Interim report on the development of a numerical

Walla Walla Basin Surface and Ground Water Model

Submitted to the Walla Walla Basin Watershed Council

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Prepared by: Arístides Petrides & Jake Scherberg

Under the supervision of Dr. John Selker & Dr. Richard Cuenca

Dept. Biological and Ecological Engineering

Oregon State University

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Notes about of this draft document

The Walla Walla Basin Watershed Council in conjunction with Oregon State University has been developing a regional hydrological model for the Walla Walla Basin. This draft report is an initial description of model development. The purpose of this report is to state the model assumptions and data resources used in developing the model. Calibration and validation of this model is an ongoing effort. Additional efforts are underway to refine estimations of inflowing surface water and inputs from the deeper basalt-aquifer into the model area.

I. Introduction

This report summarizes ongoing efforts to develop a new modeling tool for simulating hydrologic conditions in a portion of the Walla Walla Basin of eastern Oregon and Washington. The Walla Walla Basin Watershed Council (WWBWC) and the department of Biological and Ecological Engineering at Oregon State University have worked collaboratively to develop this model. A model, as it is referred to in this report, is a simplification of a natural system, such that quantitative descriptions of all major components of the system are represented. The collected information is formatted for input into modeling software, calibrated for accuracy, and validated by comparing model outputs to observed data. Once this is achieved, parameters can be varied to represent different conditions.

This work describes a geographical expansion of a previous model completed in 2008, through a previous collaborative effort between WWBWC and a research team from Oregon State University. This earlier model focused on approximately 10,700 acres in the vicinity of Milton-Freewater, Oregon. The current version extends the original model to the north and west, along the Walla Walla Valley, covering approximately 58,000 acres, or 90 square miles.

The new modeling effort has involved collecting data records from several state and federal agencies, monitoring records from the WWBWC, and consulting firms. Additional information has been determined by utilizing scientific techniques developed for addressing questions in hydrology. This report contains explains data sources and methods used for data analysis.

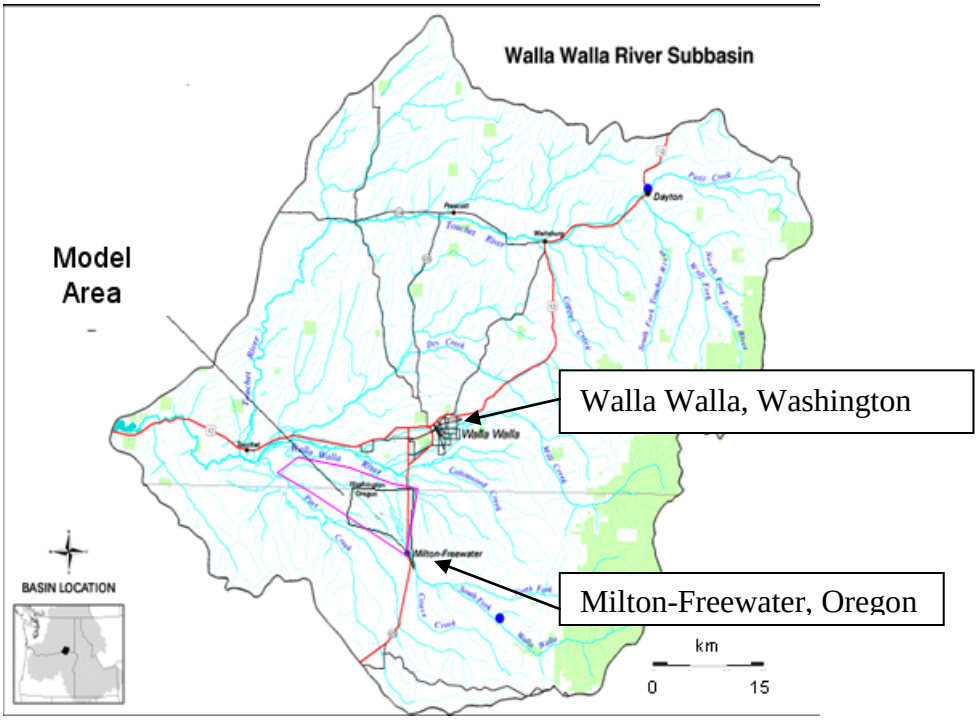


Figure 1. Walla Walla Watershed, pink delineation of new model area, black delineation of previous model area Petrides (2008).

The Walla Walla basin spans the boundary of Eastern Oregon and Eastern Washington, draining into the Columbia River. The primary land use in this basin is agricultural. Urban areas, riparian areas, and native vegetation comprise about 20% of the total area. Fruit orchards, grapes, onions, alfalfa, wheat and several types of vegetables are the primary crops grown in the model region (For detailed descriptions see section 2.13 *Land use*). Agricultural demands for water, as well as instream flow requirements for species protected by the Endangered Species Act, have caused an increasing stress on the areas' supply of both groundwater and surface water resources. In response, there is interest in developing methods of water conservation that allow the agricultural sector to continue thriving while also meeting the environmental needs in the region. One method currently in use is artificial aquifer recharge. This involves diverting surface water into infiltration basins where it percolates into groundwater. This practice was initiated in the basin in 2004, and is an important area for research with the potential for applicability in other regions.

This model is intended to be a tool for assessing the systems used for distribution of water to users in the study area, as well as predicting responses to changes in that system. The purpose of this model is to simulate scenarios which have been devised to predict the impacts of current and proposed water management strategies. These include aquifer recharge projects, lining irrigation canals with impermeable surfaces, a new reservoir, and changing crop distribution. Once calibrated and validated, the model will be a powerful tool to address future questions and concerns in the Walla Walla Basin. In addition, it will promote the regions' status as a leader in innovative solutions to water supply issues.

1.1 Previous hydrologic research in the Walla Walla Basin

Initial recognition of water supply limitations and an increasing water demand for agriculture led to an extensive report on the geology and groundwater conditions of the Walla Walla Basin by R.C. Newcomb of Washington Division of Water Resources (1965). The questions about water supply raised in Newcomb's work provided motivation for several previous modeling efforts, focusing on several aspects of the basins' hydrology. These range from systemic models to those focused on the interpretation of experiments with aquifer recharge.

In 1976, Barker and MacNish completed two complementary computer models; one simulated the gravel aquifer, and the other simulated the underlying basalt aquifer. Their goal was to make use of water use data and local geologic records to develop a reliable estimate for the basins' water budget. Their model was calibrated with data from year of observations in 1970. They point out the need to revisit scenarios and predictions from their modeling to see if they are reliable.

Some hydrologic modeling parameters, attributed to the geological conditions do not change over the timescales in question (e.g., aquifer thickness,

porosity, and hydraulic conductivity). Other model parameters change as the land and water uses changes over time (e.g., agricultural consumption). Specifically, the hydraulic conductivity rates in the gravels determined for the Barker and MacNish report (20.4 to 44.5 meters per day) are of the same order of the average value for zones in the gravel aquifer used in this model. On the other hand, the volume of annual groundwater pumping has changed dramatically over this time period (Petrides, 2008).

There have been two investigations into implementing aquifer storage and recovery (ASR) techniques in and around the city of Walla Walla, Washington. The first of these was a USGS study in which water from Mill Creek was injected at a Walla Walla municipal well. Though the water table rose, this appeared to be a localized effect in the vicinity of the injection well. This brought about speculation that the aquifer was being clogged by the accumulation of suspended sediments or the entrapment of entrained air. An alternative explanation was that an aquifer boundary was reached (Price, 1960).

Subsequently, Golder and Associates inc. analyzed the potential for ASR in the basalt aquifer below Walla Walla using the USGS MODFLOW program. This model covers a greater extent to the north, but less territory in the south and west compared to the current WWBWC-OSU model. Golder and Associates have produced estimated aquifer capacities for ASR under several pumping scenarios, and predicted the impacts of these scenarios on well productivity from the basalt aquifer (Golder and Associates, 2007).

The Washington Department of Ecology has published a report assessing surface-water and ground-water interactions in the area of The Walla Walla River, Mill Creek, and the Touchet River. Though much of this study pertains to an area outside of the boundaries of the WWBWC-OSU model, the general conclusion is that the upper reaches of the watersheds in question are losing reaches while the lower reaches are gaining (Stejskal, 2003). The model area in this report is predominantly losing surface water to ground water in the agricultural areas of the Walla Walla Valley (Petrides, 2008). These findings do

not necessarily contradict each other because a large portion of the study areas are not overlapping.

In 1995 the Washington Department of Ecology provided several important pieces of information in an assessment of the Walla Walla watershed. In this report it was documented that there are a total of 513,200 acre-feet per year of water rights allocated in the watershed, of which groundwater withdrawal permits comprise 51%. Actual withdrawals were thought to be below these permitted levels. Irrigation was found to be the primary use of both surface water (99%) and groundwater (97%). Remaining water withdrawals are divided between domestic, municipal, and industrial applications. This study also concluded that water level declines in the basalt aquifer were significant, while the gravel aquifer had been relatively stable for 30-40 years (WDOE, 1995).

A previous version of the model described here also employed the Integrated Water Flow Model (IWFM) hydrologic model. This effort was completed by the WWBWC-OSU team in 2008. The 2008 work focused on a sub-section of the basin in the vicinity of Milton-Freewater, Oregon. It was intended to estimate a localized water budget and analyze the initial results of a shallow aquifer recharge project within the Hudson Bay Development and Improvement Company (HBDIC) irrigation District (Petrides, 2008).

In this report we have considered information obtained through these previous modeling efforts, and made every attempt to supply the most recent and complete data available while being mindful of the methodologies and conclusions of previous modeling approaches.

1.2 Modeling Objectives

The model described here is intended to both to improve understanding of the relative importance of specific current conditions, and make quantitative estimates of the impacts of several proposed management scenarios.

1. Conversion of irrigation canals to pipelines

There are ongoing efforts to convert canals into pipelines due to the factor of leakage from permeable canal beds. This has effected operations of the irrigation districts, as it must be accounted for in water deliveries (increased supply). On the other hand, canal leakage is known to be a significant source of aquifer recharge, and conversion to pipelines will have the concurrent consequence of cutting off this significant source of aquifer replenishment. This effect has been associated with decreased spring flow in some areas (Petrides, 2008). Setting stream bed permeability in the IWFM model to zero will simulate the effect of converting unlined canals into pipelines. This will provide water managers a predictive tool to inform such decisions.

2. Managed aquifer recharge

Within the current practice of the Walla Walla basin, managed aquifer recharge refers to the practice of diverting water into excavated basins, lined with coarse gravel material to facilitate percolation of surface water into groundwater. This is achieved by diverting surface water to recharge basin via the irrigation canal network. These operations occur over winter and early spring, when there are typically high stream flows and little or no agricultural demand. The recharged water both enhances stream base-flow for habitat restoration and is available for withdrawal over the summer when surface flows are low and irrigation demand is high. This practice is conceptually equivalent to using the naturally occurring sand and gravel aquifer as a water storage reservoir.

The incentives for using aquifer recharge are improved stability of the water table and potential restoration of the aquifer. The limitations are related to the volume of water that can be infiltrated, the slow velocity of groundwater flow, and issues with clogging as biological layers develop in the basins' substrate. All of these variables can be incorporated into IWFM simulations.

The Walla Walla basin has three ongoing aquifer recharge projects. These are operated seasonally, diverting high flows in the winter when irrigation

demand is low for utilization in the summer when surface flows are low and demand is high.

An important aspect of current modeling efforts is to identify optimal locations for additional recharge basins based on groundwater flow characteristics, existing supply networks, and groundwater demand.

3. Estimating the water budget

Simulations will provide predictions of the systemic responses to varying conditions in terms of total water volume and three dimensional distributions. Initially, the model will first be calibrated and validated using a data set representing conditions over the years 2007 through 2009. The following step will be to apply the model to hypothetical conditions representing proposed management and land use scenarios.

Our ability to accurately model processes across a wide range of spatial and temporal scales is controlled by the resolution and accuracy of input data, as well as computational limitations. Resulting output data will be analyzed in terms of the water budget; specifically surface water and ground water distribution over time and area. The goal is to develop reliable estimates for systemic responses to various management strategies in terms of the water budget.

II Model development

2.1 Model selection

There are several computer models available for simulating regional hydrologic processes. These include MIKE-SHE of the Danish Hydraulic Institute, HEC-HMS of the U.S. Army Corps of Engineers, and MODFLOW of the USGS, all established modeling packages. The IWFM was designed for modeling large-

scale agriculturally dominated hydrologic systems, and was selected for this effort for the following reasons.

1. The physical parameterization specifically for irrigated agricultural systems provides for a flexible model, capable of incorporating subtlety through a wide range of input variables.
2. IWFM is unique in its ability to calculate demand from land use parameters as specific as crop type.
3. Operational permutations such as time tracking vs. simulation mode, and user settings for water supply sources enable flexibility with minimal changes to inputs.
4. Operating speed compares favorably to several other options (MIKE-SHE, HEC-HMS).
5. The model authors provide extensive support directly to the OSU staff.
6. Free software facilitates broad applicability, specifically for the non-profit Walla Walla Watershed Council.

Simulated outputs from IWFM can be compared to other models developed for the Walla Walla Basin. Concurrence between hydrologic simulations may support the validity of the model, while discrepancies may either highlight research needs or stem from the limitations of a particular model.

2.2 Description of IWFM

Integrated Water Flow Model (IWFM) has been designed as a tool for planning and management of groundwater and surface water resources. It is a physically based finite difference model using the FORTRAN programming language to produce hydrologic simulations. The model consists of parameters representing physical systems and a finite element grid used as a spatial reference within the model. In this grid, areas are represented by discreet triangular elements, and discreet points at the element corners are nodes.

Nodes that intersect streams are referred to as stream nodes. A detailed description of the model grid is provided later in this report.

The finite element grid provides a basis for calculations over time and space. Through these features, IWFM is able to output simulations of water table elevations, surface flows, and the interactions of surface and subsurface systems. The physical parameters for model input are determined using field data and interpolation. For example, stream widths may be measured at several locations while the intermediate locations are assigned based on the known measurements.

An important feature of IWFM is that it is designed to calculate water demand from land use data inputs.

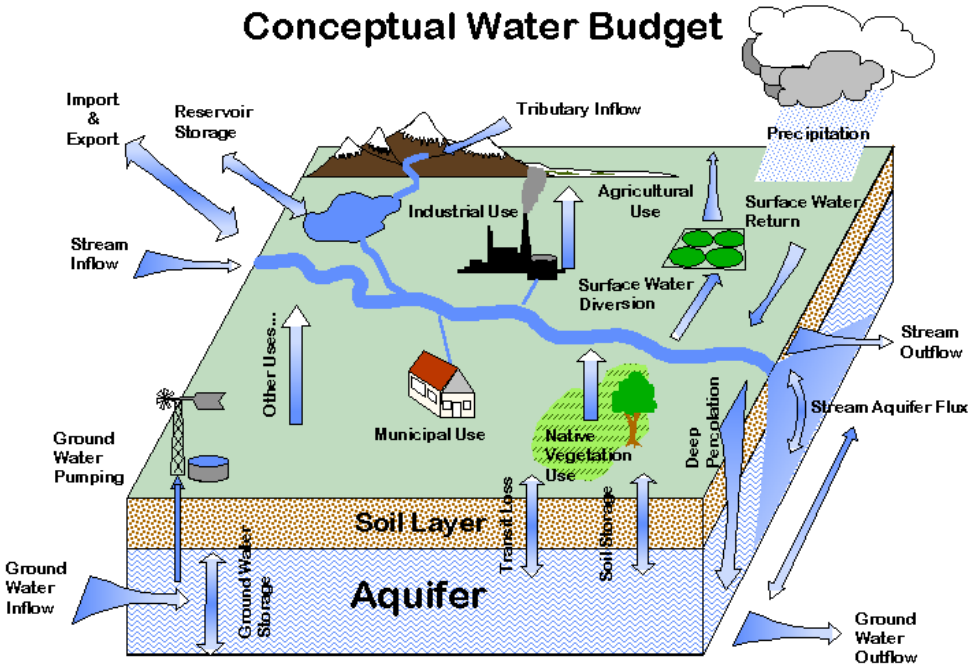


Figure 2. Illustration of hydrologic fluxes modeled by IWFM. Source: IWFM Theoretical manual v2.4.

A water budget is calculated for each element, with groundwater and surface water being quantified in terms of inflows and outflows. These parameters are calculated based on geological and physical properties, land use,

soil type, precipitation, initial conditions and bordering elements. The result is represented by a mass balance equation of the form:

$$S = Si + Qin + Gin + P - Qout - Gout - ET$$

S = water volume stored in element at given time step
Si = initial water volume at given time step
Qin = Surface water inflow (Stream inflows and runoff)
P = Precipitation
Qout = Surface water outflow (Outflows across the model boundary and withdrawal for land application)
Gin = Groundwater inflow (from boundaries and percolation)
Gout = Groundwater outflow (at boundaries and from extraction)
ET= evapotranspiration (a function of land use)

Outputs are given in terms of water table elevations at nodes and hydrographs at stream nodes. Elements can also be grouped by sub-regions within the model area. These regions provide a device to distinguish areas with different characteristic properties. In this case, sub-regions have been selected based on land uses and dominant properties in the vadose zone such as hydraulic conductivity.

2.3 Model Area

The area selected for the 2010 version of the Walla Walla basin IWFM model is an expansion of the 2008 version of the model. The primary surface water inflow to the model area is the Walla Walla River. Mill Creek, Pine Creek, Yellowhawk Creek, and the Touchet River also add significant amounts of discharge. The northern model boundary follows the main channel of the Walla Walla River and the southern boundary follows the edge of the Horse Heaven Hills, with inflows from Pine Creek and Dry Creek.

The area within the model boundaries is primarily agricultural, with a mixture of fruit trees, grapes, row crops, and grazed pastures. There are also several towns, namely Milton-Freewater and Umapine, Oregon and Touchet, Washington. College Place and Walla Walla, Washington, lie just outside of the model boundary.

Because the model is three dimensional, groundwater also constitutes a major inflow and outflow, as well as a vital resource. A physical aquifer characterization, flow rates, and water table elevations, are topics to be covered in depth, in later sections of this report.

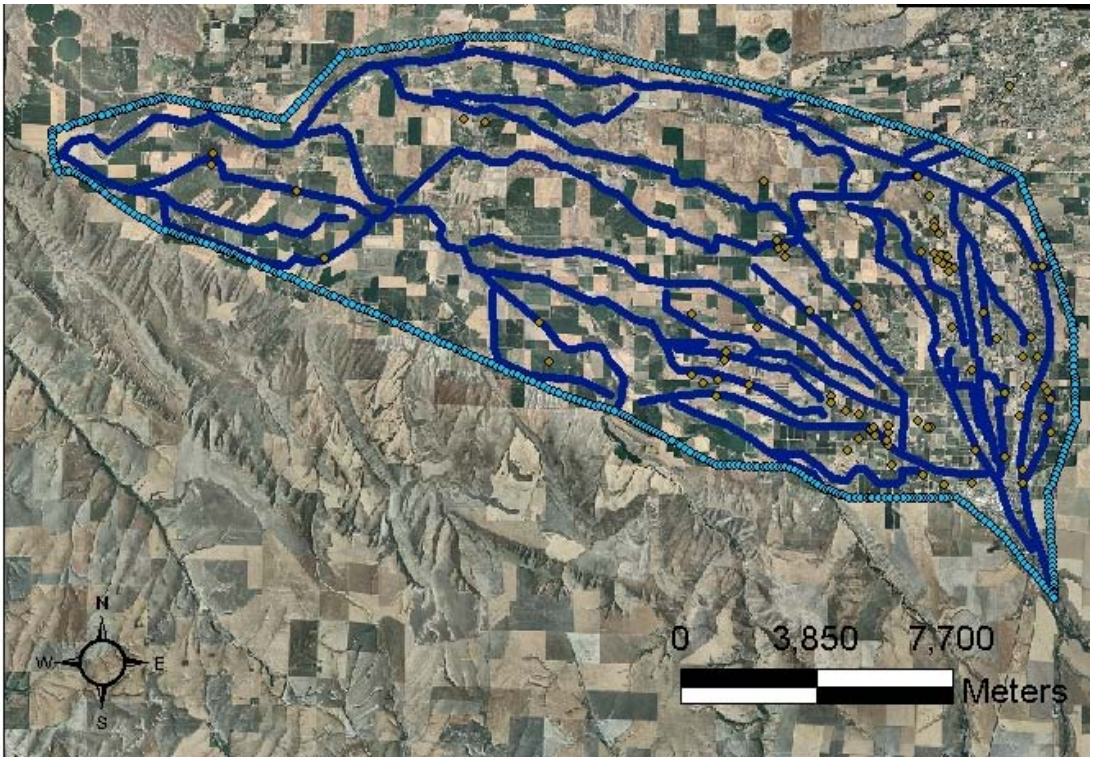


Figure 3. Model area output of GIS map. Blue lines represent the major surface water features represented in the model.

2.4 Model Grid setup

The IWFM model consists of a grid of discreet triangular elements, each defined by three nodes located at the points of the triangle. The average

distance between nodes is 100 meters. This constitutes a notable change from the previous IWFM model applied to the Walla Walla basin (Petrides, 2008) which used square elements with 330 meter sides. The goal of this adjustment is to achieve a higher resolution in the model output by having at least 3 nodes per parcel of land. In the area around the three aquifer recharge sites, the element grid has been assigned an even smaller scale, to capture the effect of the infiltrating water on the local water table (Figure 4). All together, the model domain consists of 36,486 elements, 18,520 nodes, and 2,015 stream nodes.

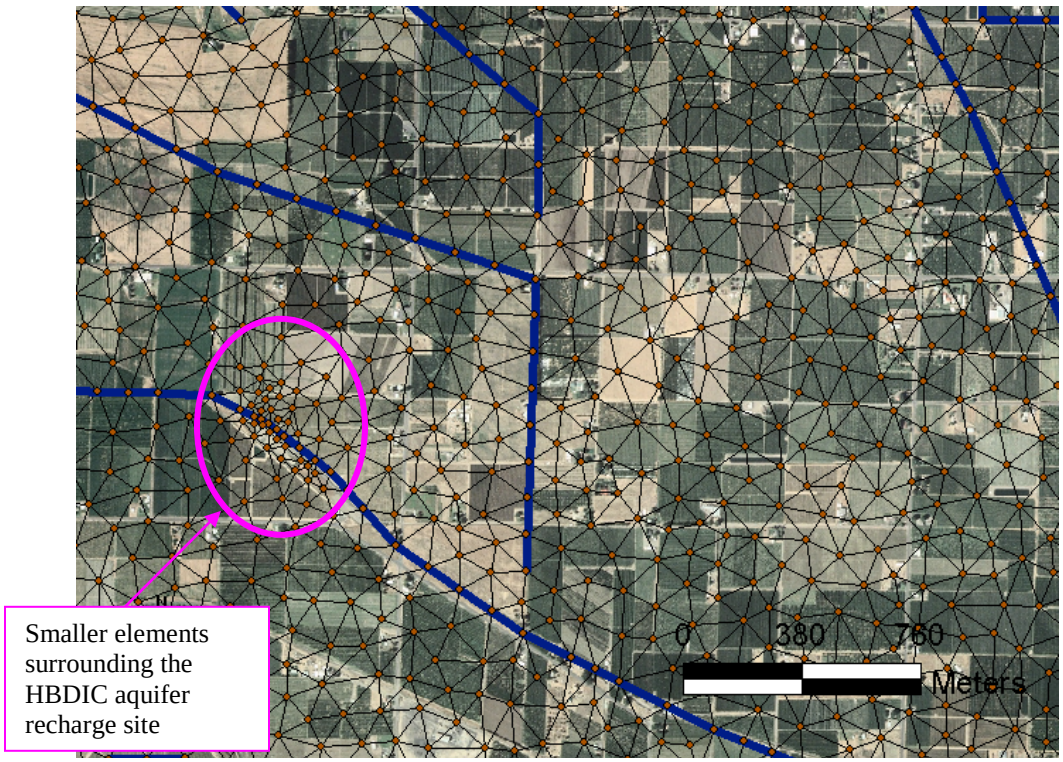


Figure 4. Triangular elements of variable areas compose the grid mesh. Note smaller elements around the artificial aquifer recharge projects. Average spacing between nodes is 100m.

Each element has characteristics based on its specific location, or assigned more generally by sub-region. These values are determined by a variety of physical parameters and land use data, including area, elevation, soil type, crop type, and hydrologic connectivity to streams and other elements. The

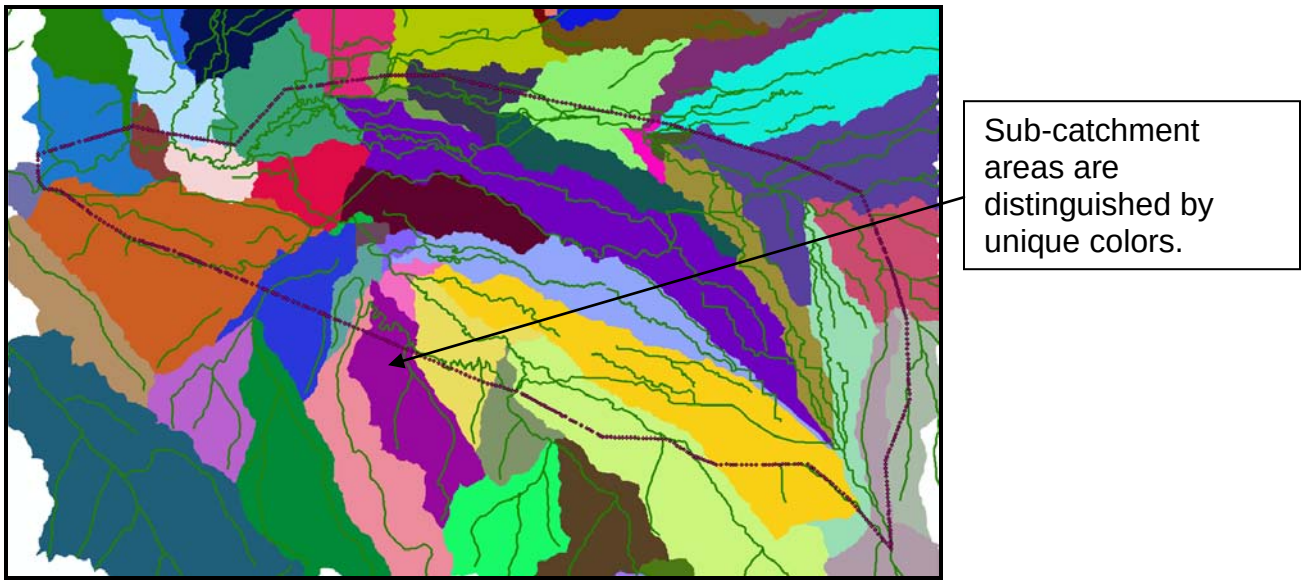
corner points of the elements are called nodes, and provide discreet reference points in the model area. Water flows are tracked through the network of nodes and stream nodes. Nodes are also reference points for output data, such as water table elevations.

The operational method of IWFM can be conceptualized by considering the fate of water as it enters an element from a neighboring element or from outside the model boundary. This may occur as a surface water inflow, groundwater inflow, or as precipitation. Over a given time interval, this water may remain in the element as it entered or it may flow vertically, horizontally, or both. Vertical flows represent the flux between groundwater and surface water. These may be natural, such as infiltration or evapotranspiration, or human induced, such as groundwater pumping or aquifer recharge. Horizontal flows represent water movement across an area; such as stream flow, irrigation diversions, and groundwater seepage. These are the primary mechanisms of water imports and exports for individual elements.

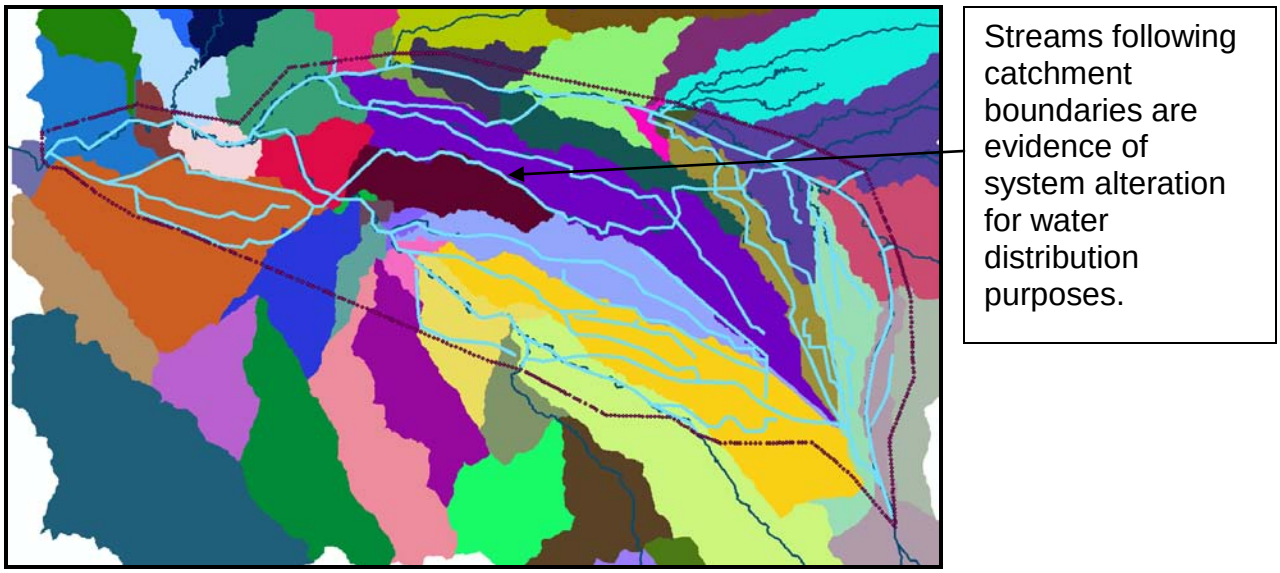
IWFM uses an algorithm to quantify these flows based on the input parameters. These determine factors such as water demand, aquifer characteristics, vadose zone characteristics, and surface conditions within the model framework. This information is used to calculate water storage within elements, sub-regions, and the model as a whole.

2.5 Surface Water

This section provides an explanation of the methods used to incorporate surface flows into the Walla Walla Basin hydrologic model. Surface water enters the model as inflowing streams, runoff from precipitation, and applied water from wells in the basalt aquifer. Once in the model area, the stream network is complex due to the alteration of natural systems to enable the feasibility of agriculture. This means that some canals flow perpendicular or diagonally across natural drainages, while others follow natural flow paths. As a result several canals cross each other via pipelines (See figure 5).



A. Streams in the model area shown with sub-catchments, as determined by topographic analysis with GIS terrain processing tools.

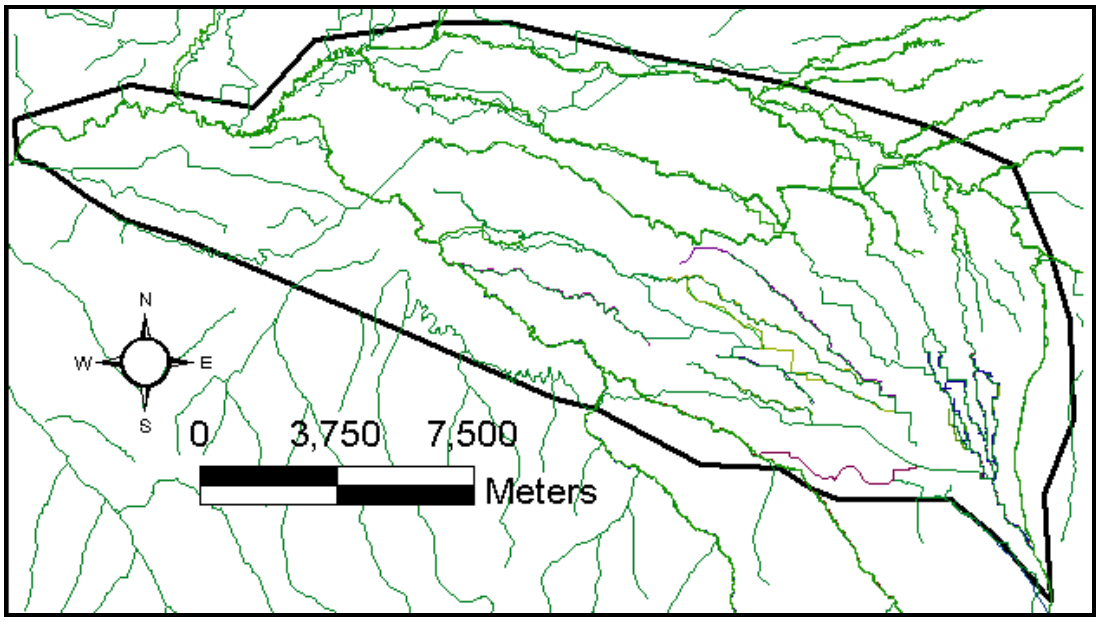


B. Stream and canal network as considered for modeling purposes.

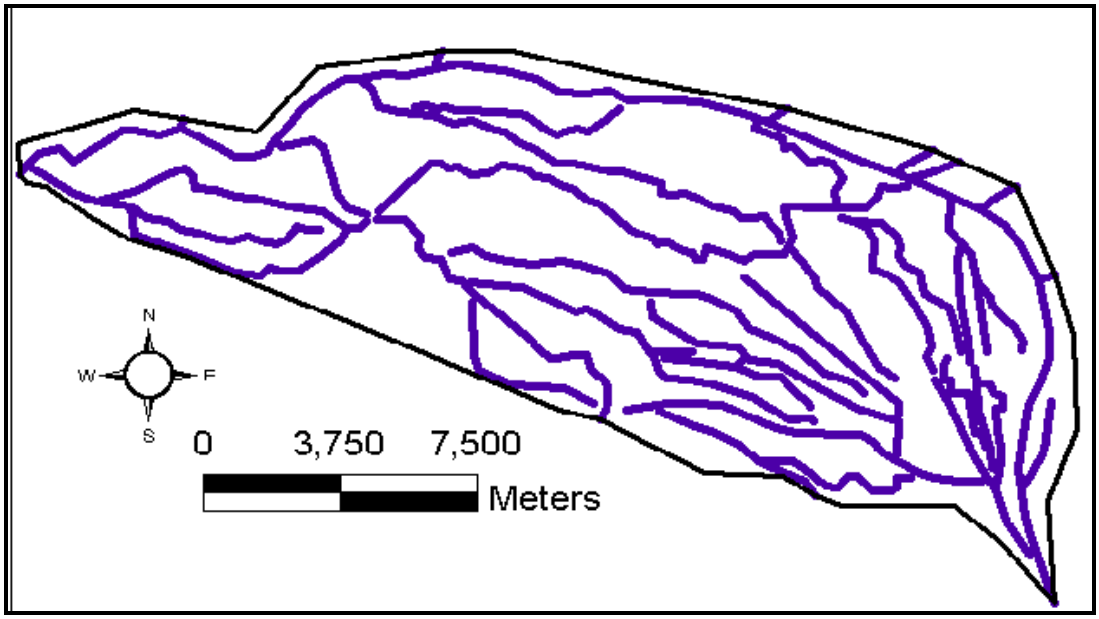
Figure 5. Illustration of the stream network in the model area highlighting signs of alterations for irrigation distribution.

2.6 Surface Water in IWFM

Like all models, this representation is, by necessity, a simplification of reality. In this case, the smallest-scale surface channels (e.g., irrigation laterals) are combined where they run parallel within 300 meters of each other. This was done both to match the resolution of the grid and because many of the laterals in the distribution network have little or no pertinent records available, so the best option for simulation and validation is tuning the model resolution to a scale that can be represented with available data. A 300 meter threshold for lumping canals gave an appropriate drainage density (area / total stream length in the area) for capturing points with known flow measurements, both current and historic. Figure 6 provides an illustration of the stream network in the basin as it has been mapped by the WWBWC, and the stream network as it is represented in this modeling effort.



A. Streams and channels in the model area, a sub-region of the Walla Walla Basin.



B. Streams as they are currently represented in the IWFM model.

Figure 6. Illustration of the simplification of the stream network in the model area.

IWFM has three key descriptors for surface water flow simulation. These are rating tables, diversions points, and bypasses. Rating tables express a relationship between depth and discharge in a stream, giving a scale reference for the magnitude of the stream or canal. Rating tables are also used to determine the flux through the stream bed by associating surface water head with a cross sectional area of stream bed. This represents the exchange between the surface water and groundwater associated with stream flow. It is determined by IWFM using the following equation.

$$q = -T * (dh/dn)$$

q = boundary flux

T = transmissivity of stream bed

h = groundwater head

n = distance perpendicular to boundary

Source: IWFM Theoretical Manual v 2.4

In this version of the model, rating tables were developed based on WWBWC surface water monitoring records and historic records from Washington Department of Ecology, USGS, and Oregon Water Resources Department stream gauging stations. Field measurement and pertinent observations were also used to complete this data set. In cases where time and funding limited the number of measurements that could be taken at a particular site, the Manning equation was applied to a single measurement to create a rating table. The rating table was then input into the software, Tablecurve, which was used to fit an appropriate stage-discharge equation. This was then applied to the collected stage data to estimate streamflow based on pressure transducer data.

The Manning equation calculates flow velocity based on slope, hydraulic radius, and a stream bed friction parameter known as the roughness coefficient.

$$V= N * Rh^{2/3} * S^{0.5}$$

V = average cross sectional velocity (L/t)

N = Roughness coefficient (unit-less)

Rh = Hydraulic radius (Cross sectional area / wetted perimeter)

S = Slope (L/L)

The roughness coefficient is the most difficult of these parameters to measure in the field, but can be calculated from the other variables in the equation. This can then be coupled with observed evidence of bank full depth and width estimate discharge under high flow and intermediate conditions. An important tuning factor to be used in model calibration is the seasonal variability of the roughness coefficient due to changing instream vegetation over the year.

Diversion points occur at stream nodes throughout the model area. These define locations where water can be directly exported from the stream as a means of supply for agricultural or other demand. Where IWFM determines there is crop demand, depending on the setting, it will first withdraw water from an associated diversion point or an associated well, then supplement as needed from the other water source. Diversion flows are computed by IWFM on a demand basis, subtracting groundwater applications if specified in the user settings as previously discussed.

Supply options for agricultural and urban water demand:

Surface Water Diversion = Total Demand

Surface Water Diversion = Total Demand - Groundwater Pumping

Bypasses represent human controlled connectivity between streams. They can be used for canal diversions and bifurcations, piped reaches, and flow in and out of the recharge basins. In this version of IWFM, 35 diversions have been defined, including three that are assigned to the recharge basins.

Bypasses are programmed in IWFM by defining the proportion of flow at the bypass location that is exported to the receiving channel. The rest remains in the original stream. This is another means by which stream magnitude can be defined and controlled within the model inputs.

Losses in the water budget are categorized as recoverable or non-recoverable. Recoverable losses are percolation from surface water to groundwater. Non-recoverable losses refer to hydrologic fluxes out of the model boundary. These include evaporation, transpiration, and deep percolation out of the aquifer.

2.7 Precipitation

It is estimated that 20% of precipitation in the valley percolates to the water table, recharging the gravel aquifer (Petrides, 2008). This comprises a major source of available groundwater.

Precipitation values are currently taken from Ag-Weather Net stations at Touchet and College Place. Elements are grouped by sub-region and each sub-region is assigned the daily precipitation values of the closest rainfall station for each time step in the simulation period. A planned revision of the model will be to incorporate additional weather stations operated by Agrimet and WWBWC to improve the resolution of rainfall data in the model area.

2.8 Stream inflows

A primary controlling factor for surface flow in the Wall Walla Basin model area is the magnitude of stream inflows. The basic principal is that the volume and timing of inflowing water provides a baseline for stream discharge in the model area, both directly and indirectly. Inflowing water is also a limiting factor on the availability of water for irrigation and other demands.

There are 11 streams flowing into the model area encompassing a wide range of flow volumes. The largest inflows are the Walla Walla and Touchet Rivers. Other streams such as Birch Creek and Stone Creek are small streams

that run dry annually. All streams in the model are subject to wide fluctuations in flow volume, as is typical of arid areas. Figure 7 illustrates the layout of streams within the model boundary and highlights the locations of surface water inflows.

The Walla Walla River, the Touchet River, and Mill Creek are gauged close to the points where they enter the model area, providing direct input data.

There are 8 other streams flowing into the model area. These streams are currently being gauged with pressure transducers to record stage. This information is then correlated to discharge using a rating curve. Rating curves were developed from field measurements as described earlier in this document. The resulting values are then used to determine if flows in gauged streams correlate to streams that are currently un-gauged. Initial results from 6 weeks of data, collected in May and June of 2010 show strong correlations for all but one stream (Figure 8). This correlation has been used to estimate values for discharge in un-gauged streams as a function of flow in the Walla Walla River. The Touchet River also follows a similar pattern and could also be used as a basis for this estimation.

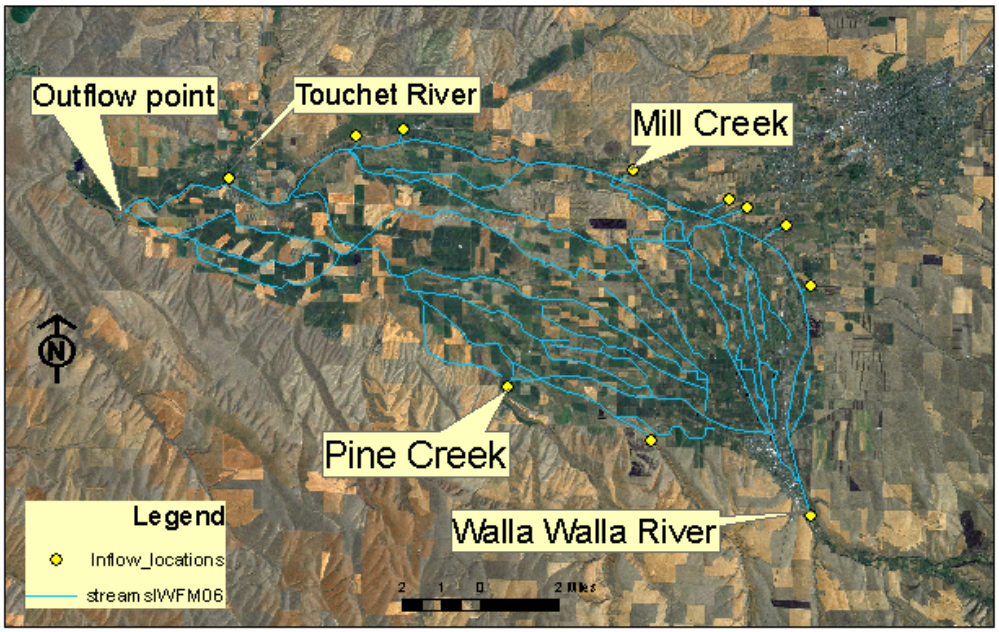


Figure 7. Locations of surface inflows in the model area. Major streams are labeled.

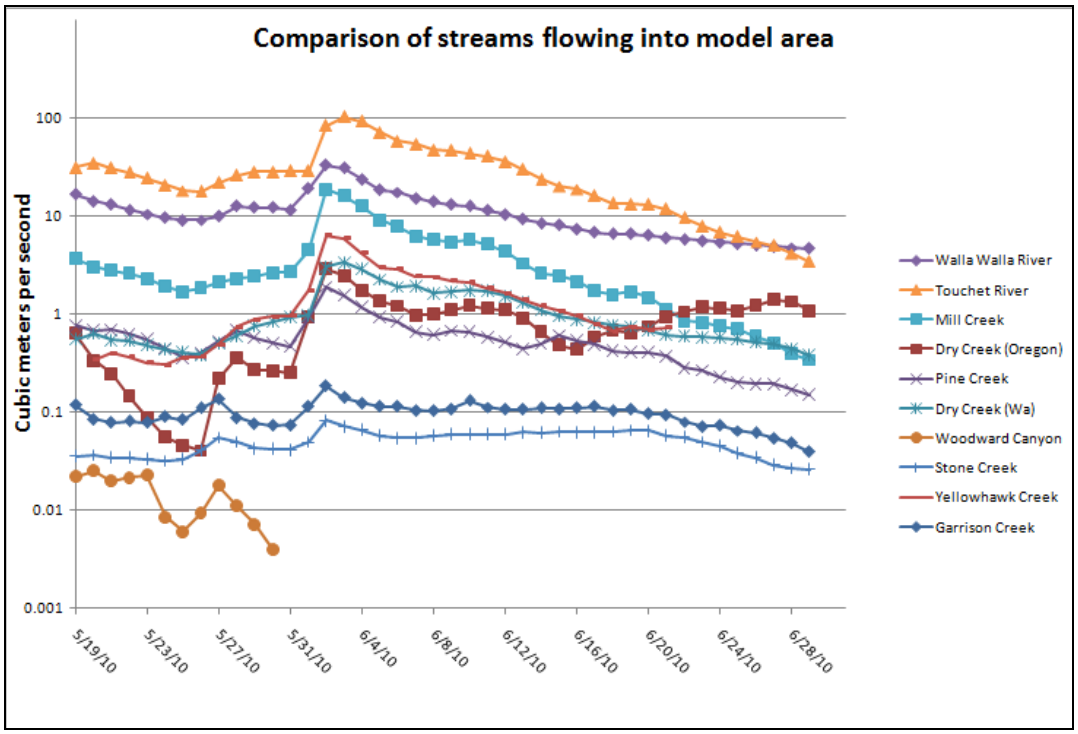


Figure 8. Discharge comparisons for inflowing streams in the model region over 6 week period. The Walla Walla and Touchet Rivers and Mill Creek are gauged while the other streams are calculated from stage data recorded by pressure transducers. Depth measurement is converted to discharge using stream rating curves. Birch Creek has been omitted because of mechanical difficulties with the transducer.

Quality estimates are particularly significant for larger inflowing streams such as Pine Creek, Yellowhawk Creek, and the two Dry Creeks. Currently there are sparse data records for these streams. Inflow volume is a determining factor in the output of this model, and therefore integral to the accuracy of simulations.

Initial results from the transducer data sets were encouraging based on the correlation between streams; however, there are several issues to be addressed with further data collection. Foremost was the determination that Dry Creek (Oregon) averaged nearly twice the discharge of Pine Creek. This is considered unlikely by WWBWC staff. Secondly, Woodward Canyon did not

follow the trend of the other streams. It in fact ran dry during the data collection period. This stream is hydraulically connected to Dry Creek (Washington) through irrigation return flows, and also drains a sub-basin to the North of the Walla Walla main stem. It may contribute significant flow over parts of the year. These questions will be addressed through additional flow measurements and continued monitoring with pressure transducers.

2.9 Canals

Canals collectively constitute a significant portion of the basins' surface water volume during irrigation seasons. They are also integrally tied to flow volume in the Walla Walla River. There are three irrigation districts within the model boundaries, operating cooperatively to supply water users and maintain the minimum instream flow requirement of 25 cfs for the Walla Walla River at the Nursery Bridge and 19 cfs at the Burlingame diversion.

The first primary diversion occurs at the head of the Little Walla Walla River, serving the HBDIC and the Walla Walla River Irrigation Districts. This canal operates from early March into January. Further downstream, the Burlingame canal serves the Gardena Farms Irrigation District which operates from March through June and from October through December. The canal systems encompass a complex distribution network of channels and pipelines designed to deliver water to farmland and deliver return flows, when present, to the main channel. These distributory channels are often referred to as laterals by irrigation managers.

An important consideration for irrigators in this region is leakage from permeable canal beds. Using stream bed permeability, defined by the user for each stream node IWFM calculates losses due to percolation. This directly effects canal operations and must be counted as part of the water budget, both in irrigation management and model validation. In contrast to the disadvantage of losing water through permeable stream beds, this leakage represents a source of groundwater replenishment (Barker and Mac Nish, 1976). Piped reaches in the canal system must also be considered because they are assumed to not leak.

The increasing movement from open channel canals to pipelines is a factor affecting both instream flow and water table elevations.

2.10 Springs

Springs are an observable connection between surface water and groundwater which are significant in the model area. There are 10 springs included in this model wherein the spring outflow is determined by the simulated groundwater level. The presence or absence of flow is an indicator of water table elevation around the spring. This is important as a validation point for model outputs, specifically, that observed spring flows reflect simulated ones.

Six springs are WWBWC monitoring points, therefore have associated data sets that are very useful. Springs near the Hudson Bay recharge site are of particular interest because they have shown a response to recharge operations. This has been particularly notable at the head of Johnson Creek, where previously dry springs have re-emerged after periods of aquifer recharge.

Calibration of the model with regard to springs can be challenging because it accounts for conditions at both the surface and the subsurface. The volume of simulated spring flow is a tunable parameter through stream bed conductivity and wetted perimeter, as well as the known groundwater head at monitoring points. The importance of accurate input data at spring locations has led to the collection of GPS points to accurate record the elevation of spring headwaters.

2.11 Artificial aquifer recharge

The Walla Walla Basin has been testing several engineered designs for artificial aquifer recharge. The purpose of the artificial recharge projects is to restore the depleted gravel aquifer in areas that will improve flow in springs and creeks. One of the main objectives of this hydrologic model is to test the effects of current and proposed projects. There are three current projects in operation.

Table 1 shows average recharge rates and the total volume of water recharge into the shallow aquifer over the last 3 years of operation.

1) Hudson Bay aquifer recharge project, managed by the HBDIC and the WWBWC, diverts water from the White Ditch irrigation canal into rectangular infiltration basins. The basins used in this project have been expanded three times in recent years. Initial analyses have shown that the infiltration rate does not increase linearly with an increase of infiltration area, but rather appears to scale more closely to the perimeter of the project, reflecting the impact of mounding of groundwater below the project (Rastogi 1998).

2) Locher Road aquifer recharge basin, managed by Gardena Farms Irrigation District, diverts water into an abandoned gravel pit with constructed circular basins. As with the Hudson Bay Aquifer recharge project, this project has expanded from its pilot scale, showing a non-linear relationship between recharge capacity and infiltration area.

3) Hall Wetland aquifer recharge. This project recharges the gravel aquifer by flood irrigating a 5 acre field pasture. This site there does not have constructed infiltrating basins.

Table 1. Current aquifer recharge projects

Project	Infiltrating Area ($X10^3$ m^2)	Average recharge rate ($X10^3$ m^3/day)	Total recharge volume ($X10^3$ m^3) 2007 to 2009
HBDIC	9.0	33.0	11,100
Locher road	6.0	17.5	300
Hall wetland	20.0	0.60	350

To represent the recharge processes we employ the IWFM model module designed to model lakes. Figure 9 shows the processes used for simulating lakes in IWFM, and the location of the three current aquifer recharge projects. A complete understanding of the effects of each of these projects in terms of aquifer recharge will require further work. To analyze these systems, consideration will be given to engineering design, basin geometry, and the effect of transferring from pilot scale to full scale projects. Scenarios from IWFM simulations will be coupled with 3D simulations of the vadose zone using Hydrus 3D modeling software. Further analysis of management and operations will also be incorporated by characterizing the groundwater mound beneath the projects and the clogging layers formed at the bottom of basins restricting the infiltrating rates.

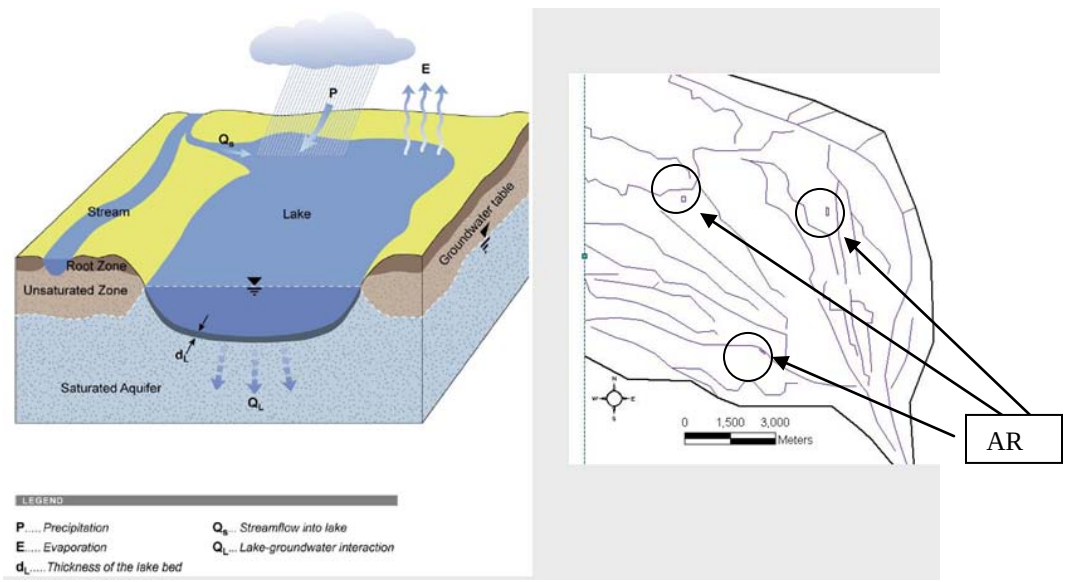


Figure 9. Artificial aquifer recharge sites are modeled as lakes in IWFM. This model includes three projects in Oregon; Hall Wetland, Locher Road and Hudson Bay

The IWFM Model, once calibrated and validated, can be used to test the effects of proposed aquifer recharge projects. The WWBWC-OSU team has begun the process of selecting suitable locations for further investigation. The procedures used for site selection include an analysis of groundwater flow vectors.

Determining groundwater direction and velocity enables calculations of the maximum amount of water appropriate for a site. A full description of this procedure and an analytical review of proposed aquifer recharge locations will be included as part of the results of this modeling effort.

2.12 Model boundaries and Initial conditions

The finite element approach used in IWFM, simulates the movement of groundwater from a set of initial conditions and boundary conditions Initial conditions are set for all nodes at the beginning time step while boundary nodes are set for the entire period of simulation. Values can be set at boundary nodes as either fluxes or groundwater elevations (Internal boundaries are not considered in IWFM) for each time step in the simulations. Initial conditions refer to groundwater elevations at every node in the model area at the first time step of the simulation period. IWFM will then map groundwater head (water table elevation) at every node for each time step. Computations are based on the boundary values and complexities of the basin including agricultural and municipal water demands and water redistribution within the model area.

A map of the potential groundwater head elevation over a given area is known as a water table map, which is typically plotted as contours, similar to a topographic map. Haitjema (2005) has shown that for unconfined aquifers that are highly permeable, the water table is considered “recharge controlled” and the top of the water table does not replicate the topography or land surface. In the model area, the Walla Walla gravel aquifer is a highly productive aquifer with hydraulic conductivities that vary from 15 to 70 m/day. The challenge here in mapping the water table within the gravel aquifer comes from complexities in the basin related to groundwater withdrawals, redistribution, and key land surface features controlling the shape of the water table (springs and creeks). A water table map for an unconfined aquifer is initially made by interpolating values of water levels from observation wells, then performing an analysis of key

hydrogeologic features in the basin, incorporating and modifying the interpolated values during the calibration process. Common methods of interpolation include splining, inverse distance weighting and ordinary kriging. Water table maps that are only based on the interpolation of water levels from observation wells and do not incorporate the key hydrogeologic features may underestimate the water table elevation by up to 40% Buchanan (2005).

The Walla Walla Basin Watershed Council maintains monitoring locations at a number of observation wells and pumping wells using automatic pressure transducers. The automatic pressure transducers record the water level in the wells daily and in some cases, hourly. The database of water elevation records includes 100 wells in Washington and Oregon. Personnel from the WWBWC collect data from all the pressure transducers every three months and perform a manual measurement with a water level electronic tape to confirm data accuracy. OSU, in conjunction with the WWBWC, performs quality assurance and quality control for the well database and water table maps.

The simulation period for this model is from January, 2007 through December of 2009. Monthly water tables have been created for this period to be used as Initial and boundary conditions. The physical water boundaries present in the area are the Horse Heaven Hills to the south and the Walla Walla River to the north and west. Figure 10 and 11 show the well network maintained by the WWBWC and the resulting water table map.

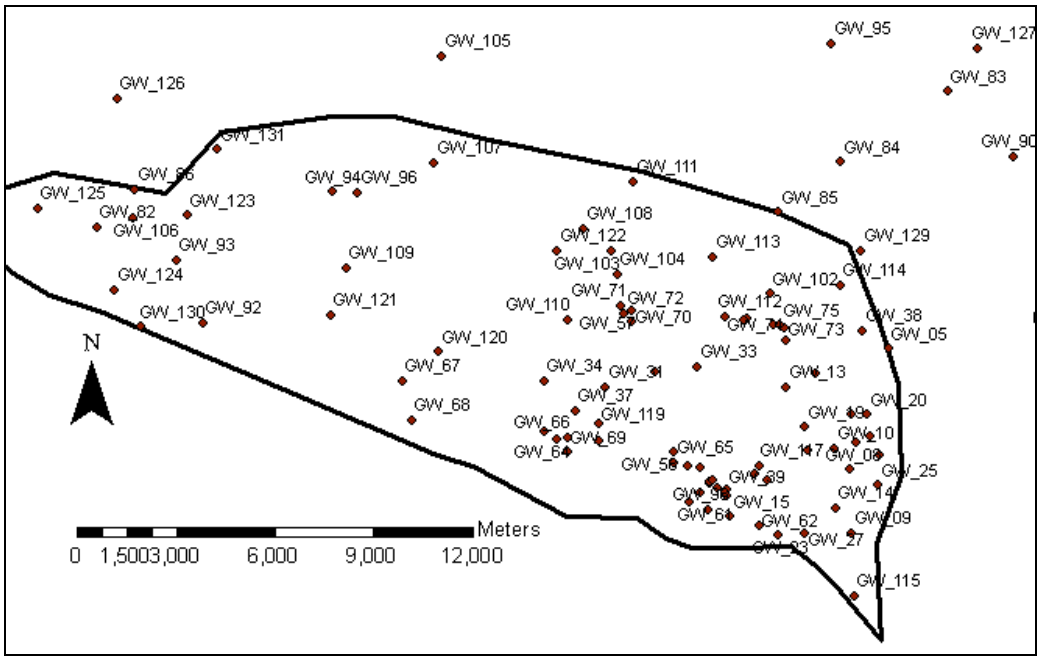


Figure 10. Well locations used for calculating water table elevations.

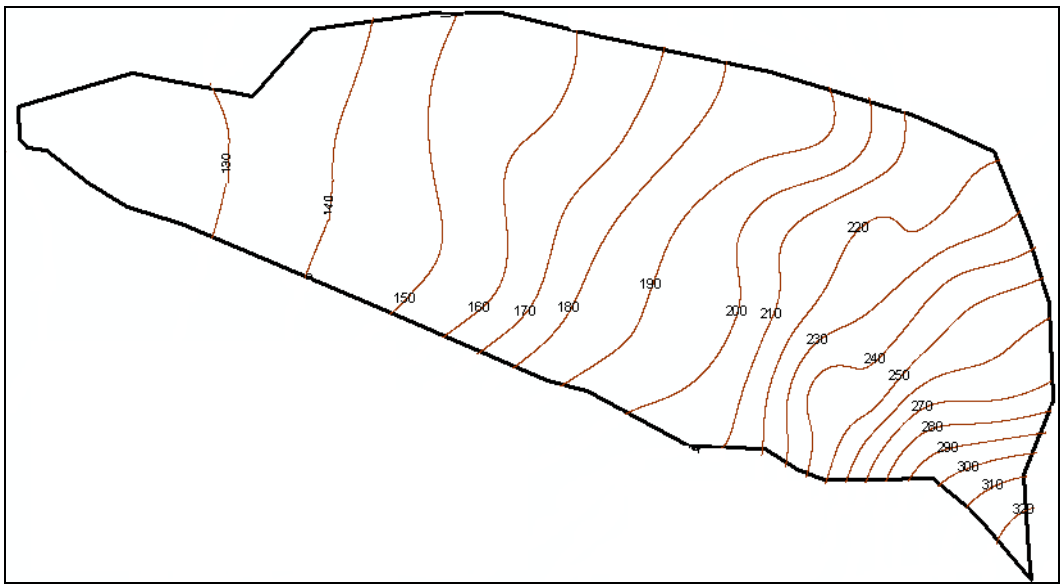


Figure 11. Water table map for the month of August 2009. (elevation in meters)

2.13 Land and Water uses

Land Use

Land use is a determining factor in water demand throughout the model area. This represents a particular strength of the IWFM model, because it uses a detailed set of user inputs to determine the volume and distribution of water demand. The model is also designed to draw water from varying sources, depending on user settings. This section will focus on water demand as determined by land use in IWFM. In addition, the adjustable factors in IWFM regarding water supply will be addressed during the calibration process.

Surveys conducted by the WWBWC in 2010 validated the land water uses included in this modeling effort. This work identified 14 agricultural land uses and 7 other types of land use (table 2).

Table 2. Land use classifications employed in basin model.

Crops	Other land uses
Alfalfa	City
Apples	Rural areas
Fallow ground	Industrial
Cherries	Riparian
Grapes	Urbanized (commercial)
Lawn	Water surfaces
Nursery	Bare soil
Peaches	
Native grasses	
Plums	
Pasture	
Row crops	
Irrigated wheat	
non-irrigated wheat	

The area coverage associated with each land use type is shown in Figure 12. For modeling purposes this map was processed in GIS by overlaying the model sub-region layer and using spatial analysis tools to determine the acreage for each land use within each sub-region. Elements are defined more coarsely. They are divided into four land use categories; agricultural, urban, riparian, and native. Each element is defined in terms of these categories by acreage or percent cover. Troy Baker of the WWBWC helped with identifying land use in the model by conducting field surveys to update previous data, and was also directly involved in the process of determining land usage by sub-region and element.

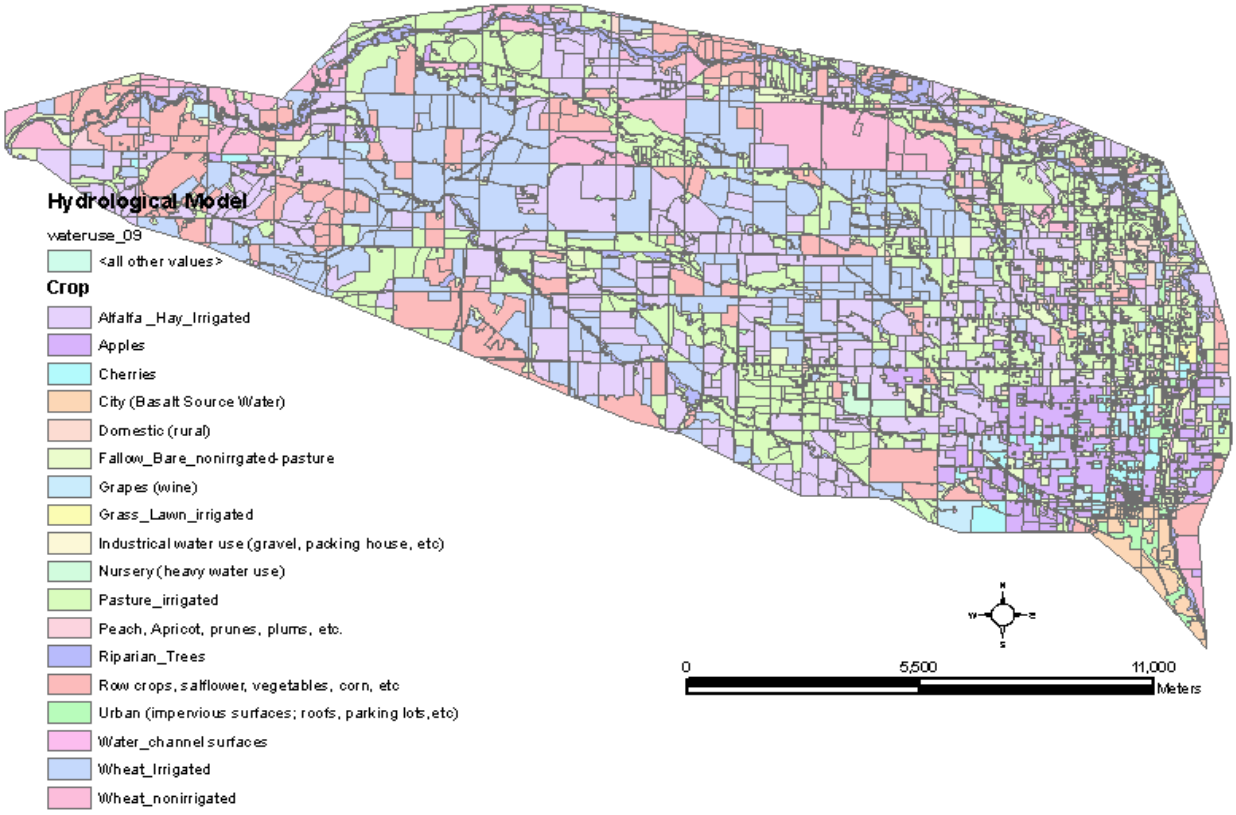


Figure 12. Land use distribution in model area.

Water allocation is determined by the proportion of diverted water specified for agricultural use. The remaining withdrawals are considered to be

for urban use. Agricultural and urban land uses add up to water demand. This is further refined by accounting for consumptive use and repeated use of water in both agricultural and urbanized areas.

Water use

Water use in the model is dependent on the available mechanisms of water distribution, namely surface water diversions and groundwater pumping. Re-use of return flow is also an available source of meeting crop demand. These are discussed in theoretical terms in a previous section. This section will provide an explanation of the way water is allocated in IWFM and the ways this can be adjusted by the model user.

Water demand is calculated by IWFM as a function of land use and crop types. The governing equation for this is:

Demand = CUAW / I.E.
CUAW = consumptive use of applied water
I.E. = irrigation efficiency

The IWFM user has the option of setting the prioritization of water sources to meet demand. One option is to withdraw surface water up to its available limit through the canal system and supplement the remaining demand with groundwater pumping. A second option is to do the reverse and use groundwater first, supplementing as required through surface water diversions. With either of these options, the user has an option of adjusting surface water or groundwater supplies independently to meet agricultural needs. This gives the model flexibility to self adjust under changing conditions, as may occur in reality. Options for supply adjustments can also be turned off.

2. 14 Evapotranspiration

Crops comprise the bulk of water demand in this model, with evapotranspiration (ET) being the primary consumptive water use. Each crop or other land use has a characteristic rate of ET. Some of these are available directly in the ET reference manual, FAO 56, while others must be estimated based on known parameters. ET varies among crops as well as between developmental stages. In addition to this some crops grow on an annual cycle (e.g., grapes) while others can be harvested and replanted several times a year (e.g., alfalfa, wheat).

Evapotranspiration (ET) is calculated in comparison to reference ET, which is a measurable parameter, based on known values for grass or alfalfa as determined with data recorded at weather stations. This is multiplied by a crop-coefficient, a parameter that varies with crop type, stage, and season. The result is an estimate for ET for each sub-region resulting from each crop type. IWFM also accounts for soil moisture in its ET calculations, which holds a strong influence on crop demand, and therefore total water demand and consumption. Crops have variable soil moisture requirements in comparison to field capacity. When a minimum threshold is reached, water stress coefficients are required to adjust ET under such conditions. Crop efficiency is also a user input parameter that refers to the percentage of applied water that is directly used by the crop, as opposed to the portion that evaporates, percolates, or becomes runoff. Crop efficiency was determined by a 2004 Army Corps of Engineers study in the Walla Walla District (HDR Engineering, 2004). This factor reflects the efficiency of different irrigation systems, as well as crop type.

Currently, ET data used is from the College Place Ag-Weather Net station. Future work will include incorporating available data from seven additional stations (Agrimet, WWBWC) to increase the resolution of the crop demand calculations in the model. IWFM incorporates a water stress coefficient factor to modify ET calculations when modeled soil moisture drops below a minimum

value. This value is a characteristic of each crop, and a parameter that can be used for tuning the model.

2. 15 Soil

The soil parameters used in IWFM are hydraulic conductivity, a measure of permeability, field capacity, a measure of the capacity of soil to retain water, and curve number, a measure of runoff potential. These values are considered characteristics of different soil types, and vary with antecedent conditions. Soil data was collected using NRCS web soil surveys or each sub-region. Analysis was based on soil types that covered 4.5% or more of the model area. Weighted averages were taken to determine parameters such as hydraulic conductivity, curve number, and field capacity for each sub-region. The results, shown in Table 3, illustrate the variability of dominant soil types in the model area. Sub-regions 1-3 are located in regions overlaid by sand and gravel material, and have correspondingly high hydraulic conductivities, while regions 5-7 are located in the Touchet Bed areas, typified by silt and clay soils with low hydraulic conductivities. Region 4 is intermediate, but closer to the conductivities found in the Touchet Beds. Field capacity has the inverse trend, with less permeable soils having a greater capacity to hold water. Curve numbers are assigned based on dominant soil types and land use classification.

Table 3. Soil properties determined by analysis of NRCS reports for input into the model.

Soil Parameters				Curve numbers			
Sub-region	**Hydraulic conductivity (M/day)**	**Field Capacity (volume water / unit volume soil)**	**Porosity**	**Agricultural**	**Urban**	**Native Vegetation**	**Riparian Vegetation**
1	17.48	0.054	0.43	75	83	61	55
2	14.24	0.092	0.45	70	85	69	66
3	12.73	0.087	0.45	81	83	77	66
4	1.84	0.232	0.46	88	85	84	77
5	0.62	0.225	0.48	82	82	84	77
6	0.53	0.222	0.47	82	82	84	77
7	0.56	0.177	0.49	82	82	84	77

2.16 Hydrogeologic layers

The gravel aquifer of the Walla Walla Basin is the primary target for representation in this model. The aquifer may be considered to be composed primarily of three geological layers. 1) Touchet Beds (Pleistocene loess, felsic silt and felsic to basaltic fine to medium sand); 2) Young alluvial gravel (Holocene to Pliocene sand and gravel not well constrained); 3) Old gravel (Miocene to Pliocene conglomerate sand, silt and clay).

A complete description of the geologic layers incorporated into the model has been made by Lindsey (2004). This data is primarily based on well logs across the model area and subsequent interpolation. Interpolations of these well logs have been provided by the WWBWC in GIS layer files (Figure 13). The thickness of each layer is then incorporated into the IWFM model as the stratigraphy for each node. Parameters of each aquifer layer include vertical and horizontal hydraulic conductivities, specific storage, and specific yield. Characteristics of the interbeds and aquitards are also considered in the model.

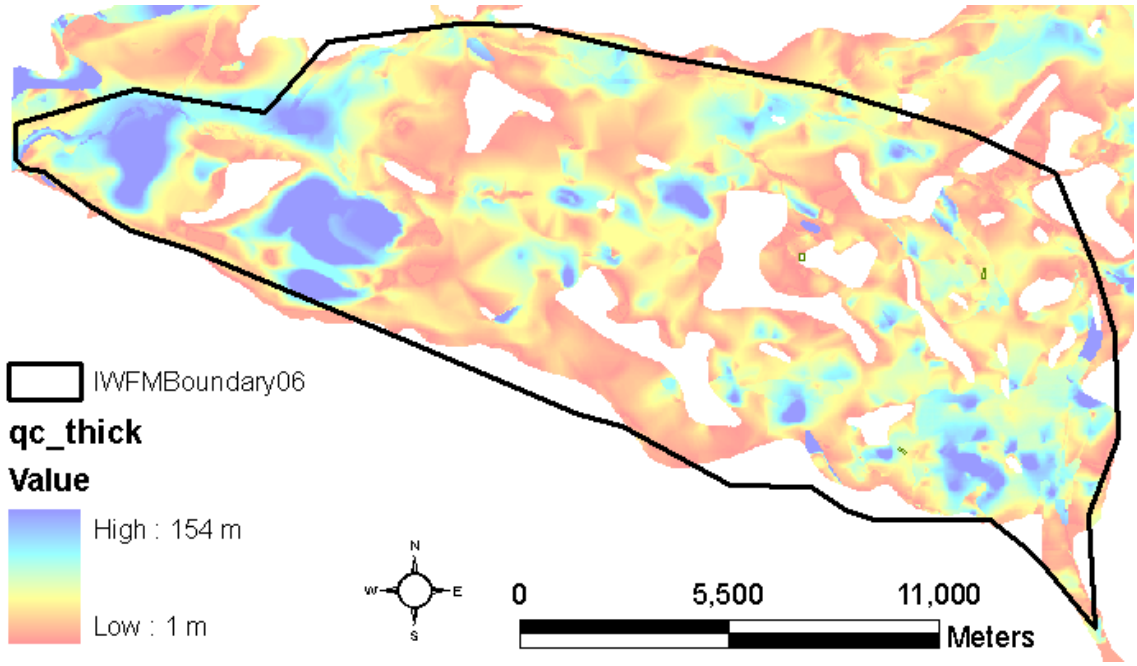


Figure 12. GIS layer representing the thickness of the Quaternary un-cemented gravel aquifer

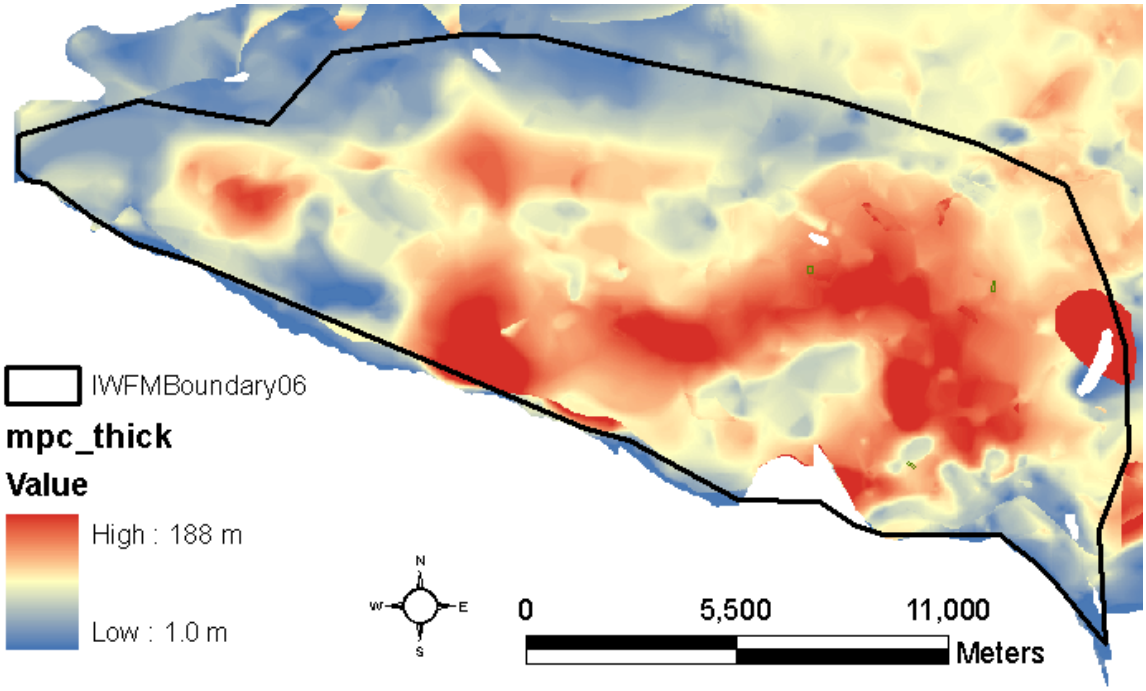


Figure 13. GIS layer representing the thickness of the Mio-pliocene gravel aquifer.

2.17 Basalt layer

The basalt aquifer found in the Walla Walla basin is part of the Columbia River Basalt formation, underlying a large portion of the Columbia Valley, including the entire model area. In this modeling effort the Columbia basalt aquifer is only incorporated as a source of water to satisfy the urban and agricultural demands. The model does not simulate movement of water in this aquifer or a direct hydraulic connection to the gravel aquifer. The model simulates a secondary water connection between both aquifers through return flows, and excess applied water sourced from basalt pumping wells as required for urban and agricultural demands. This is to say that if pumping data suggests that groundwater exploitation exceeds that which could have been supplied by the sedimentary aquifers, it is assumed that the wells have been drilled into the basalt unit. The source of this water is taken as being outside the model boundaries, in keeping with the generally accepted conceptual model of these units being recharged in the surrounding hills and mountains (Newcomb 1965).

Though the current modeling effort provides a reasonable estimate of the utilization of the sedimentary aquifer unit, further precision in the description of the basalt unit would be desirable. The WWBWC has surveyed the well logs for the basalt pumping wells in the model area. In the future the watershed council expects to estimate the timing and amount of pumping that occurs from the basalt aquifer in each of the model sub-regions. The IWFM model will then incorporate this water as an out of boundary surface water inflow, available to satisfy water demand. Excess applied water and irrigation returns flows, as determined by element in the IWFM simulation, will recharge the gravel aquifer or contribute to stream flows.

III Calibration and Validation

The calibration step consists of systematically adjusting the input data within physically realistic ranges until computed values match the field observations. The validation step consists of the statistical procedures used to demonstrate the model's ability to simulate historical hydrologic events which were not included in the validation process. Thus, we divided the data into two sets, 2007 - 2008 for model calibration, and 2009 for model validation. The calibration of the model has to be performed separately for surface water and groundwater. The calibration for groundwater can be made by matching observation wells to simulated groundwater elevations. For surface water, flows in the rivers, canals and springs have to match field surface gauges. The parameters shown in Table 4 are going to be modified during calibration. Final values will be presented as part of model results. Reader can refer to these calibrated values for further hydrological analysis.

Table 4. Geologic parameters to be varied during calibration.

Variable	**Definition**
CN	curve number runoff
%Rf	Fraction of applied water that becomes retuned flow urban settings.
Dr	rooting depth of the crops, (L);
θr	soil moisture content of the root zone, (dimensionless);
θf	field capacity of the root zone, (dimensionless);
θt	simulation time step
AWag	agricultural applied water, (L/T);
ET0	grass or alfalfa evapotranspiration, (L/T);
Kc	Crop coefficient
fDp	deep percolation fraction between 0 and 1; 0 means entire soil moisture above field capacity becomes return flow and 1 means entire soil moisture above field capacity becomes deep percolation.

Dr	Thickness of root zone.
Ssi	inelastic specific storage
Sse	elastic specific storage
bo	initial thickness of the interbed
Clki	conductance of the lake bed material
Clki	conductance of the river bed material
Csi	Stream conductance determine by (Ksi/dsi) * LiWi
Ksi	Hydraulic conductivity of the stream bed material
Dsi	thickness of the stream bed
Li	length of the stream segment
Wi	wetted perimeter
Clki	Lake conductance determine by (Klki/dlki) Alki
Klki	hydraulic conductivity of the lake bed material
Dlki	thickness of the lake bed material (recharge project)
Alki	Area of the lake (recharge project)
Rt	Rating tables for springs, rivers and canals

The validation and calibration of the model will employ the mean square error (ME) and mean absolute values of error (MAE) as the statistical tools to evaluate the modified hydrological parameters. ME and MAE are describe by D. Wackerly (2002) as:

$ME = (X_{obs} - X_{sim})^2$ and $MAE = \left| X_{obs} - X_{sim} \right|$

Where Xobs = observed elevation of groundwater at a specific node or well and Xsim = simulation results for groundwater elevation per node.

The relative root mean square error and the coefficient of efficiency Eff by Nash and Sutcliffe (1970) are determined as:

$$RRMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \hat{x})^2}{n-1}} \qquad Eff = \frac{\sum_{t=1}^{n}\left(x_i - \bar{x}\right)^2 - \sum_{t=1}^{n}(\hat{x} - x_i)^2}{\sum_{t=1}^{n}\left(x_i - \bar{x}\right)^2}$$

Where

x_i= measured value

$\hat{x}$ = estimated value

$\bar{x}$ =mean value of x_i

n=number of observations

and the correlation coefficient R can be estimated as

$$R = \sqrt{Eff}$$

The coefficient R represents the fraction of the variation in the observed values explained by the simulation model and the coefficient Eff represents the percentage to fit a linear relation to the observed values. In other words it represents how well our model fits the observed values. The correlation coefficient can vary between -1 to 1 showing perfect inverse and perfect direct relationships between measured and modeled values.

Surface water in the model area is divided into segments, referring to lengths of streams or canals. This can enable calibration of the model by tuning segments independently. A helpful method of doing this tuning is by estimating flow at the upstream and downstream end of each segment. In this process, inflows and outflows are balanced, and an expected flow value is determined for each point. These values can be compared to gauge reading at the given time, and tuning can proceed by varying parameters described earlier in this section. Figure 14 shows gauged flows in April of 2009 along with the end point locations of each segment.

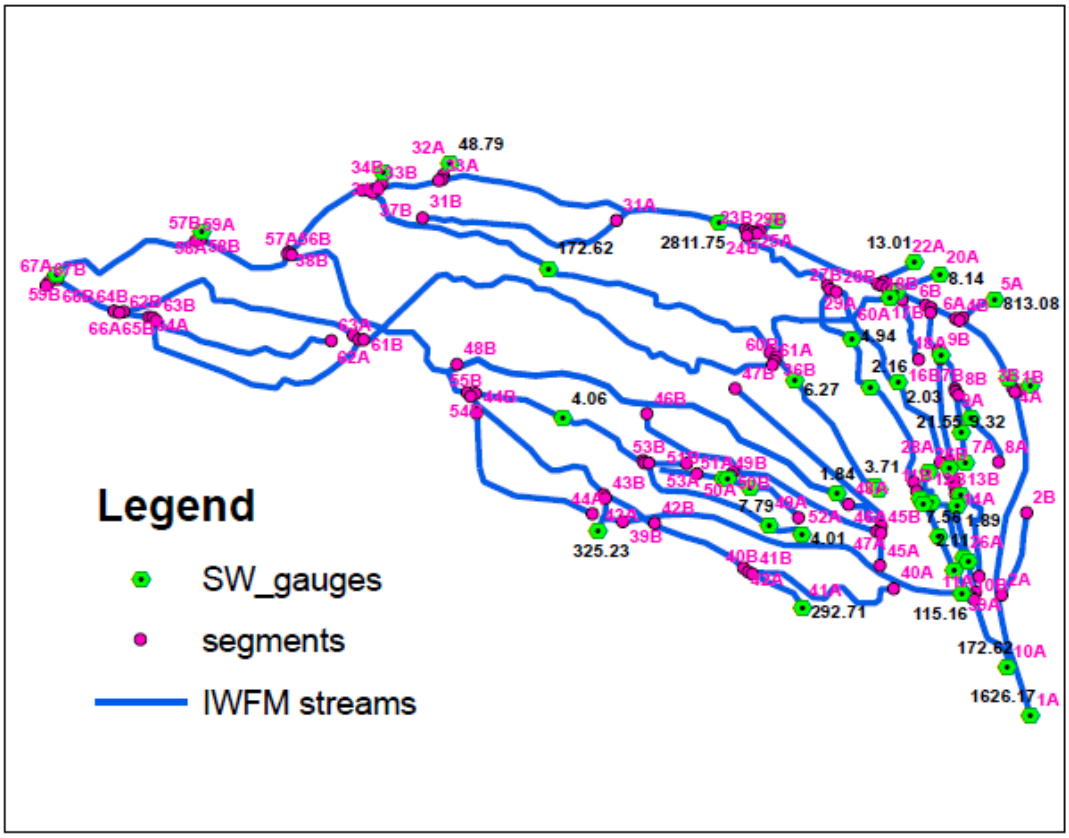


Figure 14. Segment locations and gauge records in model area. Segments are numbered; “A” indicates upstream end of segment and “B” indicates downstream end of segment. Surface water gauges are displaying flow records for April, 2009 where available, in m³/day * 1000.

IV Results and model scenarios

Once the model has been calibrated and validated, model outputs can be analyzed from several scenarios. Model outputs from IWFM include the groundwater head elevation at every node, the flow rate at streams nodes and budget analysis for surface, groundwater, soils and water demands. One of the strong components of IWFM is the water budgets outputs, which are useful for water management decisions. Groundwater head elevations and stream flow rates are use for testing the effects of the proposed scenarios.

4.1 Water Budgets

A water budget organizes the water resources of each models' sub regions such that all the inputs and changes in storage equal the outputs. The water budgets are divided for surface water, groundwater, soils, and water demand. Depending on the budget being generated the following variables are summarized:

Table 5. Variables in time for IWFM water budget analysis.

IWFM Variable	Brief Explanation
GW STORAGE_IN (_OUT)	Ground water Storage L^3
STREAMS_IN (_OUT)	Flow rate for each stream segment L^3/T
NET DEEP PERCOLATION_IN (_OUT)	Natural Recharged water into the gravel aquifer L^3
SPECIFIED HEAD BC_IN (_OUT)	Groundwater from boundaries
LAKES_IN (_OUT)	Artificial Recharge water into the gravel aquifer L^3
PUMPING BY ELEMENT_IN (_OUT)	Pumping estimate for the entire model L^3

VERTICAL FLOWS_IN (_OUT)	Flows between aquifer L^3/T
FLOW FROM ZONE XXX_IN (_OUT)	Flows between sub regions L^3/T
xx. DISCREPANCY(IN-OUT)	Percentage of discrepancy within each budget.

Examples of the water budgets can be reviewed from the previous hydrologic model for the Oregon side of the model area. One example is source of water used for agricultural purposes. Figure 14 shows that half the water in the Oregon side comes from surface water diversions and that almost half of the pumped water comes from the gravel aquifer. These results are expected to change drastically as the model area expands to Washington and more irrigation districts are involved. It is estimated that in the Washington area most of the water used for irrigation comes from the surface water diversions.

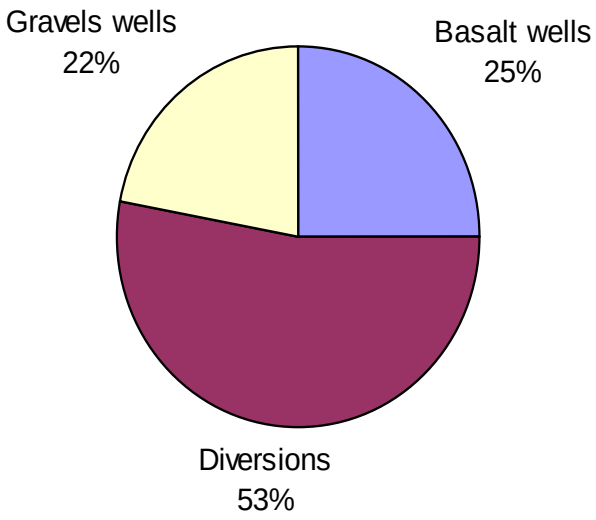


Figure 15. Water sources for agricultural purposes. Results are from the 2008 model simulating the Oregon side of the model area

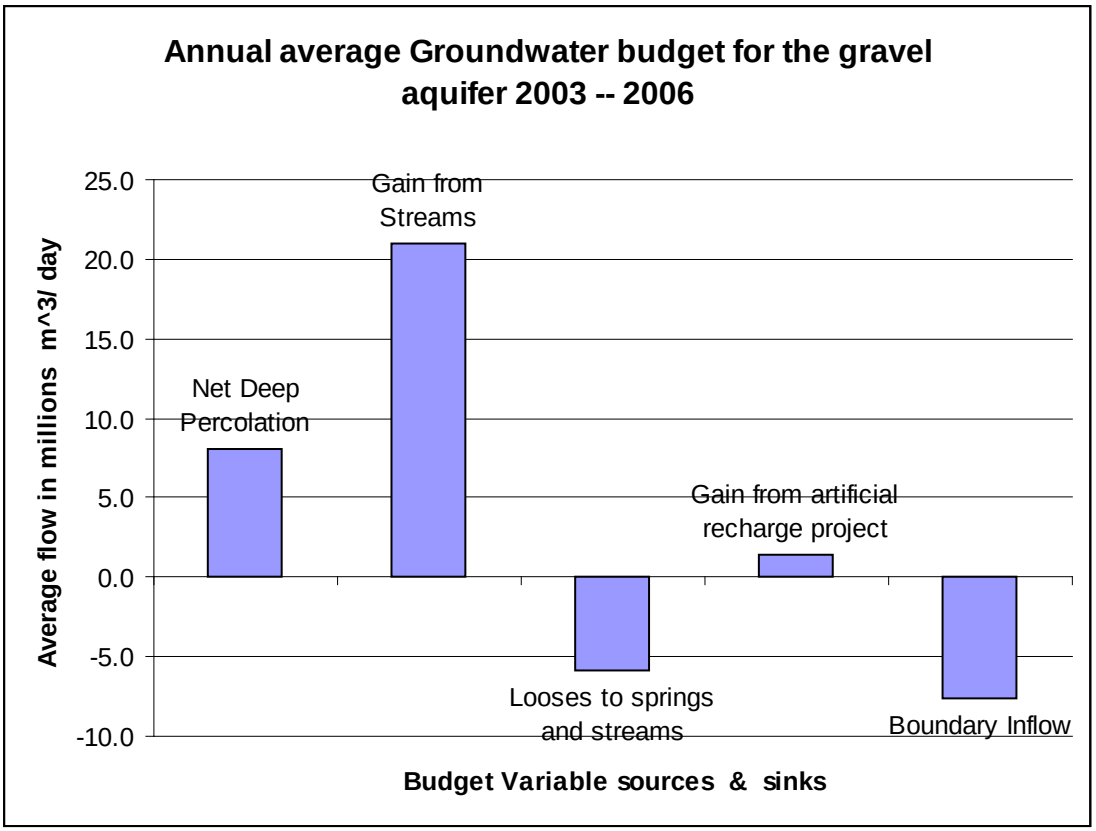


Figure 16. Simplification of the groundwater budget for the Oregon side of the model area. Previous results from 2008 model.

4.2 Simulated Scenarios

The objective of this modeling effort is to first summarize the water resources in the area accounting for the complexity generated by the land and water uses. These include pumping, losses of irrigation canals, aquifer recharge etc. Water budget analysis summarizes the total amounts of flow per sub-region. Once the model has been calibrated and validated, specific scenarios can be tested. An example can be found from the previous 2008 model. Effects of the HBDIC recharge project were compared to scenarios of lining the White Ditch irrigation canal as well as in the scenario of lining all the irrigation canals in the Oregon side of the basins. Results show that the majority of flow in the springs is generated by water lost through unlined irrigation canals recharging the gravel aquifer (figure 16). In this new modeling effort OSU, in conjunction with the

WWBWC, will test the effects of lining or piping specific irrigation canals and the effects of proposed projects for aquifer recharge.

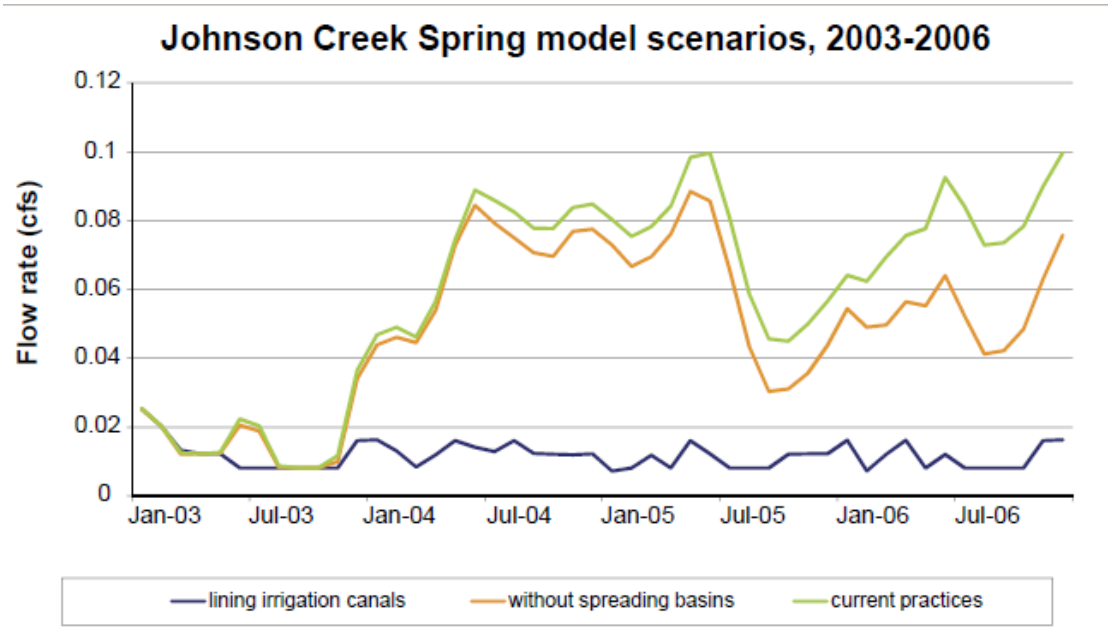


Figure 17. Model scenario for the Oregon portion of the model area. Results were analyzed during development of 2008 Model.

V Summary and Conclusions

Creating a hydrologic model for the Walla Walla Basin will have widespread benefits for the communities whose livelihood depends on reliable access to water resources in the region. Water allocation and distribution are vital to the agricultural sector and the regions' economy as a whole. Urban areas, industry, tourism, and wildlife are all also directly impacted by hydrologic conditions. As the area faces increasing difficulty of meeting all demands, efficient management of water resources will become increasingly crucial. Many solutions have been proposed to address issues with water distribution. Model simulations are a valuable method of analyzing potential advantages or difficulties to various solutions without large investments of time and resources allowing the opportunity to compare possible scenarios.

The WWBWC has been engaged in monitoring programs since 1999. Over this time period the WWBWC has gathered a large volume of background data and local knowledge. This data has proven to be a rich resource for this modeling effort. Simultaneously, model development helps organize and perform a quality assurance and quality control for these data. The model is a beneficial use of this collective body of data. Records from groundwater and surface water monitoring have provided data directly and informed interpolations necessary to complete model inputs. It has also highlighted areas where there are data gaps and additional monitoring and research could benefit the objectives of the WWBWC. Certain parameters, such as vertical leakage out of the gravel aquifer, and aquifer effective porosity, which determines volume, can at this stage be only estimated through modeling efforts.

To this point, the collaborative work of WWBWC and the OSU research team have brought about an ongoing aquifer recharge program in the Walla Walla Basin. This project has grown to include several new recharge basins, and

others are being proposed. It has also produced important research data with well pumping tests and tracer studies for aquifer characterization, leading to the establishment of new monitoring locations for important surface water inflows and groundwater wells.

This modeling effort is an ongoing project. Results to this point are preliminary and the process of calibration and validation are currently underway. A specific approach for analysis and calibration of input information is detailed in this document.

Important management decisions lie ahead in the Walla Walla Basin. There are several existing proposals for future changes in regional water management. All scenarios have inherent strengths and weaknesses. There are numerous perspectives, but all have a unifying objective for management outcome. This is a balanced use of water resources that allows agriculture and wildlife to thrive, maintains a stable aquifer, and meets water quality standards. The ability to simulate proposed water management scenarios will provide a valuable predictive tool for people involved in the decision making process. Ideally, this will translate into the ability to develop a refined water budget in the Walla Walla Basin.

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Appendix 1 Summary of anticipated work for Walla Walla Basin modeling.

This is an outline of the work remaining to do for the IWFM modeling effort in the Walla Walla basin. Many of the specific items addressed are difficult to gauge in terms of the time required and unforeseen difficulties are to be expected. The objective is to develop a validated model through a collaborative effort, while learning the specific characteristics of the gravel aquifer. This work will facilitate a nuanced approach to modeling a variety of water management scenarios. The specific scenarios will be addressed with input from WWBWC. This will form the basis for Jake Scherberg's Masters Thesis work and part of Ari Petrides' Ph.D. thesis. An additional objective is to work with interested parties at WWBWC in operating the IWFM software. This will enhance the models' value and utility, and should be a useful tool. The following information is an overview of the items for which further review is likely to benefit the overall goals of this modeling project and a summary remaining work to be done.

Field Work

- Single point discharge measurements will be taken in selected locations in the Hudson Bay and Gardena irrigation districts. These will be applied to rating tables in the model area. Additional measurements will be taken to compare expected streamflows based on Manning equation calculations to observed flows at gauging sites. A calibration adjustment for the roughness coefficient is expected due to seasonally variable conditions. One possible method of addressing this is to use a sin function to create a seasonally variable roughness coefficient.

- Further interviews with irrigation managers, and other knowledgeable parties. The aim of this is to improve understanding of operational timing, irrigation distribution, and the location of piped reaches.

Data Analysis

- Stage data collected with pressure transducers at 7 locations will be translated to discharge volumes using rating tables. This data will be analyzed to determine the relationship between gauged inflow locations and ungauged ones. Relationships established using this data will be used to estimate historic inflow in the validation data set. Additionally, transducer data will also be used to inform input data for future modeling applications.

- Modeling of Diversions will be an important tuning parameter in the model. It is through this network that water is distributed for land application. The amount of available water, demand on an area basis, timing, and local physical characteristics of an element influence on the water balance on a localized scale. Accurate modeling of this aspect has the potential to improve the models resolution and flexibility.

- It may be necessary to add an inflow point at Woodward Canyon pending review of transducer data. Alternatively this stream may be combined for modeling purposes with Dry Creek, a possible water source via diversion.

- Interpolation of precipitation and ET values using GIS Kriging tools. At present data sets for 7 stations have been collected from Agrimet and AgWeathernet. Stations maintained by WWBWC will also be incorporated once a full time series data set is acquired for 2007-2010, and reference ET data is included (it is missing from present data sheets).

- The urban demand water demand data set would benefit from further research. Field based and literature research will be used to improve data inputs in this area.

- Basalt pumping data. Location and Flow rate expected to satisfy the land and water use demand per subregion.

Model Calibration

A tuning of modeled parameters such that expected simulation outputs reflect observed data. This work will include a sensitivity analysis. Adjustable parameters include stream bed permeability, diversion locations, diversion volumes, values used for soil characterization, land use distribution, and crop water demands.

Model Validation

Model validation will be performed through a demonstration of the models ability to simulate flow volumes and distribution in the model area using the data set from 2007-2010. A water balance based on collected inflows and outflow will be a key parameter for determining the accuracy of model outputs.

Analysis of observed versus expected water table elevations and surface flows will be used to estimate the models margin of error.

Model Scenarios

A number of management scenarios can be modeled. These include existing and proposed aquifer recharge sites, conversion of canals to pipelines for water distribution, a variety of crop distributions, a new reservoir, and varying climatic conditions.