 and

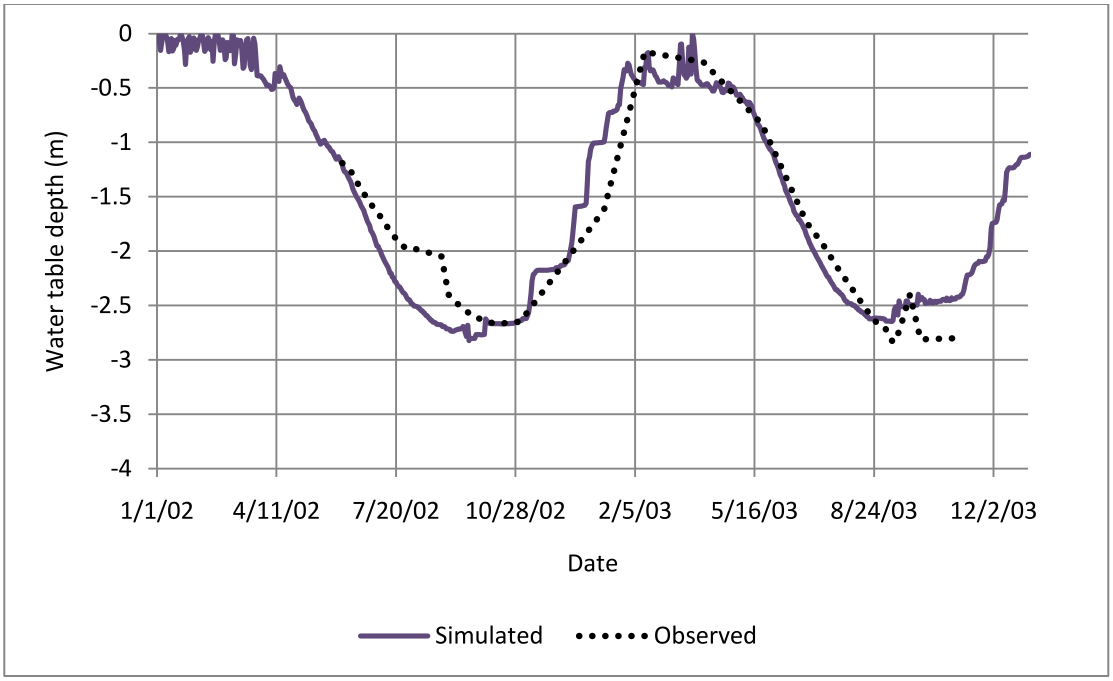

Figure 27: Calibration results for site P2. Nash-Sutcliffe efficiency = 0.806.

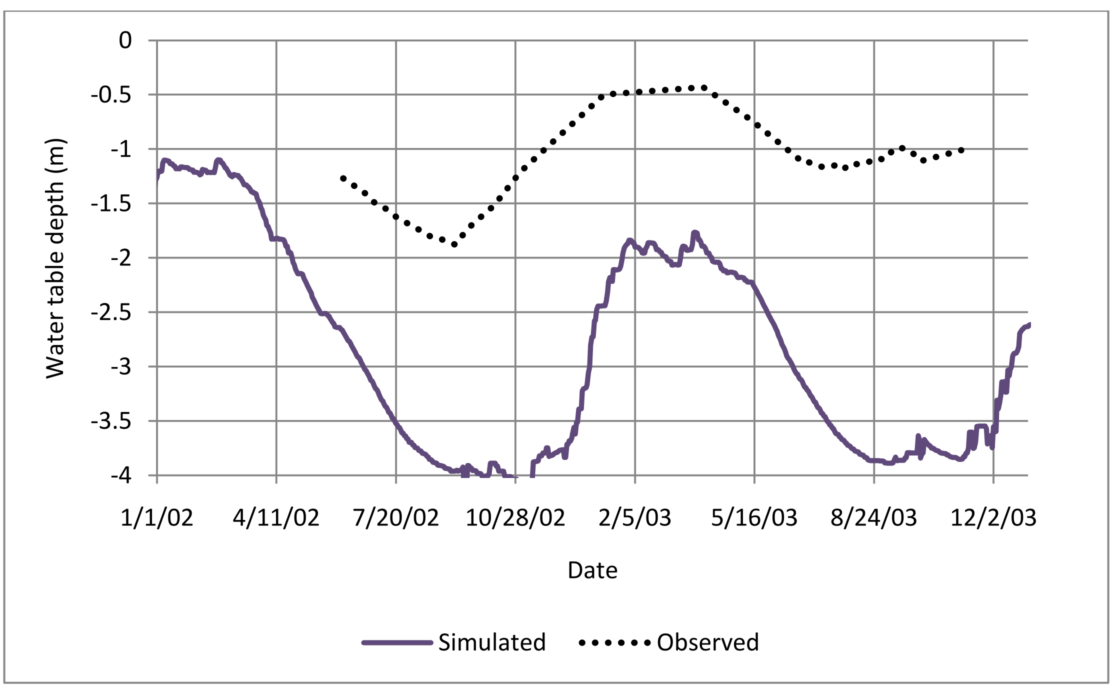

Figure 28: Calibration results for site P3. Nash-Sutcliffe efficiency = -39.08.

P2. The 2N observed data shows a rise in water table much later than the other non-irrigates sites in the basin. This inconsistency indicates that the piezometer may not have been accurately recording water table depths. The 6N site simulated water table stays about 1m to 2m below the observed water table at all times. This is likely caused by its proximity to the model boundary. The western boundary of the model is specified as a gradient flux boundary, allowing water to come into the model domain. This flux is modeled as being constant along the boundary, though spatial variation is evident given the numerous spring complexes that occur along this boundary (Figure 18). Using the average value is suitable for describing the model interior where spatial and temporal variability in the boundary flux will average out, however at the boundary the water table will be controlled more by local conditions that are not included in the model, contributing to the poor fit at this location. The Kirk site (Figure 25) was not included because it behaves similarly to the 6N site.

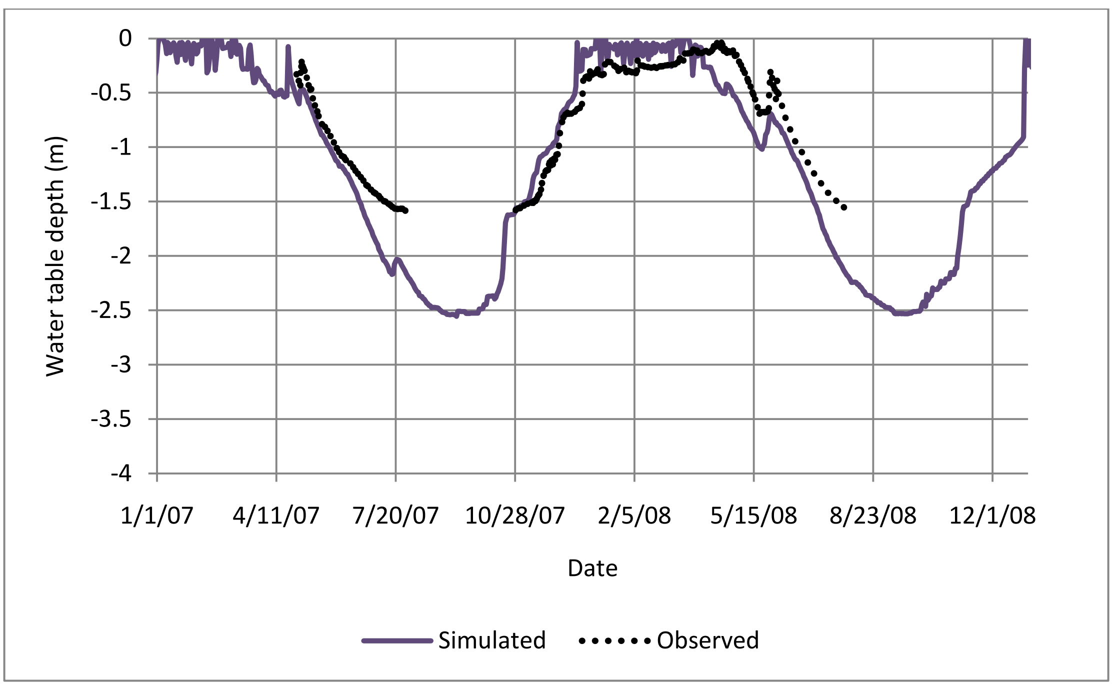

Figure 29: Validation results for site 4N. Nash-Sutcliffe efficiency = 0.713.

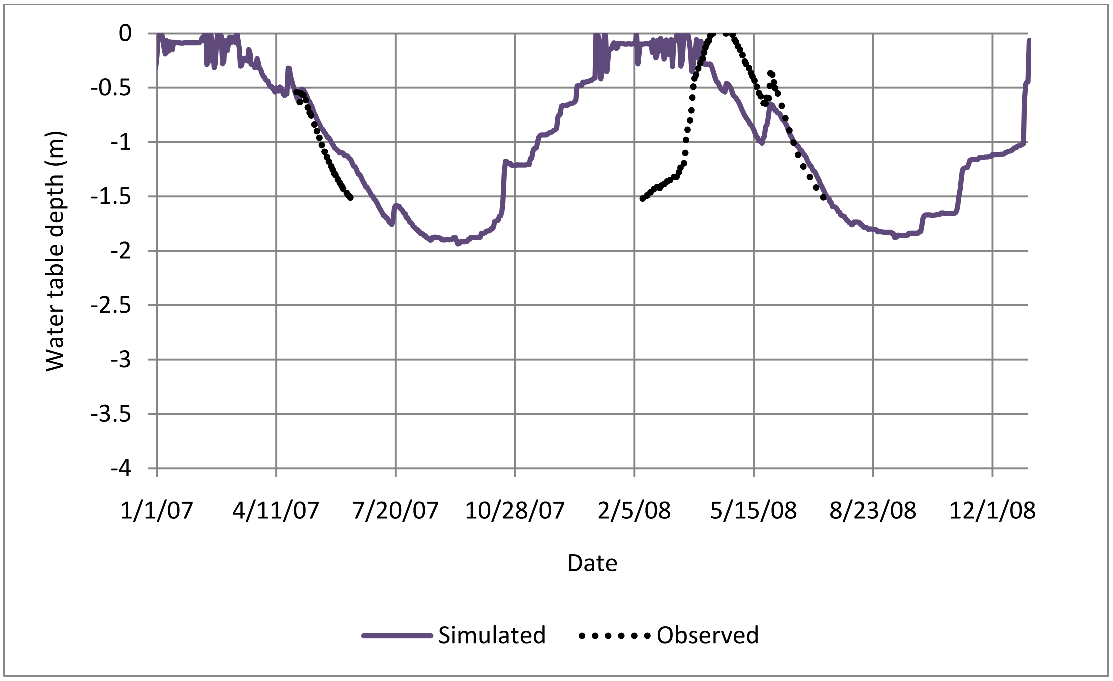

Figure 30: Validation results for site 2N. Nash-Sutcliffe efficiency = -0.665.

The simulation for the two irrigated sites 3I (Figure 32), and 6I (Figure 33) are consistent with the observed data. The water tables for both the simulated and observed remain at shallow depths throughout the year, the water table rises sharply in response to irrigation, and the water table recession curves are similar. For 3I the simulated water table is consistently lower than the observed water table whereas for 6I the simulated water table is consistently higher than the observed water table. These discrepancies are probably due to variations in irrigation applications during the observation periods.

The scope of this research is not to simulate local variations in the basin, but to evaluate the overall hydrologic basin response to irrigation management strategies. The model performed well at the interior evaluation sites, but not at sites near the boundary or near rivers with unique local conditions. If local scale phenomenon were to be modeled a much finer grid cell resolution could be used.

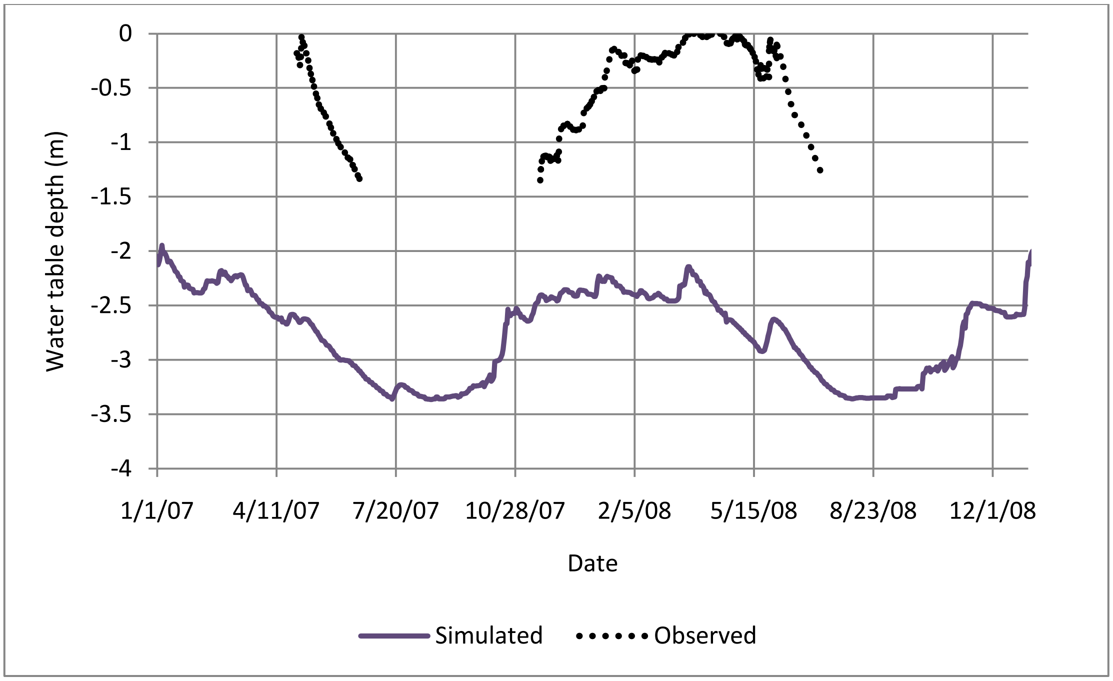

Figure 31: Validation results for site 6N. Nash-Sutcliffe efficiency = -28.34.

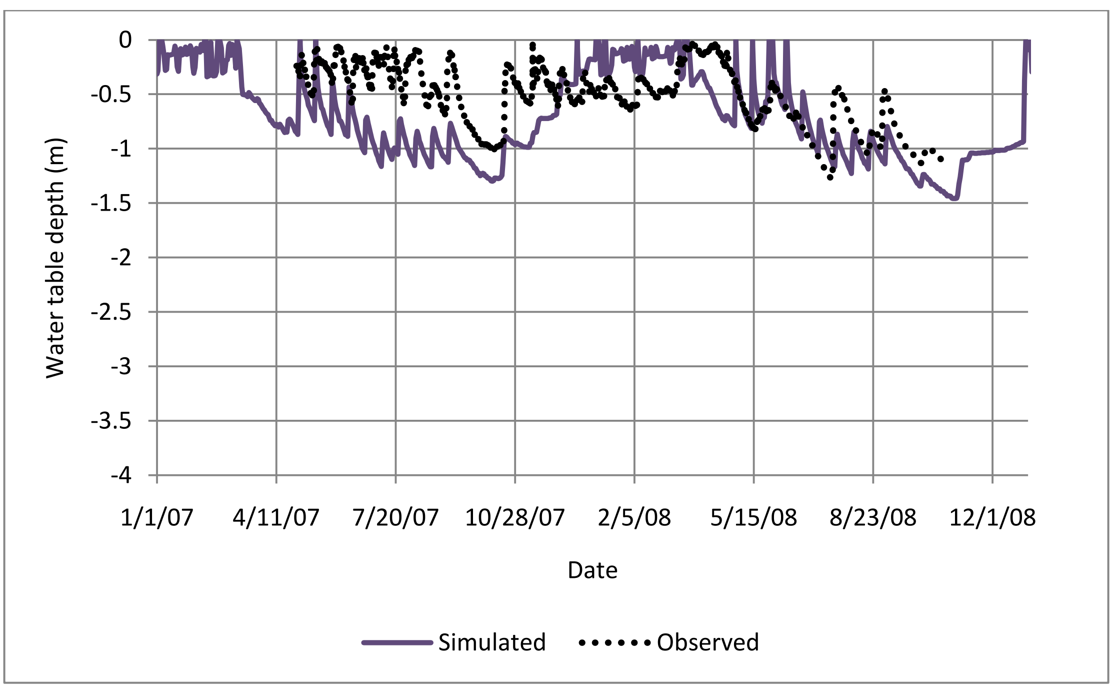

Figure 32: Validation results for site 3I.

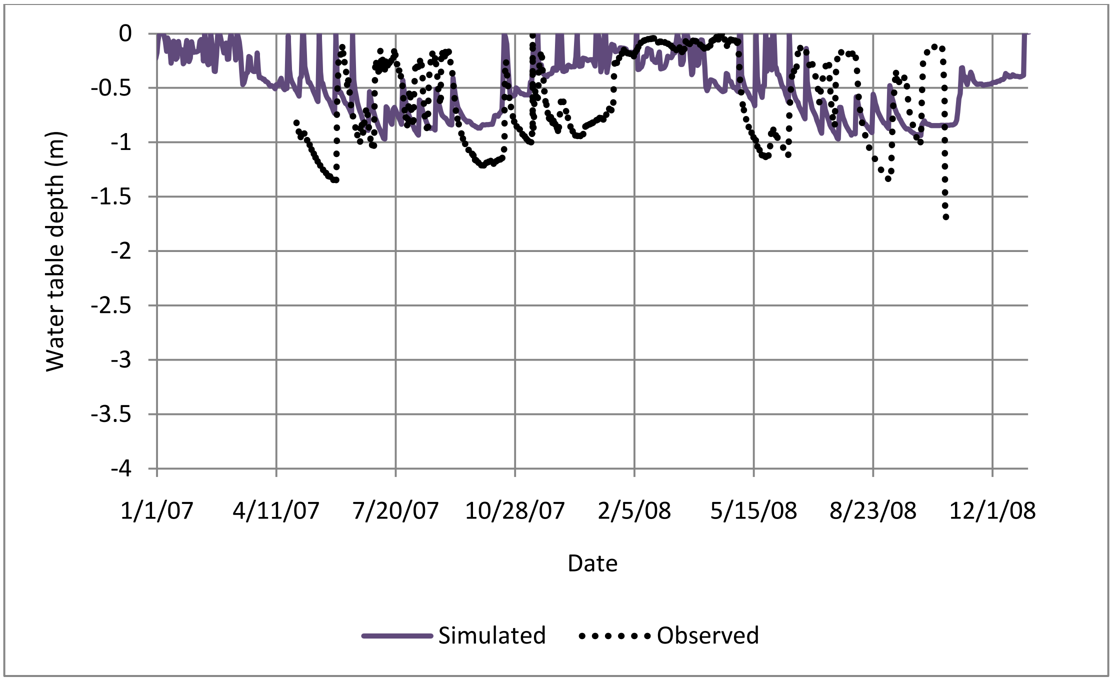

Figure 33: Validation results for site 6I.

Once an acceptable model is calibrated, a review of calibration parameter values is important to ensure that these values are consistent with the conceptual model of the basin and the processes that are known to occur. The calibrated parameter values are summarized in Table 12.

Table 12: Final values for the calibration parameters.

Parameter	Unit	Calibrated Value
Irrigation Application Rate	mm/hr	2.2
K_s for unsaturated zone A horizon	m/s	$9.1x10^{-6}$
K_s for unsaturated zone B horizon	m/s	$5.5x10^{-5}$
K_s for unsaturated zone C horizon and saturated zone shallow aquifer	m/s	$4.5x10^{-4}$
K_s for saturated zone deep aquifer	m/s	$2.0x10^{-4}$
Specific yield for all aquifers and lenses	()	0.2
Lower level (thickness) of deep aquifer	(m)	-150
North boundary flux gradient	()	0.007
West boundary flux gradient	()	0

A calibrated north boundary flux gradient of 0.007 (37 ft/mi) is very close to the 0.0076 (40 ft/mi) gradient reported by USGS (2007) and is driven by the presence of Crater Lake to the north. The calibrated west boundary flux gradient was 0, meaning that there was no water flow into the basin from the mountains to the west. This was a little surprising given the groundwater gradient that exists within these mountains will cause water to flow toward the basin (USGS, 2007). One possible explanation is that there is resistance to flow into the basin due to its saturated condition, forcing water to flow to the surface along the faults. This explanation is borne out by the numerous springs and seeps that occur here.

The irrigation application rate was adjusted to match typical water table dynamics observed in irrigated sites, which included water table rise in response to individual applications and the water table being within a meter of the surface at the end of the growing season in late-September. Higher application rates resulted in wetter conditions the following spring and a slower groundwater recession. An irrigation rate of 2.2 mm/hr (0.09 in/hr) indicates that the basin wide irrigation efficiency is about 50% if actual application is consistent with the water rights (section 0).

4.2 Model Error and Sensitivity

Water table observations were the best observed data available because they were widely available throughout the basin and over long periods of time. Therefore they were used to evaluate the model. Unfortunately water table data for a non-irrigated tract was not available in the interior of the basin because the non-irrigated tracts were all along the basin boundary. If this data were available then the calibration and validation would be more robust because more sites could be considered.

Other observations that could be used to evaluate the model include evapotranspiration data or soil moisture data. Some evapotranspiration data were available, but the data record was not as extensive as the water table data. Soil moisture data was not available. Compared to evapotranspiration and soil moisture data water table data is much easier to measure because it uses a single sensor that is simple to calibrate, and installed below ground where it is protected from the elements. Evapotranspiration measurements require a system of multiple sensors that complicate data gathering and processing. Soil moisture sensors require site-specific calibration, and multiple sensors have to be installed to obtain a soil moisture depth profile.

For the Wood River Basin water table data is ideal for model evaluation because it responds rapidly to the major hydrologic processes due to the importance of groundwater inflows to supply water, and the high hydraulic conductivity of the material. Percolation losses during irrigation are quickly seen with a rising water table (Figure 16), likewise a lowering of the water table is evident with evapotranspiration losses that cause an upward flux of water from the saturated zone to the unsaturated zone (Figure 14).

Figure 28 and Figure 31 show that there are some local errors in simulating water table levels in the model. The affect of these errors on the overall basin-wide water balance can be assessed by looking at the evapotranspiration response to the water table depth. This was done by considering a vertical 1-dimensional model of only the unsaturated zone. The bottom boundary condition was specified as a constant water table depth. The top boundary condition and export of water via roots was specified as a constant ET_r. There were no other water inputs, therefore the only sources of water to supply ET was the upward flux from the saturated zone into the unsaturated zone, or the direct withdrawal of water from the saturated zone by the roots if the saturated zone and root zone overlapped. Each simulation was run until steady state was reached, where the inputs from the saturated zone were equal to the outputs from ET, and there was no change in unsaturated zone storage. Multiple simulations were run with combinations of water table depths ranging from 0 m (0 ft) to 5 m (16.4 ft) and ET_r ranging from 3 mm/day (0.12 in/day) to 9 mm/day (0.35 in/day), the results are shown in Figure 34.

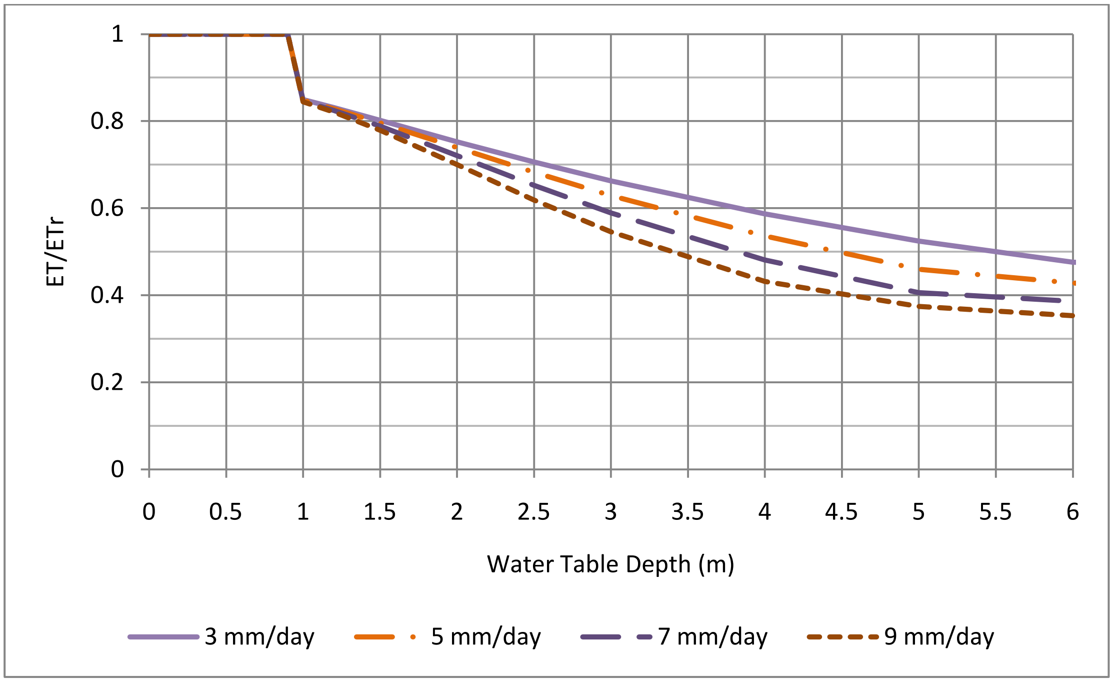

Figure 34: Reduction of evapotranspiration (ET) with increasing water table depth.

If the depth to water table was less than 1 m (3.3 ft) there was no plant stress and ET occurred at the maximum rate (ET_r). When the depth to water table was greater than 1 m (3.3 ft) the plants became water stressed and ET was reduced. For a given water table depth the ET/ET_r ratio increased as ET_r decreased. For example in site P3 (Figure 28) the maximum observed water table depth was 2 m (6.6 ft) and the maximum simulated water table depth was 4 m (13.1), which occurred in August. The average ET_r in August was 5 mm/day (0.20 in/day) (Figure 9). For an ET_r of 5 mm/day (0.20 in/day) a water table depth of 2 m (6.6 ft) results in $ET/ET_r = 0.74$ (ET = 3.7 mm/day, 0.15 in/day), and a water table depth of 4 m (13.1 ft) results in $ET/ET_r =$

0.54 (ET = 2.7 mm/day, 0.11 in/day), a difference of 1 mm/day (0.04 in/day). The greatest ET_r occurred in July and averaged 6.5 mm/day (0.26 in/day) (Figure 9), during this period in site P3 (Figure 28) the observed water table depth was 1.5 m (4.9 ft) ($ET/ET_r = 0.80$, ET = 5.2 mm/day, 0.20 in/day) and the simulated water table depth was 3.5 m (11.5 ft) ($ET/ET_r = 0.55$, ET = 3.6 mm/day, 0.14 in/day), a difference of 1.6 mm/day (0.06 in/day). If considering ET contributions from the water table alone for site P3, the observed water table results in an annual ET of 920 mm (36.2 in) and the simulated water table results in an annual ET of 650 mm (25.6 in), a difference of 270 mm (10.6 in). For a single grid cell an ET reduction of 270 mm (10.6 in) is equal to 6.7×10^4 m^3 (54.7 ac-ft).The total annual ET for each of the sites shown in Figures Figure 26 to Figure 31 is summarized in Table 13. The two sites with very poor fits between the simulated and observed water tables are P3 and 6N. For P3 the difference in average annual ET between the WRBIrrigated and WRBNonIrrigated scenarios is 234 mm (9.2 in), within the standard deviation for the sites with good fits (P1, P2, 2N, and 4N). The average annual ET for each of the scenarios is about 170 mm (6.7 in) less than the sites with good fits. Therefore, in site P3, the relative difference between the WRBIrrigated and WRBNonIrrigated scenarios is not affected by the poor model performance, but the annual ET is underestimated by about 170

Table 13: Average Annual ET for non-irrigated calibration and validation sites.

Site	Total Annual ET (mm) by model scenario			(WRBIrrigated) – (WRBNonIrrigated)
	WRBActual	WRBIrrigated	WRBNonIrrigated	
P1	862	980	763	217
P2	873	998	733	265
2N	865	989	761	228
4N	827	993	795	198
Average	857	990	763	227
Standard Deviation	20	8	25	28
P3*	691	822	588	234
6N*	649	731	627	105
Average and Standard Deviation is calculated using only sites P1, P2, 2N, and 4N. * Sites with poor fit between the observed and simulated water tables.				

mm (6.7 in), or 4.3×10^4 m^3 (34.5 ac-ft) for a single grid cell.

For 6N the difference between in average annual ET between the WRBIrrigated and WRBNonIrrigated scenarios is 105 mm (4.1 in), about half the average for sites with good fits. This decreased difference is because the average annual ET is underestimated more for the WRBIrrigated scenario than for the WRBNonIrrigated scenario. The average annual ET is 259 mm (10.2 in) and 136 mm (5.4 in) less than the average for sites with good fits in these scenarios respectively.

The difference in average annual ET between the WRBIrrigated and WRBNonIrrigated scenarios is 227 mm (8.9 in) when considering sites with good model performance evaluated based on simulated and observed water table depths (Table 13). If the entire Wood River Basin behaved similar then this difference applied to the 763 pasture managed cells in the model results in a total volume of 4.33×10^7 m^3 (35,100 ac-ft) of decreased ET. This is a 17% increase compared to the total decrease of 3.71×10^7 m^3 (30,000 ac-ft) when considering the basin wide water balance of the WRBIrrigated and the WBRNonIrrigated scenarios (Section 4.4.1). However, the entire basin does not behave similarly and there are areas with higher water tables and areas with lower water tables.

The errors in sites P3 and 6N both resulted in an underestimation of ET, therefore actual ET difference in response to non-irrigation may be greater than the model results. However, there is also a small local area at the northeast of the model area where the water tables are elevated above what would be expected, staying close enough to the surface during the WRBNonIrrigated scenario to result in maximum ET, and a possible overestimation of ET. Local model error can result in both overestimation and underestimation of the ET for the error location and affect the overall water balance calculations.

Performing a detailed analysis of model sensitivity to changes in parameters values was not done because it is computationally intensive and impractical given the number of parameters within MIKE SHE and the length of time required for each model run. A simple sensitivity analysis was performed by testing the high and low values of the calibration range for some of the parameters identified in Table 12, resulting in 10 total simulations (Table 14). The WRBActual scenario was used the base scenario because it was used for calibration. For simulations 2a and 2b the K_s of all the layers that made up the unsaturated zone were adjusted together. For simulation 6 the low value was not tested (-120m, 394 ft) because it was close to the final calibrated value (-150 m, 492 ft).

Table 14: Simulations used for sensitivity analysis.

Simulation Number	High/ Low	Parameters Adjusted
1a	High	K_s for saturated zone deep aquifer
1b	Low	
2a	High	K_s for unsaturated zone A horizon K_s for unsaturated zone B horizon K_s for unsaturated zone C horizon and saturated zone shallow aquifer
2b	Low	
3a	High	North boundary flux gradient
3b	Low	
4a	High	Specific yield for all aquifers and lenses
4b	Low	
5	High*	West boundary flux gradient
6	High*	Lower level of deep aquifer
*Only high values were simulated because the final calibrated value was equal or very close to the low value.		

The model is most sensitive to the K_s parameters and the deep aquifer thickness (lower level of deep aquifer). Increased deep aquifer K_s or thickness results in increased transmissivity where more water can be moved through the aquifer for a given hydraulic gradient. The model responds to these two parameters very similarly. This can be seen when examining water table depths in site P2 (Figure 35) and site 4N (Figure 36). Increasing K_s or aquifer thickness to the high values caused elevated water tables over the entire model domain of about 0.25 m (0.82 ft) and 0.5 m (1.64) respectively. The calibrated K_s value ($2.0x10^{-4}$ m/s (28.3 in/hr), WRBActual) is close to the high value ($3.0x10^{-4}$ m/s (42.5 in/hr), Simulation 1a), explaining the small water table depth differences between these two scenarios. The low value of K_s ($1.0x10^{-5}$ m/s (1.4 in/hr), Simulation 1b) caused water table declines of more than 1.5 m during the growing period, which would impact the simulated ET significantly. The decline in water table was about 1 m (3.3 ft) if the site was irrigated (site 4N, years 2002-2005) or close to irrigated tracts (site P2, years 2006-2009).

The unsaturated zone was considered with two simulations by adjusting the three K_s values that characterized the unsaturated zone and the shallow aquifer geologic layer in the saturated zone together to the high and low values. The results for these two simulations (2a and 2b) are shown in Figure 37 and Figure 38. The low values of K_s attenuated the water table fluctuations, the water table stays within about 0.75 m of the surface during all times of the year. A possible explanation is that the lower K_s decreased water flux from the saturated zone to the unsaturated zone resulting in decreased evapotranspiration withdraws. The high values of K_s also attenuated the water table fluctuations; the water table elevation is increased by about 0.75m (2.5 ft) during the growing season. This could be due to increased flux of water from neighboring irrigated tracts.

The flux boundary gradients had a large impact on sites near the boundary, but no affect further away. The northernmost site is 6I where the high north boundary flux value elevated the water table to within 0.5 m (1.6 ft) of the surface and maintained the water table at the surface over prolonged periods of time. The low north boundary flux value lowered the water table by about 2 m at all times, the water table was kept between a 2 m (6.6 ft) and 3 m (9.8 ft) depth most of the time. The

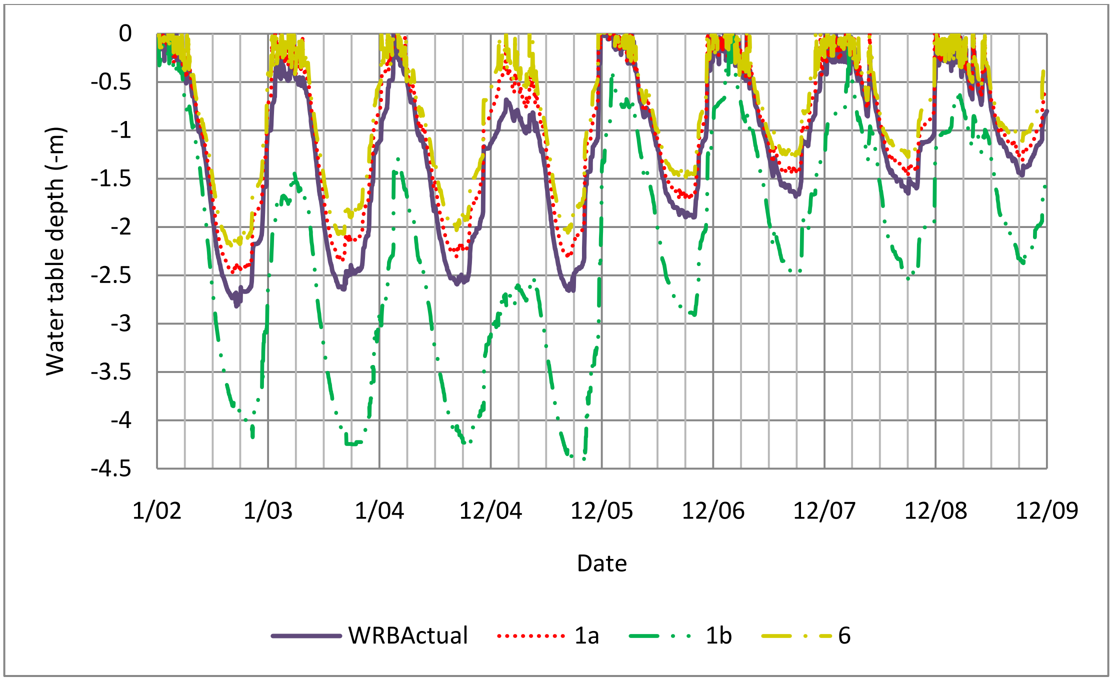

Figure 35: Site P2 water table depth for sensitivity simulations of high (1a) and low (1b) hydraulic conductivity, and high (6) aquifer thickness for the deep aquifer geologic layer.

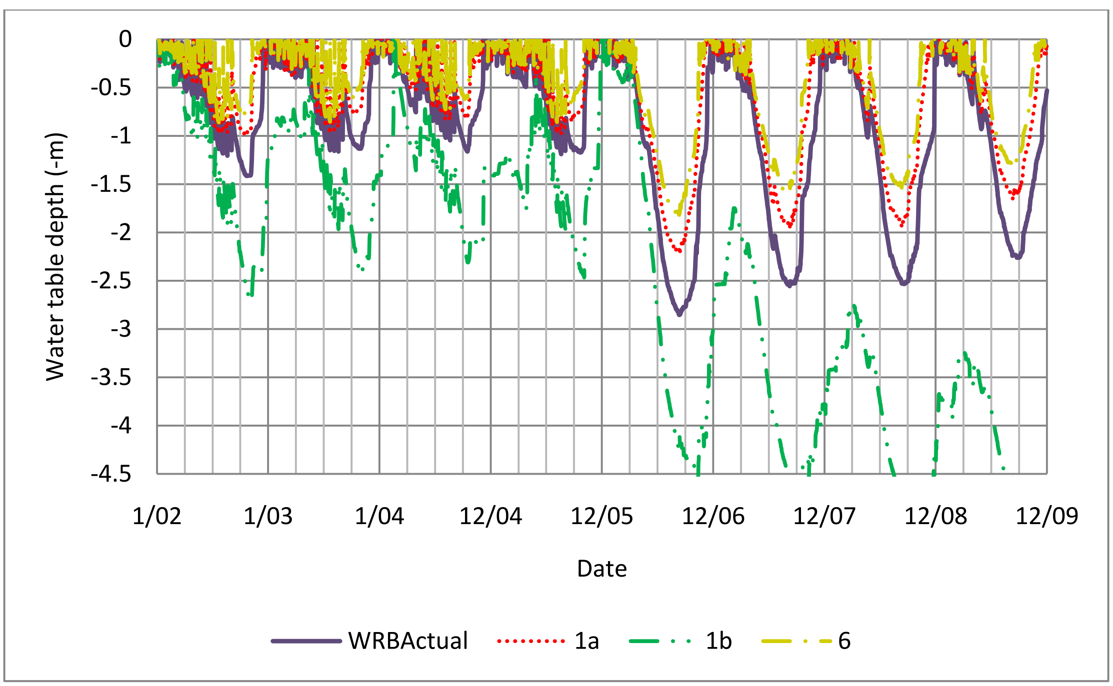

Figure 36: Site 4N water table depth for sensitivity simulations of high (1a) and low (1b) hydraulic conductivity, and high (6) aquifer thickness for the deep aquifer geologic layer.

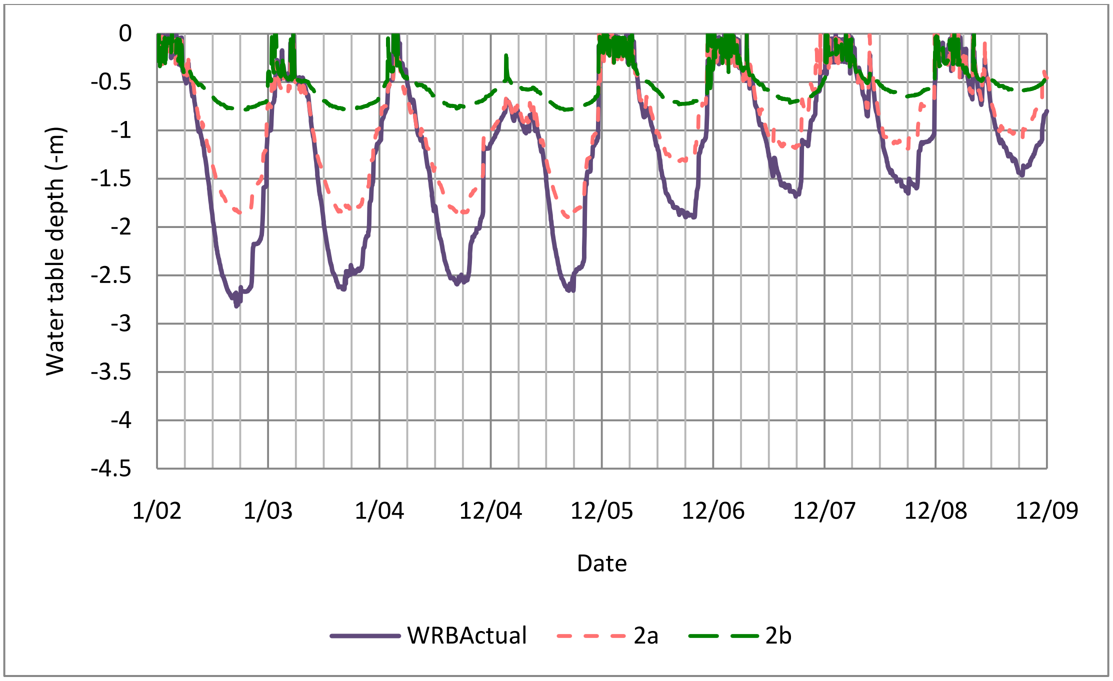

Figure 37: Site P2 water table depth for sensitivity simulations of high (2a) and low (2b) hydraulic conductivity for the unsaturated zone and shallow aquifer geologic layer.

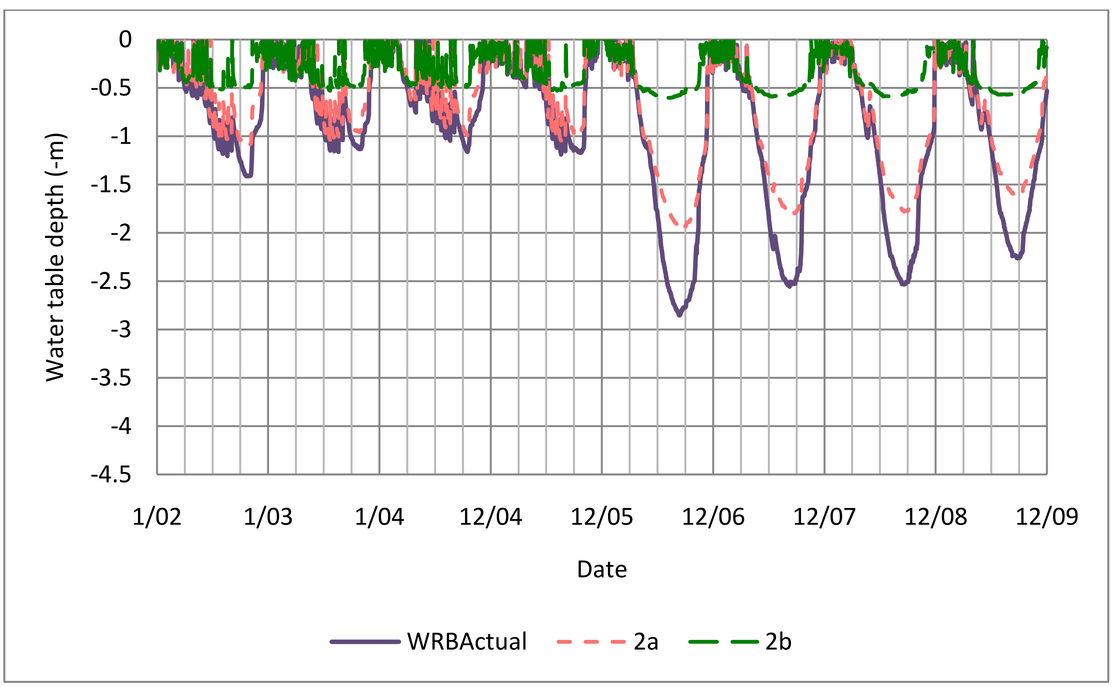

Figure 38: Site 4N water table depth for sensitivity simulations of high (2a) and low (2b) hydraulic conductivity for the unsaturated zone and shallow aquifer geologic layer.

westernmost site is 4N and it behaved similarly in response to the west boundary flux, the high value kept the water table within 0.5 m (1.6 ft) of the surface at all times. Site 3I, in the center of the Wood River Basin, had a very slight change in response to changes in both the north and west boundary flux gradients. Sites P1, P2, and 2N had no response to the north and west boundary gradients. The northern Wood River Basin water tables are controlled by the northern boundary flux gradient, but the southern areas are not. Results elsewhere indicate that the southern water tables are controlled by flux from Agency Lake (section 4.4.3)

Changes in specific yield had no impact on the model.

4.3 Water Table and Evapotranspiration Response to Irrigation Management

The water table and evapotranspiration response to the simulated scenarios was evaluated by examining a subset of calibration and validation sites that had the best performance, including P1 and 4N (Figure 25). The P1 site was not irrigated for both the 03 period (no irrigation in 2002, 2003, 2004, and 2005) and the 06 period (no irrigation in 2006, 2007, 2008, and 2009), however from the 03 period to the 06 period the area of this non-irrigated tract was reduced from 41 grid cells (1025 ha, 2530 ac) to 22 grid cells (550 ha, 1360 ac). The water table dynamics for this site are shown in Figure 39. In the WRBActual scenario the water table dropped to a maximum depth of about 2.5 m (8.2 ft) during the 03 period and to a maximum depth of about 2 m (6.6 ft) during the 06 period. During the 06 period the water table came to the surface every year and remained for about 2 months, this contrasts with the 03 period where the water table comes to the surface in two of the years (the beginning of 2001 is not included because it follows an irrigated year), but only stays at the surface for a couple of days to a week. The difference in water table dynamics between the 03 and 06 periods reveals that the size of the non-irrigated tract exerts a control on water flux into the tract from surrounding irrigation. In the WRBIrrigated scenario the water table drops to a maximum depth of about 1.5 m (4.9 ft) during the summer and comes to the surface every year, staying within a 0.5 m (1.6 ft) depth for about 3 months. In the WRBNonIrrigated scenario the water table drops to a maximum depth of about 3.5 m (11.5 ft) during the summer and comes to the surface during wet years (2006), but otherwise remains about 1 m (3.3 ft) below the surface. These results show that the water tables in non-irrigated tracts remain elevated due to surrounding irrigation.

The WRBNonIrrigated scenario has full irrigation until 2002 when the irrigation stops. If inefficient surface irrigations caused an inter-annual increase in saturated zone storage then this storage would be expected to decrease when irrigation stops and plants draw on the storage for transpiration. This would result in an inter-annual trend of decreasing water tables. This trend has not been observed in the basin (Figure 39), meaning that there is not much excess storage capacity in the basin and water applications that percolate to the saturated zone are cycled back to the

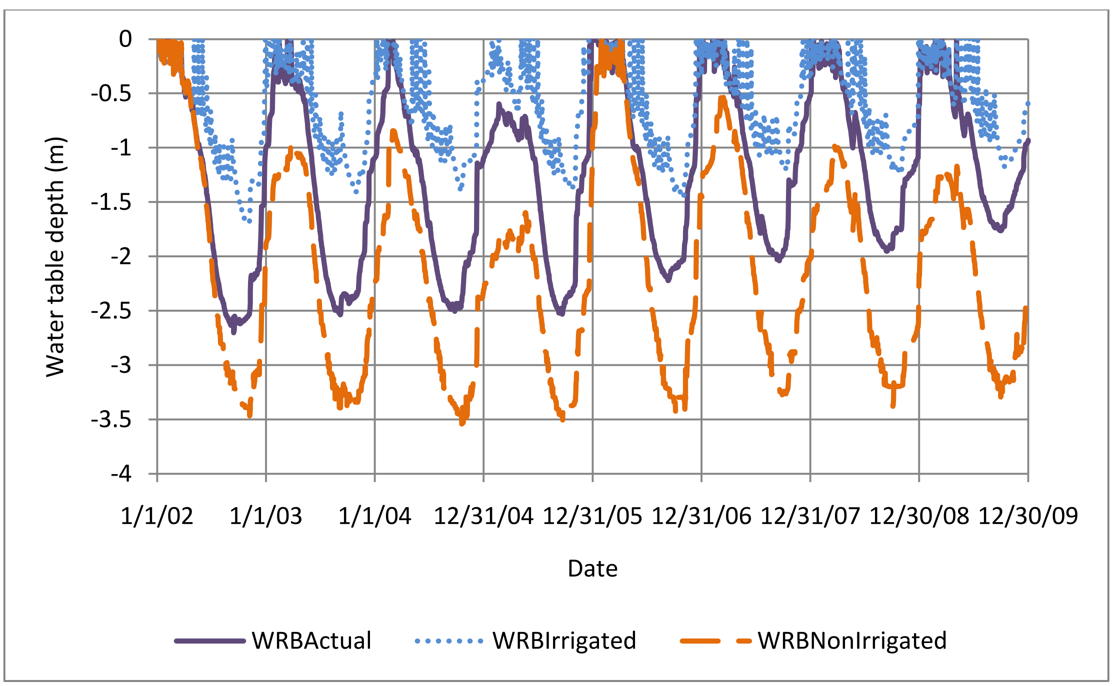

Figure 39: Site P1 water table dynamics for three simulated irrigation management scenarios.

surface water or used for evapotranspiration relatively quickly. In the WRBNonIrrigated scenario maximum storage occurs periodically when the water table comes to the surface in winter (2006, Figure 39), essentially resetting the system at maximum storage.

The increased water table depths resulted in decreased ET (Figure 40) because the water table drops far enough below the root zone to make the water less accessible to plants. The average percent difference in annual cumulative evapotranspiration between the WRBIrrigated and WRBActual scenarios is 13%. Between the WRBIrrigated and WRBNonIrrigated scenarios the percent difference is 25%.

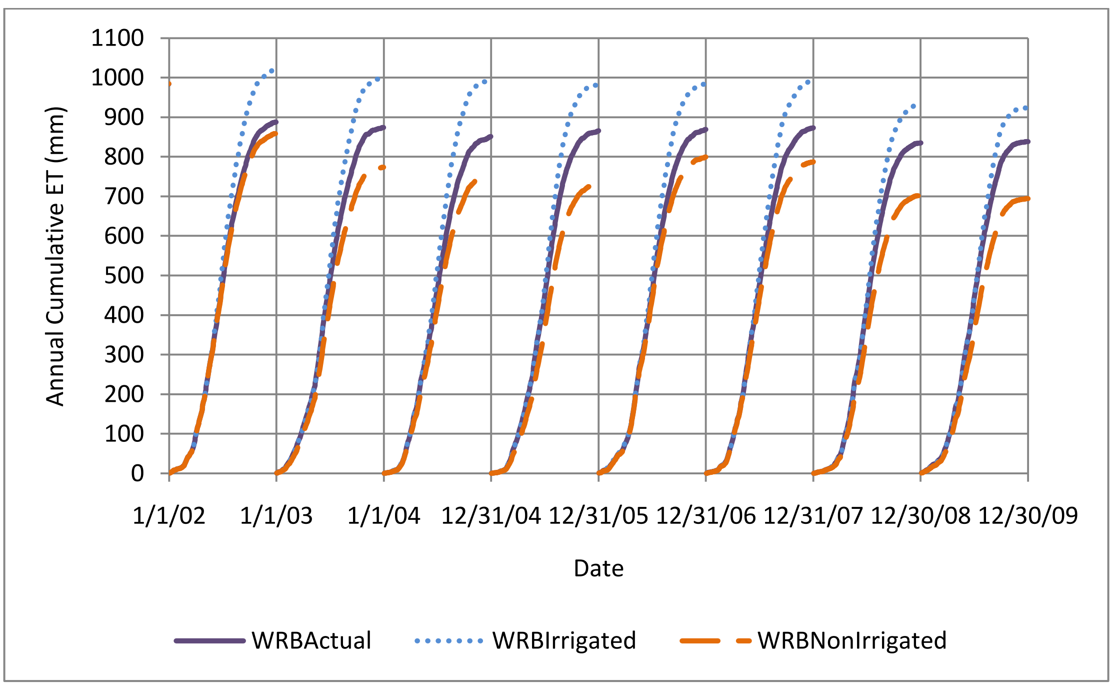

Figure 40: Site P1 annual cumulative evapotranspiration.

In the WRBActual scenario the 4N site was irrigated during the 03 period and non-irrigated during the 06 period in the 06C Tract (Figure 25). This is shown in Figure 41 where the WRBActual and WRBIrrigated scenarios behave similarly, but with the water table in the WRBActual scenario being slightly deeper. This could be due to water flowing out of this area and into the nearby non-irrigated 03C tract. The water table during the 06 period is similar to that described for the P1 site except that it came up to the surface almost every year and remained within 0.5 m (1.6 ft) of the surface for multiple weeks to months. The difference between the maximum water table depths between the WRBActual and WRBNonIrrigated scenarios was about 0.5 m (1.6 ft), whereas it was about 1 m (3.3 ft) for P1. This is reflected in the fact that the WRBActual and WRBNonIrrigated scenarios have similar cumulative annual ET for the 06 period (Average percent difference = 4%, Figure 42). The average percent difference in cumulative annual ET between the WRBIrrigated and WRBNonIrrigated scenarios over the entire period is 24%, almost the same as the P1 site.

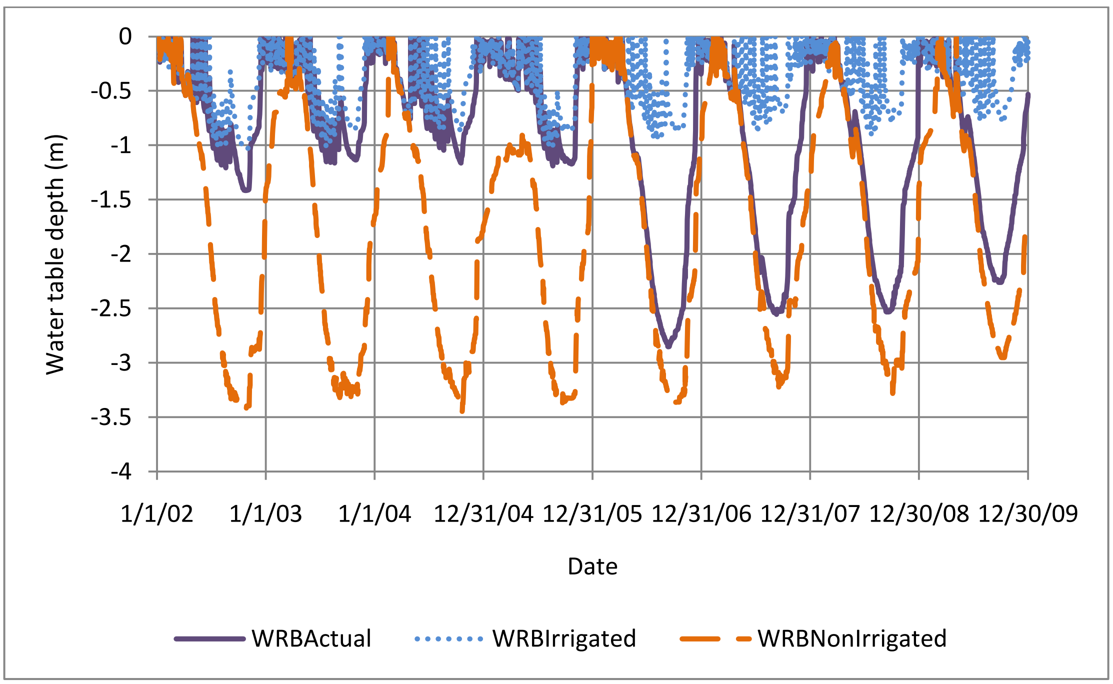

Figure 41: Site 4N water table dynamics for three simulated irrigation management scenarios.

If ET is taken as a proxy for plant growth then these results would indicate the plant productivity would only decrease about 20% going from the WRBIrrigated to WRBNonIrrigated scenarios, however this may not be a sound conclusion to make. The pastures in the Wood River Basin are dominated by Kentucky bluegrass (Stringham and Quistberg, 2008), a cool season grass that prefers temperatures between 15.6 °C (60 °F) and 32.2 °C (90 °F) (NRCS, 2002). In the Wood River Basin this means that the best pasture productivity would occur early (April, May) and late (August, September) in the growing season with reduced productivity in the middle. If the late growing season in August and September is a period of moisture stress for the pasture then productivity may drop considerably even though the ET demand during this period is not high.

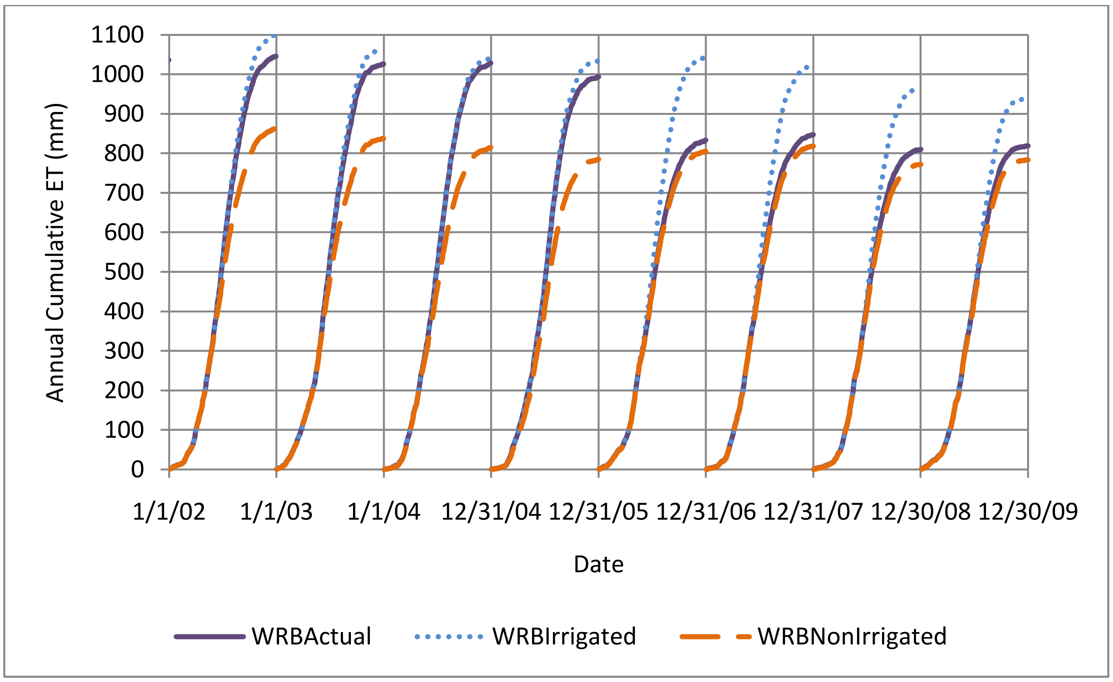

Figure 42: Site 4N annual cumulative evapotranspiration.

4.4 Basin-Wide Water Balance

MIKE SHE contains a water balance tool for summarizing the water balance either over the entire domain or over a sub-catchment. The output is given in storage depth (mm) averaged over the summary area. The model domain consisted of 811 grid cells, each 25 ha (62 ac). A 1 mm (0.04 in) storage depth over the entire domain is equivalent to 2.03×10^5 m^3 (164.6 ac-ft). The output can be either incremental or accumulated and the time-step can be specified. For all water balance analysis an incremental daily time step was used because all of the inputs were in daily resolution. This also reduces the amount of data, making analysis more efficient.

4.4.1 Evapotranspiration and Consumptive Use

Comparing total evapotranspiration (consumptive use) between the model scenarios provides a good metric for total water savings and how much additional water will be available for downstream or in-stream users. The basin-wide average evapotranspiration for the growing season from April 1 to September 30 is summarized in Table 15. On average the WRBNonIrrigated scenario had a consumptive use of 3.70×10^{7} m^3/yr (30,000 ac-ft/yr) less than the WRBIrrigated scenario (percent difference = 27.0%), and the WRBActual Scenario had a consumptive use of 7.64×10^{6} m^3/yr (6,200 ac-ft/yr) less than the WRBIrrigated Scenario (percent difference = 9.4%). The values are reported for the growing season because this is the period were water savings need to occur to provide the biggest benefit to in-stream or downstream uses.

Table 15: Total basin-wide growing season evapotranspiration (mm) by year for the three model scenarios.

Growing Season (4/01 to 9/30)	Total growing season ET (mm) by model scenario		
	WRBActual	WRBIrrigated	WRBNonIrrigated
2002	754	789	628
2003	726	761	574
2004	720	759	569
2005	736	771	571
2006	740	781	608
2007	730	773	589
2008	725	763	576
2009	701	737	557
Average	729	767	584
Total Volume (m^3)	**1.478×10^{8}**	**1.555×10^{8}**	**1.184×10^{8}**
Total Volume (ac-ft)	**119,800**	**126,000**	**96,000**

Evapotranspiration was also summarized within each of the non-irrigated tracts shown in Figure 25. The average total growing season ET of the WRBActual and WRBIrrigated scenarios for each tract is summarized in Table 16. The 03 tracts were averaged over the 03 period and the 06 tracts were averaged over the 06 period. Due to the transport of water from irrigated tracts to non-irrigated tracts it has been concluded that larger continuous non-irrigated tracts will result in more water savings (USGS, 2005). This trend was most apparent if the data presented in Table 16 were plotted by tract as the difference in total average growing season ET between the WRBIrrigated and WRBActual scenarios vs. the ratio of tract area to perimeter (Figure 43). The maximum value for the y-axis in Figure 43 is 183 mm (7.2 in), which would occur if the entire basin was converted to non-irrigation, simulated in the WRBNonIrrigated scenario. The minimum value for the x-axis is 0.25, which would result from a single non-irrigated grid cell. Large continuous non-irrigated tracts are required to reduce sub-irrigation contributions to consumptive use.

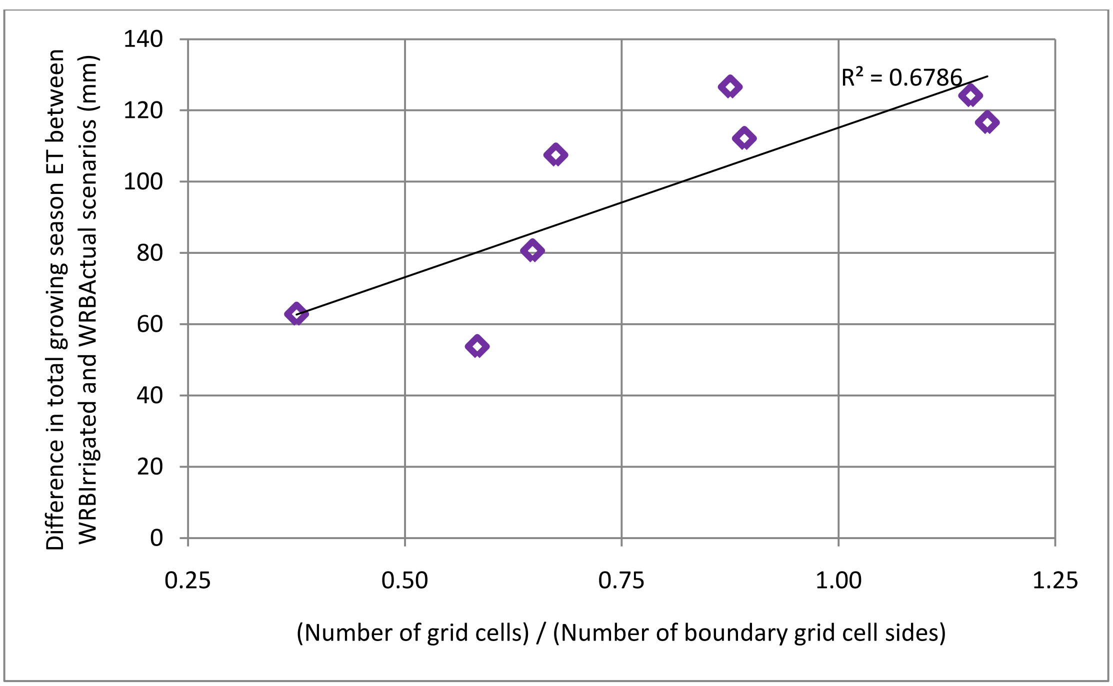

Figure 43: Reduction of total growing season ET from non-irrigated tracts as a function of the ratio of tract area to perimeter.

Table 16: Average total growing season evapotranspiration (mm) for non-irrigated tracts.

Tract	Average Total Growing Season ET (mm) Model Scenario		Number of Grid Cells	Number of Boundary Grid Sides
	WRBActual	WRBIrrigated		
03A	663	775	41	46
03B	675	799	53	46
03C	690	816	21	24
03D	703	766	3	8
06A	728	809	22	34
06B	674	781	31	46
06C	664	781	82	70
06D	633	687	7	12

4.4.2 Surface Water Flow to Agency Lake

Streams were simulated to evaluate the total surface water flow into Agency Lake. The rivers and creeks were modeled as having constant inflow rates making absolute flow and volume calculations inaccurate, however the relative flow between the model scenarios was used to describe total difference in surface water outflow between the different model scenarios. Irrigation water is withdrawn from the rivers and creeks, excess irrigation water is returned through either the drainage network or as baseflow from the saturated zone.

The two streams that flow into Agency Lake in the model are Wood River and Sevenmile Creek. The simulated hydrographs from these streams were summed to get the total flow into Agency Lake for each scenario. The WRBIrrigated hydrograph was subtracted from the WRBActual and WRBNonIrrigated hydrographs to get the relative difference in flow. The WRBIrrigated scenario was chosen as the baseline because it has been established for the past century. The relative difference in flow was accumulated to calculate the total outflow volume to Agency Lake for each water year (October 1 to September 30). The results for water year 2007 is presented in Figure 44, there was little variability between years so only one year is presented.

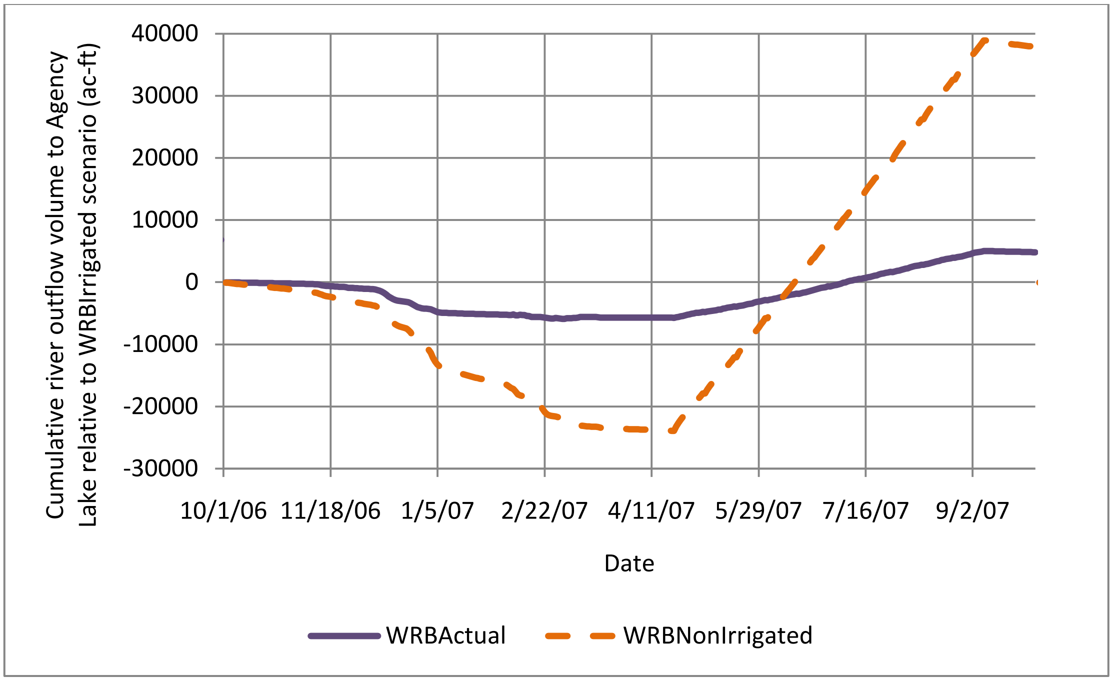

Figure 44: Difference in cumulative water year outflow to Agency Lake relative to the WRBIrrigated scenario.

If the total cumulative value presented in Figure 44 is considered, we see that the total increase in outflow to Agency Lake from the WRBIrrigated scenario to the WRBActual scenario is 6.17x10^6 m^3 (5,000 ac-ft) and for the WRBNonIrrigated scenario it is 4.81x10^7 m^3 (39,000 ac-ft). A closer look reveals that the real benefit during the critical summer months may be greater. At the beginning of the water year to the beginning of the irrigation season the outflow to Agency Lake decreases. For irrigated conditions the soil moisture storage capacity is replenished in September and not reduced substantially by ET over the remainder of the year. This means that when precipitation and snow inputs occur during the winter there is no storage capacity and these inputs runoff fairly quickly, resulting in increased winter flows. This trend occurs until the first diversions take place for irrigation in April. The total increase in flows from irrigation management scenarios during the growing season can therefore be considered as the difference in cumulative flow between the beginning and end of the irrigation season. This resulted in a total increase in outflow to Agency Lake for the WRBActual scenario of $1.36x10^7$ m^3 (11,000 ac-ft) and for the WRBIrrigated scenario of $7.77x10^7$ m^3 (63,000 ac-ft).

One effect of irrigation is to transfer flow from the summer time, when it is needed most for endangered species and downstream users, to the winter time. A management option to increase flows into Agency Lake would be to perform the final irrigations in August to effectively reduce the soil storage and take advantage of winter precipitation to refill this storage. Simulated (Figure 40) and observed (Figure 11) ET show that ET is not reduced from non-irrigation until the soil moisture is adequately depleted in mid-June. If the irrigation season is reduced to occurring from mid-June to early-August there could be substantial gains in outflow to Agency Lake without a reduction in pasture productivity. This scenario is discussed in section 4.5

4.4.3 Subsurface Flow

Subsurface flow into the model occurs primarily at the northern boundary, most likely driven by Crater Lake, which is 18 km (11.2 mi) to the north with a 585 m (1920 ft) increase in elevation resulting in a gradient of 0.0325 (170 ft/mi). Crater Lake is 592 m (1940 ft) deep (National Park Service, 2001), the bottom of the lake and the northern boundary of the Wood River Basin are at about the same elevation. Model animations of subsurface flow vectors show that water also flows into the basin from the southern boundary, although this flux is very small compared to the northern boundary. The lowest water table elevations in the longitudinal profile taken from the WRBNonIrrigated scenario occur 6 km (3.7 mi) to 8 km (5.0 mi) north of Agency Lake. The water table is highest in February and lowest in October, therefore the water table elevations were averaged during these months over the simulation period to create the respective profiles in Figure 45. This modeling result is consistent with the Pacific Groundwater Group (2003) study that showed water table elevations near Agency Lake below lake elevation.

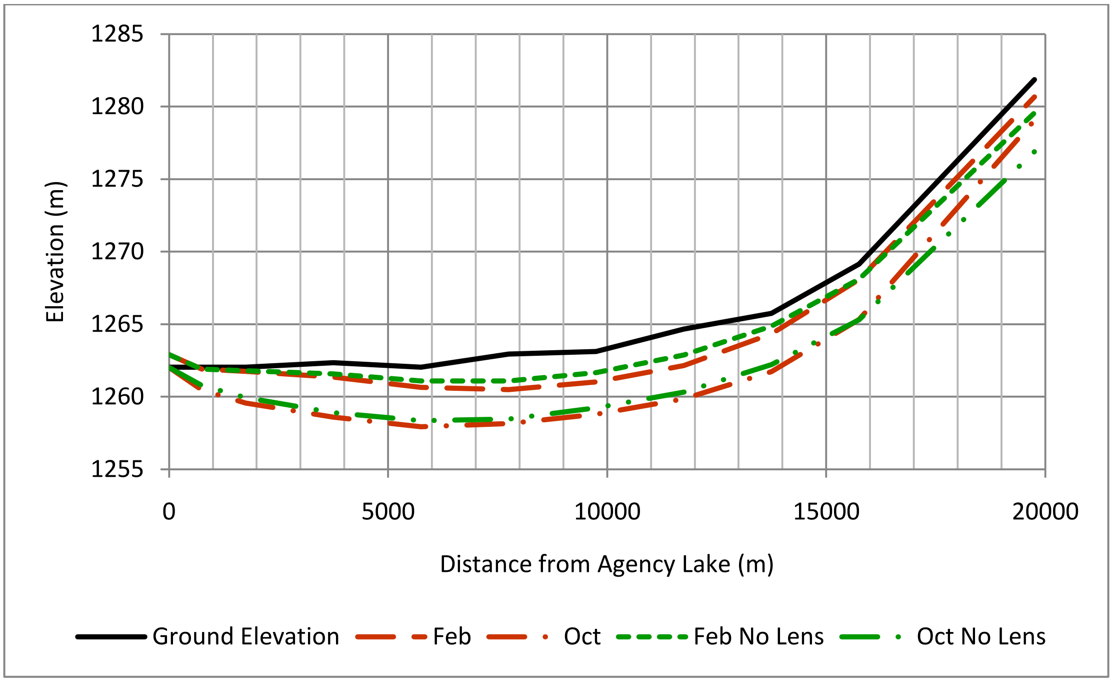

Figure 45: Longitudinal water table elevation. Data for the "Feb" and "Oct" profile is from the WRBNonIrrigated Scenario. Data for the "Feb No Lens" and "Oct No Lens" series is from the same scenario but with clay lenses removed from the saturated zone. The profile elevations are the average monthly water table elevation during the months of February and October respectively.

A possible explanation for the occurence of water table elevations below Agency Lake is the presence of thick clay lenses in the center of the basin that are not extensive in either the north or south ends. The lenses may act as a barrier to subsurface flow and force the ground water to be backed up behind them, resulting in elevated water tables up-basin and lowered water tables down-basin. To examine this interpretation the WRBNonIrrigated scenario was simulated without the presence of the clay lenses in the saturated zone. The results for comparison are shown in Figure 45 (profiles "Feb No Lens" and "Oct No Lens"). Overall the lenses did not appear to have much of an influence. Removing the lenses resulted in water table elevations to be increased by about 0.5 m (1.6 ft) in the lower basin and to be decreased by about 1 m during the winter ("Feb No Lens" profile) and about 2 m (6.6 ft) during the fall ("Oct No Lens" profile) in the upper basin. Although this difference is small when considering the longitudinal profile they could have large impacts on the ET response and therefore the inclusion of the clay lenses is warranted in the model. Water table elevations were still below the lake elevation for the "No Lens" scenario.

The area where the water table elevations are lower than the Agency Lake elevation is reclaimed land between the lake and Sevenmile Creek. Dikes prevent flooding onto this land from the lake, if the land was not reclaimed it would be marshlands, much like the neighboring Upper Klamath National Wildlife Refuge. An alternative explanation for the presence of low water table elevations in this area is that drainage and pumping for land reclamation, in combination with evapotranspiration, export enough water from this land to make it a sink for surrounding water sources. If this land were converted back into marsh the base level ground water elevation for the basin would increase, possibly resulting in elevated water tables up-basin.

Overall the exchange of subsurface flow between the Wood River Basin and Agency Lake is minimal compared to other water balance components with small amounts of water flowing into the basin from the lake. Accurate measurements of water inputs into Agency Lake from the Wood River Basin can be made by considering only the surface water outflows and pump rates from reclaimed areas.

4.5 Possible Water Conservation Strategies

Reduction of irrigation applications will increase flows to Agency Lake as long as the reduction takes place extensively throughout the basin, or over large management tracts. In the WRBNonIrrigated scenario soil moisture did not begin to severely limit ET until June and earlier irrigation may not be required. In the WRBIrrigated scenario late irrigation filled the soil storage capacity and led to winter runoff because it was not used for evapotranspiration. If a soil moisture deficit was allowed to occur in the late growing season from decreased irrigation then precipitation could effectively be used for soil moisture recharge and early season growth the following year. Two reduced irrigation scenarios were simulated, called "Red1" and "Red2". In both of these scenarios the reduced irrigation management occurs over all of the pasture management cells in the Wood River Basin

The Red1 scenario reduced irrigation to occur only in June and July. The same rotation period and application rates were used, resulting in a total of 4 irrigation rotations. This represents a 60% decrease in total annual irrigation diversions. The Red2 scenario used the same irrigation season as WRBIrrigated, but only applied irrigation every 28 days using the same 14 day rotation. After a 14 day irrigation rotation was complete no irrigation was applied for another 14 day period. In this scenario there were a total of five irrigation rotations, representing a 50% decrease in total annual irrigation diversions.

Average monthly consumptive use from the Red1 and Red2 scenarios is shown in Figure 46, with the other scenarios. The average total growing season ET for the Red1 scenario is 666 mm (26.2 ft) and for the Red2 scenario is 680 mm (26.8 in), a percent difference of 14% and 12% respectively when compared to the WRBIrrigated average total growing season ET of 767mm (30.2 in).

Compared to WRBIrrigated the Red1 scenario resulted in a flow increase of 2.47×10^7 m^3 (20,000 ac-ft) to Agency Lake over the 2007 water year (Figure 47), the result of a flow deficit of 1.97×10^7 m^3 (16,000 ac-ft) from October to April, and a flow surplus of 4.44×10^7 m^3 (36,000 ac-ft) from April to September. The Red2 scenario resulted in a flow increase of 2.10×10^7 m^3 (17,000 ac-ft) to Agency Lake over the 2007 water year (Figure 47), the result of a flow deficit of 1.73×10^7 m^3 (14,000 ac-ft) from October to

April, and a flow surplus of $3.82x10^7$ m^3 (31,000 ac-ft) from April to September. These reduced irrigation scenarios show that changes in basin-wide irrigation management can be effective in increasing flows to Agency Lake, although it is not clear how pasture productivity will respond to decreased ET.

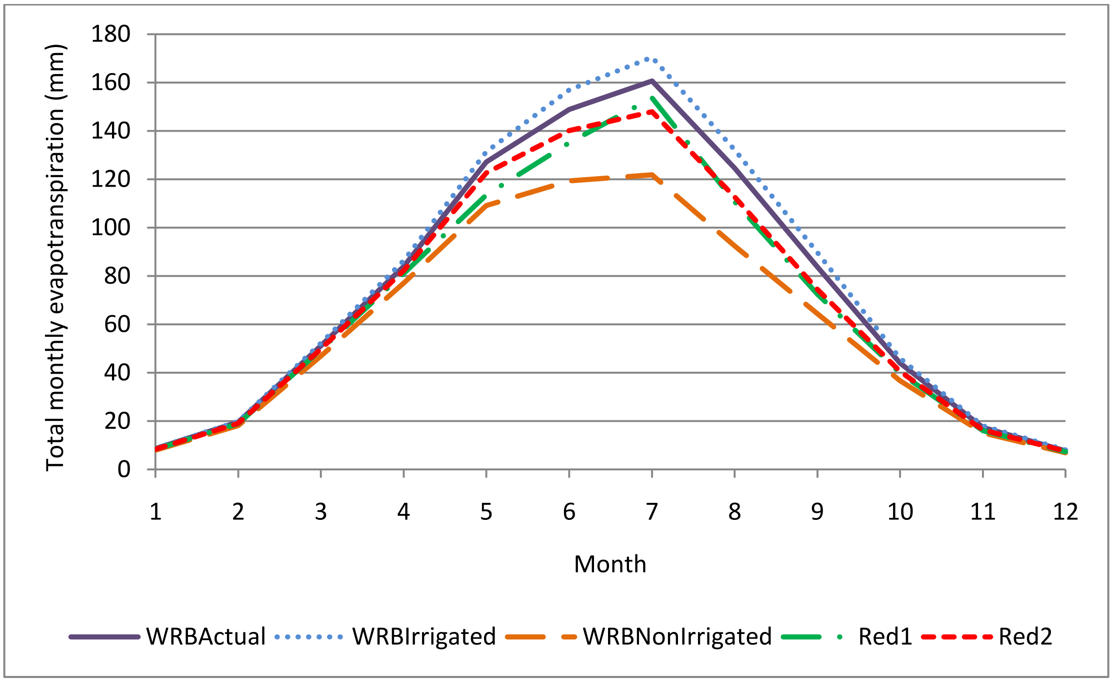

Figure 46: Average monthly ET (mm). The total ET for each month was averaged over the 8 year simulation period.

If the estimated irrigation efficiency of 50% is accurate, half of the water diverted for irrigation and applied to land is returned to streams. During land application water picks up sediment and nutrients that are then transported to the streams, contributing to the impairment of stream and lake water quality. Decreasing the total irrigation diversions would improve water quality and the resulting retention of nutrients within the pastures may offset some of the productivity losses from reduced ET. If water quality in the Wood River is improved then Agency Lake may be able to act as a refuge area for sensitive species when the conditions in Upper Klamath Lake are inhospitable due to eutrophication.

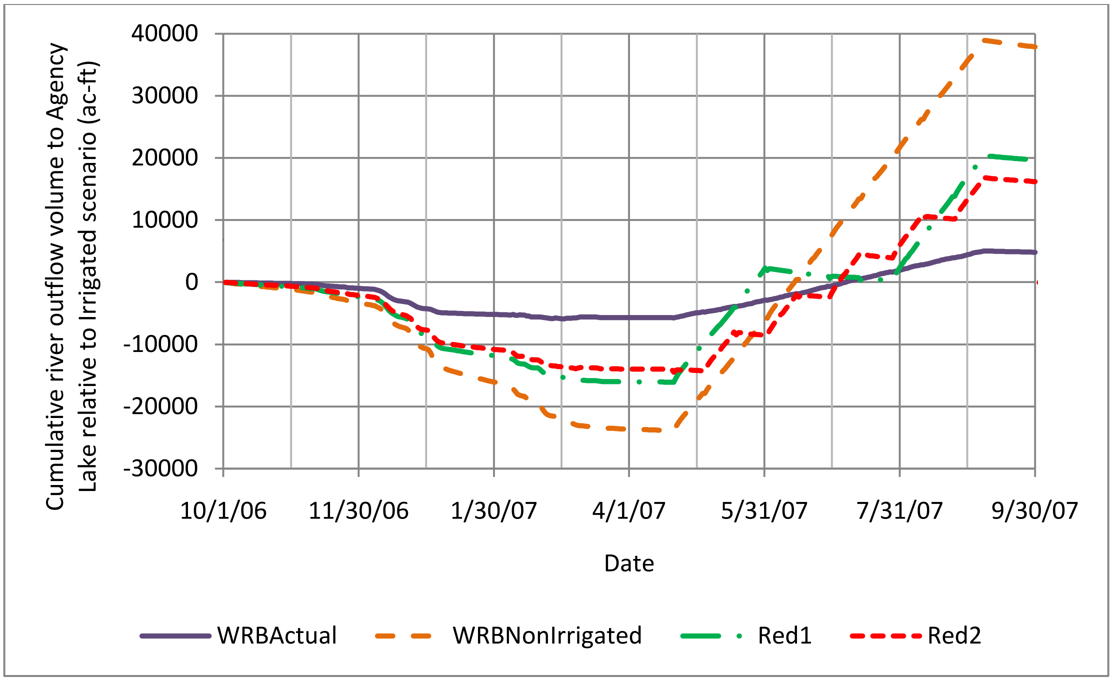

Figure 47: Difference in cumulative water year outflow to Agency Lake relative to the WRBIrrigated scenario, including reduced irrigation scenarios Red1 and Red2.

5 Conclusions and Recommendations

MIKE SHE proved to be a very capable model and was able to simulate all of the major hydrologic process in the Wood River Basin, including irrigation applications and withdraws from streams. Previous groundwater, surface water, soils, evapotranspiration, and vegetation studies in the Wood River Basin allowed for model parameters to be tightly constrained for the calibration process. It is rare to have this much information available for a basin and if this information was not available then the use of MIKE SHE for this study may be impractical because parameters would either have to be calibrated over a wide range, or used with default parameters that would represent a "reasonable" value, but not necessarily a correct one. The extra calibration load would take considerable time and computer resources. As more parameters are introduced the complex interactions between parameters means that similar model behaviors can be achieved with multiple sets of parameter values and there is no single unique solution that can optimally represent the basin (Beven, 1993).

MIKE SHE is limited by its inability to simulate vegetation dynamics. Temporal and spatial variability in vegetation can be input by the user, but these cannot respond to changes in hydrology. There is no simulated feedback between vegetation and hydrology, even though in real systems this feedback can have a considerable influence. This limitation was not severe for this study because extensive pasture throughout the Wood River Basin and rotational grazing management results in fairly constant vegetation, which was easily represented in the model. MIKE SHE can be linked to the Daisy model to simulate vegetation dynamics and the unsaturated zone, but the link could not be established for this research. Including the capabilities of Daisy and integrating it into the MIKE SHE interface would strengthen the model.

Stream inputs were simulated as constant inflows because there is very little information available to construct rainfall-runoff models that could simulate the inputs. The streams interact with the model domain though runoff, subsurface drainage, gains and losses to the saturated zone, and irrigation diversions. Since there is little surface water flow data available the accuracy of the simulated interactions between the streams and model domain cannot be verified. Collecting observation data to construct a surface water balance to compare to the model simulations would be intensive given the complexity of surface water in the Wood River Basin. Multiple springs and seeps are developed for irrigation and contribute to surface water flows, as well as numerous irrigation diversions that would have to be accounted for. However, the biggest contributors to the stream flow water balance are irrigation diversions and return flows are simulated well by the model based on the similarity of simulated and observed water tables in irrigated areas.

It was originally thought that inefficient surface irrigations may have led to inter-annual increases of subsurface storage and that reduced irrigation over the basin may lead to depletion of this storage resulting in falling water tables basin wide over multiple years. This was not borne out by modeling results. Compared to basin-wide irrigation, basin-wide non-irrigation resulted in maximum water table depths to increase by 1 m (3.3 ft) to 1.5 m (4.9 ft) during the driest period, and by about 0.5 m (1.6 ft) during the wettest periods. The irrigated scenario led to saturated conditions with the water table near the surface for about two months during each winter. In the non-irrigated scenario the water table only came to the surface on occasional years and then only stayed there for about a week, although in one year (2006) the water table stayed at the surface for over a month. The water table coming to the surface represents maximum water storage in the basin. In the non-irrigated scenario this maximum water storage was occasionally achieved, explaining why there was no inter-annual trend of storage reduction when going from irrigated to non-irrigated.

There is not much excess storage capacity available and when the maximum storage is reached it resets the system and removes any additional storage that may have been present.

Subsurface flow was not evaluated in detail, however it was noted that subsurface watet flows from Agency Lake into the Wood River Basin where the lowest water table elevations are below the Agency Lake water surface elevation, and occur 6 to 8 km to the north of the Lake. This area is reclaimed land that is below the lake level and used to be part of the marsh that now makes up the Upper Klamath National Wildlife Refuge. I interpret this to occur due to drainage and pump-out from the area, in combination with evapotranspiration, depleting the moisture faster than it can be replenished from subsurface flow. The subsurface flux from Agency Lake to the basin is minimal compared to the flux into the basin from the north. Total water exports from the basin to Agency Lake can be adequately estimated by considering only surface water sources.

The Wood River Basin has been the target for water conservation programs over the past eight years, and various tracts were managed without irrigation. A vegetation study (Stringham and Quistberg, 2008) concluded that there was about a 20% difference in pasture productivity between irrigation and non-irrigated tracts, though there was not a significant difference between the two treatments. The maintenance of productivity in non-irrigated tracts has been attributed to sub-irrigation. Vegetation characteristics changed in the non-irrigated tracts with fewer rushes, sedges, and obligate wetland plants. If irrigation were to be reduced the plant community may be adaptable to the new soil hydrology regime and reach similar productivity levels. Vegetation management during the transition period would be critical for maintaining productivity and should be studied further. Vegetation growth and productivity in response to these scenarios was not simulated and it is unclear how the vegetation would respond to the modeled evapotranspiration dynamics.

Ultimately irrigators are most interested in pasture productivity and would adopt water conservation strategies if payments for participation offset the lost productivity, or if productivity could be increased. If pasture productivity is severely limited by moderate decreases in evapotranspiration then these strategies will not be adopted. However, there may be different forage varieties or range management options that would maintain pasture productivity despite decreased evapotranspiration. Without knowing the vegetation response to reduced irrigation it is difficult to formulate a recommendation for water conservation, pasture management, and water valuation. The two reduced irrigation scenarios resulted in a decrease of growing season ET of about 100 mm (3.9 in) compared to the irrigated scenario. This is within the range of non-irrigated tracts that were included in the Stringham and Quistberg (2008) vegetation study, where the decrease in growing season ET ranged from 60 mm (2.4 in) to 130 mm (5.1 in) compared to the irrigated scenario. Therefore, lower pasture productivity in response to the reduced irrigation scenarios would probably be comparable that reported in the vegetation study, about 20%

A review of the USBR water bank (USGS, 2005) recommended that large continuous non-irrigated tracts be given priority for irrigation forbearance because sub-irrigation will be reduced. This study showed that there is a trend where water savings from non-irrigated tracts is dependent on the ratio of tract area to perimeter, which confirms the sub-irrigation hypothesis. Therefore, the amount of water savings from enrolling land in irrigation forbearance will depend on whether neighboring lands are also enrolled. This will complicate valuation of irrigation forbearance programs and make it difficult for irrigators to compile bids for consideration to a water bank or other water conservation program, if there is no coordination amongst the irrigators in the Wood River Basin.

Due to sub-irrigation, effective strategies for increasing water conservation must be adopted over the majority of the Wood River Basin, otherwise total consumptive use would be controlled by the irrigated tracts. Extensive adoption of new management strategies would be a major impediment to implementing these strategies because it would require coordination with numerous irrigators. This coordination would also be necessary to manage irrigation deliveries, irrigation tailwater from upstream irrigators make up an important supply of irrigation water for those downstream. If diversions and applications are reduced upstream there could be damage to downstream users that do not want to take part in water conservation programs, but will have their water supply reduced.

The total growing season (April 1 to September 30) consumptive use for basin-wide irrigation was $1.55\text{x}10^8$ m^3/yr (126,000 ac-ft/yr) and for basin-wide non-irrigation was $1.18\text{x}10^8$ m^3/yr (96,000 ac-ft/yr), a reduction of only $3.7\text{x}10^7$ m^3/yr (30,000 ac-ft/yr). There was still high consumptive use under non-irrigated conditions showing that intensive irrigation may not be required to maintain pasture productivity. Without irrigation the period of greatest moisture deficits would be in August and September, which is a very productive period for the cool season grasses in the Wood River Basin. The total difference in growing season evapotranspiration of $3.70\text{x}10^7$ m^3/yr (30,000 ac-ft/yr) between the basin-wide irrigated and non-irrigated scenarios might be interpreted to mean that during the growing season this amount would be gained for in-stream flows if the entire basin stopped irrigation. However, the inclusion of stream modeling showed that the actual gains for in-stream flows during the growing season would be about $8.01\text{x}10^7$ m^3/yr (65,000 ac-ft/yr). Irrigation caused increased winter flows and decreased summer flows. From October to April the non-irrigated scenario is in a flow deficit compared to the irrigated scenario, due to irrigation causing saturated conditions to persist throughout the winter and precipitation to go directly to runoff instead of to soil moisture storage.

Having a patchwork of non-irrigated tracts surrounded by irrigated tracts was found to be ineffective in reducing the overall consumptive use of the basin, but there may be alternative strategies for reduced irrigation and increased water conservation. One such strategy is to reduce the irrigation season to only June and July. Soil moisture is generally adequate to sustain growth through the spring and allowing a moisture deficit at the end of the season that would allow it to be replenished by winter precipitation. This scenario was simulated resulting in a total growing season consumptive use of 1.35×10^{8} m^3/yr (109,500 ac-ft/yr), 2.03×10^{7} m^3/yr (16,500 ac-ft/yr) less than the irrigated scenario. The total increase in flows to Agency Lake during the growing season for reduced irrigation scenario was 4.44×10^{7} m^3/yr (36,000 ac-ft/yr).

Another possible strategy is to maintain the original irrigation season from April to September, but lengthen the time between applications from 14 days to 28 days. The soils in the Wood River Basin have a high water holding capacity and can likely store enough water to support pasture for a 28 day period. The benefit of this scenario over the previous one is that the ET deficit will be spread equally over the entire growing season which will stress plants less than if there is a sudden ET deficit. This scenario was simulated resulting in a total growing season consumptive use of 1.38×10^{8} m^3/yr (112,000 ac-ft/yr), 1.73×10^{7} m^3/yr (14,000 ac-ft/yr) less than the irrigated scenario. The total increase in flows to Agency Lake during the growing season for reduced irrigation scenario was 3.82×10^{7} m^3/yr (31,000 ac-ft/yr).

Reducing irrigation, either by shortening the season or by reducing the application rotation, substantially increases stream flows during the growing season, but when considered over the entire year the stream flow increase is much less. If the goal of increasing stream flow is to supply more water during the growing season to downstream or in-stream uses then these conservation strategies are very promising and the Wood River Basin would be a good source for additional water. If the goal is to secure a consistent additional supply of water that can be stored on an inter-annual basis and released when needed downstream, then these strategies are less promising because an increase of flow during the growing season is offset by a decrease in flow during other times of the year.

Improved water quality may also result from reduced irrigation because there would be less tailwater flow carrying sediments, nutrients, and heat to the streams and lake. If the water quality in the Wood River, and hence Agency Lake, were improved considerably then Agency Lake could act as a refuge for sensitive species when Upper Klamath Lake is inhospitable due to eutrophication.

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