AN ABSTRACT OF THE THESIS OF

Jacob N. Scherberg for the degree of Master of Science in Water Resources Engineering presented on March 19, 2012.

Title: The Development of a Hydrological Model of the Walla Walla Basin Using Integrated Water Flow Model

Abstract approved: ____________________________________________________________

John S. Selker

Abstract

The Walla Walla basin lies in an arid region of Eastern Washington and Oregon. A large portion of the area is devoted to agricultural production, relying on irrigation water diverted from the Walla Walla River and underlying aquifers occurring within Quaternary and Mio-pliocene era gravel deposits, as well as a supplemental source from the Columbia River Basalt formation. Heavy water demand over summer months has resulted in a fully allocated surface water supply and significant drawdown in groundwater levels. The Walla Walla River also hosts two salmonid species listed as threatened under the endangered species act and entitled to federal protection. Specific questions have emerged regarding regional water supply as stakeholders work towards management strategies that meet water user demands, well also addressing concerns such as groundwater depletion and fish habitat. Currently, there are proposals aimed at increasing water use efficiency such as the lining of permeable canal beds and the expansion of a shallow aquifer recharge program. Effective implementation of such strategies, in part, relies on understanding the interactions between surface water and groundwater within this region.

This project used the distributed hydrologic model, Integrated Water Flow Model (IWFM), for simulating surface and subsurface flows over a portion of the Walla Walla River basin spanning from Milton Freewater, Oregon to west of Touchet, Washington. This
application of IWFM uses a grid with an average spacing of 100 x 100 meters over the 230 square kilometer model area. The model was developed and calibrated using data from 2007 through 2009, with 2010 data to be used as a data set for validation. Data collection has been a collaborative effort between a research team from Oregon State University and the Walla Walla Basin Watershed Council (WWBWC).

This thesis provides explanation and documentation of model development. This includes details of data collection and processing for groundwater and surface water conditions, estimation of initial and boundary conditions, parameter calibration, model validation, and error analysis. Data sources include federal and state agencies, a gauge network managed by the WWBWC, and geologic research primarily performed by Kevin Lindsey of GSI Water Solutions with support of the WWBWC. Parameters have been independently determined from field measurements whenever possible. Otherwise they were estimated using established methods of hydrologic analysis, values drawn from previous regional studies, or the process of model calibration. Outputs include detailed hydrological budgets and hydrographs for groundwater and surface water gauges. The calibrated model has an overall correlation coefficient of 0.59 for groundwater and 0.63 for surface water. The standard deviation for groundwater is 3.2 meters at 62 well locations and surface water has a mean relative error of 22.3 percent at 34 gauges. This model intended as a tool for formulating water budgets for the basin under present conditions and making predictions of systemic responses to hypothetical water management scenarios. Scenarios of increased inputs into the Locher Road aquifer recharge site and conversion of irrigation district canals into pipelines are presented.
The Development of a Hydrological Model of the Walla Walla Basin
Using Integrated Water Flow Model

By
Jacob N. Scherberg

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Jacob N. Scherberg, Author
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1 Introduction

1.1 Project Description and background

The following thesis report details the development of a hydrological model for a subsection of the Walla Walla basin in Eastern Oregon and Washington using Integrated Water Flow Model (IWFM) software. The development of this model required extensive data collection and analysis, as well as processing and formatting for this particular application. The project has been a collaborative effort between The Walla Walla Basin Watershed Council (WWBWC) and a team from the department of Biological and Ecological Engineering led by John Selker at Oregon State University culminating from over a decade of collaborative effort.

This thesis is intended to document the outcome of the current basin-scale modeling effort as well as identify areas where data is sparse or uncertain. In cases where direct measurements are unavailable, the methods used for interpolation and estimation of basin characteristics are detailed in this report. Data analysis will be discussed with attention to model outputs compared to recorded data, with particular attention to the distribution and magnitude of error, and its likely sources. It is my hope that detailed documentation of model inputs and the development process will enable future refinement by interested parties.

The Walla Walla Basin covers over 4,600 square kilometers (1800 square miles) of Umatilla County in Eastern Oregon and Walla Walla County in Eastern Washington, draining into the Columbia River (figure 1.1). The model area covers roughly 230 square kilometers (90 square miles), with the primary surface water inflow being the Walla Walla River.
Figure 1.1: Map of Walla Walla Watershed and model area.

The Touchet River, Mill Creek, and Pine Creek from the south are the largest tributaries to the model. 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 (figure 1.2). The model area must also be considered three dimensional; therefore groundwater also constitutes a major inflow and outflow, as well as a vital resource. Ground water is primarily from the North and East toward the West. To the south, the Horse Heaven anticline is a hydrologic boundary (Lindsey, 2007).
Figure 1.2: Detail of model area, highlighting diversion point for irrigation districts and aquifer recharge sites.

This area is primarily agricultural, but includes the towns of Milton Freewater, Oregon and Touchet, Washington. The city of Walla Walla, Washington lies outside of the model boundary to the north, but still influences the hydrologic conditions within the model area. Alfalfa (33%), wheat (25%), pastures (19%), fruit orchards (6%), and vineyards (1%) are the primary crops in the model area, accounting for the majority of the land use.

Agricultural water demand in this region historically led to annual complete dewatering of the Walla Walla River during the summer months from 1900 to 1999 during natural low flow
period that occurs as crop demand is highest. Groundwater, pumped from several underlying aquifers, has been a used as an additional source of water in areas where surface water supplies are not available, and throughout the basin when surface water was insufficient to fully satisfy evaporative demand. The cumulative effect of this practice has led to a gradual decline in the water table documented by well records dating back to the 1940’s demonstrated in figure 1.3.

![Monitoring Well 18](image)

**Figure 1.3:** A record of water level measurements from a well in the model area documenting the decline in water table elevation over the last 60 years. Data source: Walla Walla Basin Watershed Council.

In 1998 the Walla Walla run of Bull Trout (*salvelinus confluens*) was listed as a threatened species under the endangered species act (ESA). The following year, the native Steelhead (*oncorhynchus mykiss*) run was also listed (WDFW, 2005). This led to an agreement between the local irrigation districts and the Washington Department of Fish and Wildlife in which minimum flow rates of 0.71 M³ per second (25 cfs) are to remain in the river at the Little Walla Walla diversion and 0.51 M³ per second (18 cfs) are to remain at the Gardena Farms diversion at Beet road, ensuring connectivity between the Columbia river and the upstream spawning habitat in the South Fork Walla Walla River. The threatened fisheries have shown signs of recovery since the implementation of this agreement, largely associated with the
planting of spawning adults in the South Fork Walla Walla River. The ratio of smolts to returning adults to has not reached the goal of 0.55%, though has shown consistent improvement since habitat restoration efforts were implemented in 2004. It is believed that downstream obstacles such as hydroelectric dams are taking a toll on the migrating fish (Mahoney et al., 2011).

A consequence of this agreement was an increased demand for groundwater to compensate for the limitation of surface water supplies. In addition, irrigation managers became increasingly concerned about significant losses due to leakage through permeable canal beds, causing inefficiency in water delivery of cultivated lands. Though reliable estimates are difficult to obtain, it is established through gauge data that at least 20 percent of the Little Walla Walla Canal is lost to seepage during peak irrigation season. This has provided incentive for the irrigation districts to embark on projects to convert canals into pipelines in order to prevent or minimize leakage. A complicating factor with this is that the leakage from canal beds is also a source of groundwater recharge. Eliminating this source of groundwater recharge has been projected to contribute to the declining groundwater levels (Petrides and Scherberg, 2010).

With these competing factors for water resource management in the Walla Walla Basin, there have been several proposed solutions. One of these is the construction of a reservoir, with several proposed sites presented in the U.S. Army Corps of Engineers’ Walla Walla River Watershed Study Reconnaissance Report (USACE, 1997). This option may be technically feasible, but also has significant direct and indirect environmental impacts, and great construction expenses that make other options worth consideration. One of these is shallow aquifer recharge (SAR), which entails diverting water into an infiltration basin where it is allowed to percolate to the water table, recharging groundwater. Several sites have been selected for demonstration projects (figure 1.2), with one particular site, operated by the Hudson Bay Development and Improvement Company (HBDIC) in cooperation with the WWBWC, being used as a test location for several variations of recharge basin design. The other sites, known as the Locher road recharge site, and Hall-Wentland recharge site, use existing basins for SAR. Aquifer depletion is a global problem, making SAR an important area for research with potential applicability in many regions. Research questions center around how to maximize the impact of
SAR in replenishing groundwater supplies. These issues include optimized basin design, site location, aquifer suitability, site maintenance, and water quality concerns.

The hydrologic complexity of the Walla Walla basin, along with the interrelated requirements of surface and groundwater users and fisheries, underscores the importance of developing a complete understanding of water resources in this region to inform management decisions. This need has led to the development of the IWFM-based model for a selected area of the Walla Walla Basin. This model is designed as a tool for assessing the water resources and distribution systems within the study area. It can be used to predict responses in the hydrologic system that may come about due to changes in water management or natural conditions. It is intended to generate simulated 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, construction of a new reservoir, and changes in crop distribution. These goals require the development of a representative framework for the hydrological characteristics of the basin, and incorporation of data or estimations to account for fluxes the hydrologic cycle and water use within the basin (figure 1.4). The collection and processing of this data into model inputs, along with the application of scientific theory for devising reasonable estimates where data is not available, is central to this thesis.
Figure 1.4: Water fluxes accounted for in IWFM (IWFM Theoretical Manual 3.0, 2007).

This model, like all hydrologic models, is a simplification of reality. The multi-scale complexity of a natural system cannot be fully represented in computer simulation due to feasible limits of data collection and accuracy of that data, as well as the limitations inherent in imposing a mathematical structure on a natural system. Heterogeneity also causes significant divergence between model setup and actual conditions. A model must be developed using a selected data set to estimate parameters that yield the best fit between simulated outputs and recorded data in process referred to as calibration. The model is then validated by applying these parameters values to a separate set of data. The result is that a validated model will have a resolution within which predicted responses can be made. This resolution is determined by the error incorporated into the model through numerous factors and the degree to which the calibration process can balance the inconsistencies inherent in model development.

The specific goals for this modeling process can be summarized as:

1. Develop a reliable, well documented model that can be used to simulate hydrologic conditions in the Walla Walla Basin, including an assessment of its limitations.
1.2 Literature Review: Previous Hydrologic Studies of the Walla Walla Watershed

A limited water supply, particularly in the late summer and fall, coupled with an increasing agricultural water demand in the Walla Walla Basin has been recognized for nearly a century. The geologic and hydrogeological conditions of the Walla Walla Basin were first described in a comprehensive manner by R.C. Newcomb of Washington Division of Water Resources (1965). This report aimed to provide a framework for understanding hydrologic regime in the watershed as well as a historic perspective of agricultural development within the valley. Newcomb identified three aquifers; the new gravels (Quaternary unit), old gravels (Miopliocene unit), and an underlying basalt aquifer, part of the Columbia River Basalt formation. Irrigation development began in late-1800’s using spring fed sources and the shallow alluvial aquifer for irrigation supplies. As canal construction allowed irrigation of higher and dryer land, seasonal shortages became an issue, and the dewatering of the main stem Walla Walla River an annual occurrence. In spite of this farming was considered viable and essential for the local economy, and development continued along with water shortages. By 1950, groundwater extraction caused a local depression in the water table up to 10 meters (Newcomb, 1965).

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 were reliable.

Some hydrologic modeling parameters, associated with geologic conditions do not change over the timescales in question (e.g., aquifer thickness, porosity, and hydraulic conductivity). Other model parameters change with land use and irrigation methods. For example, 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 which were confirmed to be reasonable by Petrides (2008). 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. ASR involves pumping water into an aquifer for later withdrawal, whereas SAR is a passive technique allowing water to percolate from the surface by gravity. The USGS performed the first ASR 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 unidentified geologic feature was acting as an aquifer boundary (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 focus of this investigation is primarily north of the model area in question in this report. It contains valuable information because it addresses the connectivity between the basalt aquifer and the overlying gravel aquifers. This report produced estimated the feasibility of using the basalt aquifer for seasonal water storage (ASR) under several pumping scenarios, and predicted the impacts of these scenarios on well productivity from the basalt aquifer in the city of Walla Walla, Washington. Their investigation centered around recharging the basalt aquifer with several of the municipal
wells in Walla Walla for 210 days per year and then pumping from the aquifer for 155 days. This yielded a net benefit by increasing basalt water levels in both the basalt and overlying gravel aquifers throughout the year when compared to pumping without recharge, confirming that there is hydraulic connectivity between these units in the vicinity of Walla Walla (Golder and Associates, 2007).

The Washington Department of Ecology published a report assessing surface-water and ground-water interactions in the area of The Walla Walla River, Mill Creek, and the Touchet River (Marti, 2005). The general conclusion of this report was that the upper reaches of the watersheds in question are losing water while the lower reaches are gaining. This assessment concurs with the adjacent and overlapping regions in the WWBWC-OSU model, in which the upper portions of the model area lose surface water to ground water, while groundwater emerges in the Pine Creek channel and the lower portion of the main stem Walla Walla River. The gaining reaches identified by this model roughly correlate to reaches identified as gaining in WWBWC seepage runs and geologic assessment of the main stem river (Baker, 2010).

In 1995 the Washington Department of Ecology provided several important pieces of information in an assessment of the Walla Walla watershed (WDOE, 1995). This report 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 comprised 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 were 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).

The primary source of quantitative and qualitative geologic information used for this project comes from the report of Kevin Lindsey (2007) prepared for the WWBWC. This document includes physical descriptions of the Mio-pliocene (older) and Quaternary (newer) gravel aquifers as well as the overlying Quaternary Fine layer, often referred to as the Touchet beds, and the underlying Mio-pliocene Fine and Basal Coarse units. Spatial representations of
the extent and thickness of these geologic units, based on interpolations from well logs and associated with this report, are essential sources of direct data input for this model.

A previous version of the model, also using IWFM, was completed by the WWBWC-OSU team in 2008. This 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 HBDIC Irrigation District (Petrides, 2008).
2 Model Development

2.1 Model selection

There are numerous models available for simulating regional hydrology. These include MIKE-SHE of the Danish Hydraulic Institute, HEC-HMS of the U.S. Army Corps of Engineers, and MODFLOW, developed by the USGS, all established modeling packages. IWFM was designed by the California Bay-Delta Institute specifically for modeling large-scale agricultural regions such as the San Joaquin Valley in Central California. This region has many issues in common with the Walla Walla Basin, leading to several features making IWFM a particularly suitable model for this application.

1. The parameterization specifically intended 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 and water use efficiency.
3. Operational permutations such as time tracking vs. simulation mode, user settings for water supply sources, and the ability to create node groups; called parametric nodes, enable the user to incorporate spatial variability to selected parameters.
4. Operating speed compares favorably to several other options (MIKE-SHE, HEC-HMS).
5. The model authors have provided extensive support for this project.

Though this investigation is focused on a single modeling effort using IWFM, simulated outputs 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

IWFM has been designed as a tool for planners and managers of groundwater and surface water resources and is available on the California Department of Water Resources Bay-Delta Office website (http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/). It is a physically based finite difference model using the FORTRAN programming language. The model incorporates numerous parameters representing the physical characteristics of a watershed applied over a finite element grid, providing a framework for spatial reference within the model. This grid consists of discreet triangular elements, the corner points of which are referred to as nodes. Nodes that intersect streams are referred to as stream nodes. A detailed description of the model grid is provided later in this report.

IWFM uses the Galerkin finite element method to create a discretized spatial domain upon which water table elevations for each aquifer layer modeled can be calculated. This entails a system of ordinary differential equations applied to at every node and element in the model. These solutions incorporate flow rates at every stream node and account for the interactions between surface and groundwater, as well as other factors such as agricultural and municipal water demands. Model inputs are based on field data when available, and otherwise interpolation or estimation is used. Physical parameters such as node coordinates, surface elevations, aquifer thickness, and stream locations are defined in a series of modules called the preprocessor. The preprocessor is run before the simulation and has an output that is directly loaded into the simulation file folder.

The simulation is then run using an executable file, with a main input file that specifies the modules to be used in the simulation. These modules are text files developed from templates formatted for input into IWFM. They contain the data inputs for the model, with individual files for factors such as precipitation, diversions, or urban water use. An example of the main input file is shown in figure 2.1.
Figure 2.1: Screen capture of IWFM main input file (unit 5) found in simulation folder. The unit numbers are listed in the left column and the corresponding descriptions of model components are listed on the right.

Several units also include settings that determine the processing schemes to be implemented in the particular simulation trial. For example, groundwater pumping rates and locations can be specified by the user, or based on crop demand calculated by IWFM from inputs such as land use, crop evapotranspiration rate, and soil moisture requirement.

A water budget is calculated for each element, with groundwater and surface water quantified in terms of inflows and outflows. These fluxes are calculated based on geological and physical properties, land use, soil type, precipitation, initial conditions and adjacent elements. The result is represented by a mass balance equation of the form:
\[ S = S_i + Q_{in} + G_{in} + P - Q_{out} - G_{out} - ET \]

Where,

- \( S \) = water volume stored in element at given time step (\( M^3 \));
- \( S_i \) = initial water volume at given time step (\( M^3 \));
- \( Q_{in} \) = Surface water inflow (Stream inflows and runoff) (\( M^3/\text{day} \));
- \( P \) = Precipitation (\( M \));
- \( Q_{out} \) = Surface water outflow (Outflows across the model boundary and withdrawal for land application) (\( M^3/\text{day} \));
- \( G_{in} \) = Groundwater inflow (from boundaries and percolation) (\( M^3/\text{day} \));
- \( G_{out} \) = Groundwater outflow (at boundaries and from extraction) (\( M^3/\text{day} \));
- \( ET \) = evapotranspiration (a function of land use) (\( M \)).

(IWFM Theoretical Manual 3.0, 2007)

Outputs include hydrographs at user specified groundwater and stream nodes, in addition to time series hydrologic budgets for groundwater, streams, soil, recharge sites (modeled as lakes), surface applications, and diversions. The topic of output analysis will be covered in detail later in this report following the discussion of model development.

The model area has been divided into 7 sub-regions based on several categories of predominant land use (Figure 2.2). Each of these sub-regions has a full series of hydrologic budgets included as model outputs. IWFM also offers the option of defining groups of nodes with common physical properties as parametric nodes. Through this feature, the model can be adjusted geographically, or by calibrating characteristic aquifer and vadose zone properties. In this application, model inputs are differentiated by sub-region where applicable while parametric nodes are not used at this point.
Figure 2.2: The seven model area sub-regions employed in the IWFM representation of the simulation area.

2.3 Model Grid setup

The model structure is defined in terms of a grid consisting of triangular elements, the corner points of which are nodes, used as discreet reference points within the model. This grid was developed by Aristides Petrides in 2008 using mesh generator software specifically for application to finite element models. The average spacing between nodes is 100 meters, with an area of roughly 30 meter spacing around the HBDIC recharge site in order to obtain improved resolution for simulation results in this area (figure 2.3).

Every element is defined in the preprocessor by its corner nodes and has an assigned subregion, rainfall station, and drainage point. Within elements, land use is distributed using the generalized categories of agricultural, urban, native vegetation, and riparian areas. Specific
crops and other land uses are designated by acreage for each subregion. Each node has a specified surface elevation, vadose zone thickness, and the thickness for each geologic layer. This data is particularly important for several reasons. Groundwater flow is driven by differences in head; therefore surface elevation, the lower confining boundary, and aquifer interface determine the rate and direction of flow. Aquifer dimensions also define groundwater storage capacity, controlling the available groundwater supply and the impact of management activities.

Streams are represented in the model as the points where streams intersect nodes, referred to as stream nodes. An example is depicted in figure 2.3. Stream nodes are spatially defined by the groundwater node with which they share a location. Stream beds also have a designated elevation which must be above the bottom of the upper aquifer at any given location. This feature is particularly critical where spring discharge is a concern. All together, the model domain consists of 36,486 elements, 18,520 nodes, and 2,443 stream nodes.

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. Simulated water flow is then tracked through the network of nodes and stream nodes within the model. Nodes also serve as reference points for output data, such as water table elevations and stream flow. Over a given time interval, a unit of water may remain in a given element or it may flow vertically, horizontally, or be transported by other means such as pumping or evapotranspiration. IWFM applies values defined in input parameters such as hydrologic conductivity and crop efficiency in a continuity equation to quantify these flows. This information is also used to calculate water storage within elements, sub-regions, and the model as a whole. User settings for water allocation and solution criteria also influence simulation results.
Figure 2.3: Illustration of a portion of the model grid, also showing nodes, streams, stream nodes, bypasses, and the HBDIC recharge site. Note smaller grid size around recharge site.
3 Geologic Setting

3.1 Geology Overview

The geology of the Walla Walla Basin defines the origins of the gravel aquifer materials that are the focus of this model. Characterizing the properties of this geologic and hydrogeologic setting is central to the ability of the model to simulate the physical system it represents. The complexity of this system also creates a limiting factor for the accuracy of model outputs due to the uncertainty of sensitive parameters such as aquifer thickness and the spatial variability of hydrologic conductivity. Geologic data used in the model is based on Lindsey (2007); this report was prepared for the WWBWC using records from well drilling throughout the basin, geologic analysis of boreholes drilled for this report, Outcrop analysis, and notes from Dr. Lindsey’s previous research (Lindsey, 2007).

The Walla Walla Basin is underlain by layers of the Columbia River Basalt (CRB) formation. This bedrock is present throughout the basin and surrounds the overlying sediments like a bathtub (Henry, 2010). Some of the horizontal basalt layers are sufficiently porous to bear a useable water supply, though this aquifer tends to be quite deep and poorly characterized. Generally the CRB is considered to be hydraulically isolated from the over-laying materials, rather being recharged laterally from outside the area modeled here (Lindsey, 2007). The CRB layers feature folding and faulting that is believed to project into the suprabasalt sediments and forming the Horse Heaven Hills, an anticline along the southern boundary of the model. Above the Columbia Basalts lie five stratigraphic units, two of which are known to be aquifers, and one that is assumed to be. These are collectively referred to as the suprabasalt sediments (Lindsey, 2007). The upper two aquifers are the strata of primary concern for the IWFM model of the Walla Walla Basin (figure 3.1) while the others are important in that they are continuous and interbedded with the aquifer layers and they are believed to store and transmit water in localized areas (Lindsey, 2007). The interaction between the CRB aquifer and the suprabasalt sediments is poorly understood, though it is assumed there is some degree of hydraulic connectivity. In this model the CRB aquifer is considered to be the lower boundary of the system.
Figure 3.1: Schematic diagram of suprabasalt stratigraphy from Lindsey, 2007. We note that the naming conventions and age categories employed by Lindsey do not comply with the International Commission on Stratigraphy, but will be employed in this report since the differences do not have direct bearing on the findings of this study.

### 3.2 Quaternary Strata

The quaternary strata, referred to as ‘new gravels’ in the 1965 report by Newcomb, of the Washington Department of Ecology, primarily consist of flood and eolian loess deposits from the Pleistocene epoch, and are classified into two distinct units. The lower of these is referred to as the Quaternary Coarse (QC) unit. It consists of primarily uncremented coarse gravels, and is the upper of the two aquifers included in the model. This unit is overlain by the Quaternary Fine (QF) unit, consisting of finer loess and silt deposits and not considered to be water bearing. The QF unit is often present in the vadose zone of the model area. The fine grained material that composes this layer originates from several sources, generally not specifically differentiated in the well drilling logs used to document these geologic units. The QF unit is not highly conductive to water, though the layer is entirely absent in some regions and not considered to
act as a confining layer; therefore the QC unit is considered an unconfined aquifer. The extent and thickness of both quaternary units have been significantly affected by post-depositional erosion from streams. They are depicted in figures 3.2 and 3.3 (Lindsey, 2007).

3.3 Miopliocene Strata

The Miopliocene strata, referred to in Newcomb’s 1965 document as ‘old gravels’, have been classified in three distinct sub-units, referred to as coarse, fine, and basal coarse. The ages given for these units should be considered an estimate. The Miopliocene strata are composed of gravel, sand, clay, and silt, and are interbedded over much of the model area. This unit collectively makes up the bulk of the suprabasalt material in the model region.

The Miopliocene Coarse (MPC) unit comprises the lower gravel aquifer in the model, underlying nearly the entire basin with variable thickness. It consists of variably cemented sand and gravels and can be distinguished from the Quaternary gravels by the presence of basalt clasts and a clay matrix that gives it a red-brown to yellow-brown appearance. Erosion and deposition in the Pine and Dry Creek drainages have produced a braided pattern of thick and thin depositional areas of this unit in the south and east portions of the basin, along the Horse Heaven Hills anticline (Lindsey, 2007). Thickness is depicted in figure 3.4.

The Miopliocene Fine (MPF) unit is primarily found below the MPC unit, though there is a significant degree of interbedding between the layers. It consists of silt, clay, sandy-clay, and sandy mud, and typically has blue, green, brown, or yellow appearance. Like the MPC unit, the MPF unit has variable thickness due to material being redistributed within the Pine and Dry Creek drainages, with a predominantly northwest orientation. Due to the interbedding of the Miopliocene strata, areas of gravel may be present within the MPF unit, and some of these appear yield a usable groundwater supply. However, the MPF unit considered an aquitard for the purpose of this model. It covers an area depicted in figure 3.5.

The Miopliocene Basal Coarse unit (MPBC) lies directly above the Columbia River Basalts. It is unclear from drill logs whether this unit is continuous in the eastern part of the
basin of occurs predominantly in several patches as it is currently mapped. Its thickness ranges up to 30 meters in places, though the unit is absent over much of the model area. It is distinct from the other Miopliocene units, consisting of arkosic-micaceous sands deposited by an ancestral river flowing from the north (Lindsey, 2007). It is incorporated into the model as an aquifer, capable of storing and transmitting water, though there is not an associated subsurface inflow because a reasonable estimate could not be made with the available data due to the overlying MPF unit and the uncertainty regarding the extent of the MPBC unit. It covers a relatively small portion of the model area, depicted in figure 3.6.

Figure 3.2: Thickness of QF layer from GIS layer provided by WWBWC. Original source: Kevin Lindsey, GSI Water Solutions, 2007.
Figure 3.3: Thickness of QC aquifer from GIS layer provided by WWBWC. Original source: Kevin Lindsey, GSI Water Solutions, 2007.
Figure 3.4: Contour depiction of thickness of MPC aquifer. This graphic is based on an edited version GIS layer provided by WWBWC. Original source: Kevin Lindsey, GSI Water Solutions.
Figure 3.5: Contour depiction of thickness of MPF aquifer from Kevin Lindsey, GSI Water Solutions, 2008.
3.4 Stratigraphy in IWFM

IWFM accounts for a variety of features that characterize the physical properties of an aquifer; these are illustrated schematically in figure 3.7. Surface elevation and the thickness of geologic strata are factors of primary importance for developing a credible model.
Surface elevation for the model region has been defined for every node with regard to their respective locations on a DEM, provided by the WWBWC, in which the Walla Walla Basin is represented on a 10 meter square grid. The thickness of each underlying geologic layer used in the model is input into IWFM in the preprocessor unit 9 (figure 3.8). The stratigraphic layers each have two associated columns for data entry. These columns list values for thickness (in meters) defined at every node; if a layer is absent at a particular point its thickness is listed as zero for the corresponding node. IWFM uses a scheme in which the first data column corresponds to an aquitard, inhibiting groundwater flow, and the second to an aquifer in which groundwater may be transmitted or stored. This sequence is repeated for each layer. In this application, three model layers are used to represent the suprabasalt sediments. Their features correspond to the QF, QC, MPC, MPF, and MPBC strata described in the previous section. The aquitard column in layer two is not used, and therefore always given a thickness of zero.
Summary of geologic strata as represented in this model:

Layer 1 Aquitard: QF unit

Layer 1 Aquifer: QC unit

Layer 2 Aquitard: Not used (thickness equals 0 meters for all nodes)

Layer 2 Aquifer: MPC unit

Layer 3 Aquitard: MPF Unit

Layer 3 Aquifer: MPBC Unit

Figure 3.8: Screen capture of input for strata thickness from IWFM preprocessor unit 9. Thickness is listed in meters for each model layer. Surface elevation is listed in column 2, and is the basis for defining the upper and lower elevation for each node in the model.
The lower boundary of the model is the Columbia River Basalts (CRB). It is assumed that in reality there is connectivity between the CRB unit and the overlying sedimentary layers; however the rate of this flow is unknown, and given the strong horizontal banding of these strata, the vertical permeability is thought to be very low. Future efforts to quantify the exchange between the CRB aquifer and the suprabasalt sediments could improve the performance of this model as well as the overall understanding of regional hydrology. In this model, the CRB aquifer is incorporated as a supplemental source of groundwater for irrigation supply as is discussed later in this report. It is important to note that the QC and MPC aquifers are hydraulically continuous allowing water to flow freely between them. In the model this creates a hydrostatic groundwater condition in these units regardless of the properties of the aquifers at any given point in the model. There are however, some variations in a few areas between the simulated groundwater head in the different aquifer units. This is likely due to the difference in hydraulic conductivity between the two aquifers. The QC (upper) aquifer is more conductive than the MPC (lower) aquifer. This would explain an accumulation of a small amount of water at the aquifer interface over the period of a time step, particularly if there is a strong wetting front as with a heavy rain or increase of irrigation. A clay lens could have a similar effect by hosting a perched water table. This type of feature is likely to occur in the physical aquifer, but is not incorporated into the model because it cannot be supported by the available geologic data.

While the thickness and elevation of the geologic layers spatially defines the position of the component features of the model, the simulation of water movement depends on aquifer parameters defined by the model user. These include specific storage, specific yield, and vertical and horizontal conductivity. These parameters represent the physical properties of the aquifer, though there is not sufficient data to characterize them with a great degree of certainty. Heterogeneity minimizes the importance of any specific measurement, while time and expense limit the feasible number of measurements. Therefore these are largely considered calibration parameters and are addressed in the calibration section of this report.
4 Groundwater

4.1 Groundwater Flow Equation

Groundwater flow is generally considered to follow Darcy's law.

\[ Q = K \cdot A \left( \frac{dH}{dL} \right) \]

Where,

\( Q \) = Volumetric rate of groundwater flow (M³ per day);

\( K \) = Hydraulic conductivity of aquifer material (M/day);

\( \frac{dH}{dL} \) = Gradient of groundwater head over specified distance (M/M).

IWFM simulates groundwater flow by applying the following the conservation of mass equation at each time step for every node in the model:

\[ 0 = \left( S_s * h \right) / t - \Delta(T\Delta h) + I_u L_u \Delta h_u + I_d L_d \Delta h_d - q_o + q_{sd} - \delta (X - X_s, Y - Y_s) Q_{sd} / A_s \]

\[ -\delta (X - X_{lk}, Y - Y_{lk}) Q_{lk} / A_{lk} \]

Where,

\( S_s \) : Storativity (dimensionless), equal to specific yield in an unconfined aquifer;

\( h \) : Groundwater Head (L);

\( t \) : Time;

\( T \) : Transmissivity (L²/t). For an unconfined aquifer this is equal to \( K(h-Z_{ab}) \);
K : Hydraulic Conductivity of aquifer material (L/t);

$Z_{ab}$ : Elevation at bottom of unconfined aquifer (L);

$I_u, I_d$: Indicator function of top (u) or bottom (d) aquifer layer;

$L_u, L_d$: Leakage coefficient between adjacent aquifer layer above (u) or below (d) (1/t);

$h_u, h_d$: Head in adjacent aquifer layer above (u) and below (d) aquifer in question;

$q_o$: Other sources and sinks, such as groundwater pumping, recharge (L/t);

$q_{sd}$: Rate of flow into storage due to interbed compaction (not used in this application);

$\delta$: Dirac delta function (dimensionless);

$X, Y$: Horizontal coordinates from IWFM preprocessor unit 8;

$Xs, Ys$: X, Y coordinates of stream locations;

$Xlk, Ylk$: X, Y coordinates of lake locations;

$Q_{sg}$: Stream-Groundwater interaction (L$^3$/t);

$Q_{lk}$: Lake-Groundwater interaction (L$^3$/t);

$A_s$: Effective area of stream bed through which stream-groundwater interaction occurs (L$^2$);

$A_{lk}$: Effective area of lake bed through which lake-groundwater interaction occurs (L$^2$).

(From IWFM Theoretical Manual 3.0, 2007)

This equation is used to calculate a field of groundwater head at each time step for the entire model area. A detailed account of the values that populate the terms of this equation in this model is included in the following sections.
4.2 Boundary Conditions

In IWFM there are several options for defining groundwater boundary conditions; this model application uses a specified head method, where groundwater head is defined in each aquifer along the model boundary where there is assumed to be flow. The model area is bordered by the Horse Heaven Hills along a southwest to northeast axis and the Walla Walla River to the north and east. The Horse Heaven Hills are considered a groundwater divide, and therefore a no flow boundary (Lindsey, 2007). There is an exception for the area adjacent to the Pine and Dry creek inflows where it is assumed some groundwater flows into the Walla Walla Valley. The flow of groundwater into and out of the model can be pictured as water percolating across a plane, defined by the shape of the model boundary and extending to the total depth of the stratigraphic layers included in the model. The flow is driven by the gradient of groundwater head, which in the case of unconfined aquifers, is equivalent to elevation head. For the ‘no flow’ portion of the boundary groundwater head is not defined in the model. For this reason sub-region 2 does not receive or export water across the model boundary. The primary groundwater inflow comes from the upper reaches of the basin to the north, entering into model sub-regions 4, 5, and 6 (figure 4.1). Figure 4.1 shows that the peak of net groundwater inflow to the model area occurs in late July, when the water table is at its annual minimum elevation. This is because agricultural withdrawals also peak around this time, creating a condition where water flows into the model area and is then extracted by pumping so outflow does not match inflow. When pumping ceases in the winter and early spring, the model shows a net outflow of groundwater.
Figure 4.1: Groundwater can flow in or out of the model area, with each region affected by conditions of adjacent areas. Sub-region 4 receives significant groundwater inflow from the north. Sub-region 6 has both gaining and losing areas. In Sub-region 7 groundwater flows out of the model area. Note that 50,000 M³ per second is approximately 20 cfs.

The rate of groundwater flow in and out of the model is governed by the user input groundwater head in each aquifer along the model boundary at every time step. To generate this prediction requires interpolation of the available well data to generate a projected water table. Values are then extracted from this surface at every point along the model boundary. This process is inherently imprecise due to limited data records and aquifer heterogeneity; however boundary conditions are a necessary baseline input for the model. They define the range of water table elevation and seasonal variability along the model boundary. Data from the WWBWC well database was used to generate the projected water tables. This data is collected at a series of wells, some dedicated for groundwater monitoring, others used for multiple purposes. Some wells are equipped with pressure transducers collecting 30 minute data and checked with periodic manual measurements of water table height. Other wells are only measured by hand on a roughly quarterly basis.
Data processing began with WWBWC personnel removing well data that appeared to be influenced by groundwater pumping. The remaining data were included in a revised database, from which I extracted monthly averages of water table elevation for each well using MS Access, and then narrowed the data set to the wells in and around the model region for the years 2007 through 2010. This data set is included in appendix C.

The data was input into a GIS feature layer in which every well was represented by a point, and the monthly data for the wells was entered as attributes for the points. A spline interpolation was done between the points for each month of the four year time period. The result was an estimated water table surface for each month (figure 4.2). To expedite this process, and facilitate a means of efficiently generating the entire group of water tables as input data was refined, I created a GIS model to execute the sequence of operations automatically. This was based on an example shared by Troy Baker of WWBWC. The model uses a GIS layer with selected wells represented by points. Each well has mean groundwater elevation for each month of the simulation period listed as attributes. ARC MAP first performs a spline interpolation between the wells for each month, generating a series of projected water tables. The next step is to extract the estimated water table elevation from the interpolated GIS layer at all boundary nodes for each month of the simulation period and join this data to a new layer featuring all boundary nodes. This output can then be exported to an excel file which can be used directly in the data processing worksheets (appendix C) to format the GIS model results for input into the IWFN boundary condition defined in unit 9 of the simulations folder. One feature of this worksheet is that it uses surface elevation and stratigraphic thickness to calculate the top and bottom elevation of the aquifers. IWFN will not allow the head at a boundary node to be below the bottom of the associated aquifer. If this is the case based on the water table projection, the groundwater head at the node in question is modified to equal the bottom of the aquifer. In these cases the thickness of the column of water crossing the boundary in the given aquifer is zero, therefore no flow being simulated for that particular location in that aquifer. This issue most often arises for the QC aquifer, when estimated groundwater head along the model boundary is below the interface of the two aquifers. In these instances, boundary head is reflected in the conditions of the MPC aquifer. The MPBC aquifer unit crosses the model boundary at several locations, though no specified head boundary condition was applied to this
unit due to its limited spatial extent, unknown recharge source, and unclear with the overlying geologic units. In the present model, the MPBC unit is primarily included to account for its presumed storage capacity. The role of the MPBC unit is an outstanding question for future improvement of this model.

Figure 4.2: Contour map of water table generated using spline interpolation function in GIS Spatial Analyst. Input data is monthly water level in highlighted wells. Boundary inflow and outflow occurs along blue portion of boundary, brown portion is no-flow boundary.

An immediate problem stemmed from the nature of the data set, specifically that data was not available for all wells for every month of the simulation period. A data set for one month could include a different set of points than for the following month or even any other month in the simulation, resulting in an erratic water table estimate from month to month. To address this issue I dropped wells that had -less than 6 data points for the first three years of the simulation period, because data from these years was the basis for model development, with
the fourth year being used for validation. The remaining data was used to estimate groundwater elevation for missing months. These was done by using known groundwater surface elevation measurements at a particular site, and varying them sinusoidally with amplitude, timing, and frequency based on other gauges, where more complete data sets were available. Estimated water measurements were only used to generate boundary conditions, not for output analysis, i.e. they are not considered the equivalent of gauge data. This procedure produced a water table that was consistent on a monthly basis within the range of observed water table variation in the model area (table 1). It should be noted that the input boundary conditions used in the model vary on a monthly basis, though the model uses a daily time step.

Table 4.1: The range of water table variability at boundary nodes was unrealistically high using raw data alone because there were different data points available on a monthly basis. This problem was greatly improved by estimating water level for missing months.

<table>
<thead>
<tr>
<th>Range of groundwater head in spline outputs at individual boundary nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inputs for interpolation from well database only</td>
</tr>
<tr>
<td>average (meters)</td>
</tr>
<tr>
<td>max (meters)</td>
</tr>
</tbody>
</table>

4.3 Initial Conditions

To run the model, the initial conditions must also be defined for each aquifer at every node in the model. This was done by using the projected water table for the beginning of the simulation period, January, 2007. As previously discussed, there is inherent error in using interpolation between irregularly spaced wells with irregular data sets to project a water table; therefore what is commonly referred to as “model spin up” was used to reduce the error in initial conditions. This was done by repeatedly taking the groundwater head results from a model run and using them as the initial conditions for a new run in which all other data is identical to the original run. This has the effect of ironing out discrepancies where the initial
conditions obtained through interpolation are poorly aligned with the water table calculated with the model input data. This process improves correlation between the simulation outputs and observed data assuming that the difference in water table elevation is relatively small compared to the presumed error of initial conditions (figure 4.3). This is particularly valuable in generating physically realistic interpolations of water levels between wells, in both time and space.

Figure 4.3: Example of the effect of using 'spin up' for initial conditions at monitoring well 106.

4.4 Pumping

IWFM offers two options for incorporating groundwater pumping into the simulation. These are using prescribed pumping rates at well locations, or calculating pumping rates based on urban and agricultural water requirements and crop water use efficiency. The latter of these options is used for this application. The characterization of water demand for specific crops as is a topic covered later in this report. Urban water use is included in the model, but has a small impact on overall water budgets in the model; therefore the discussion of groundwater
pumping is primarily focused on agricultural water demand. This section will provide a description of the inputs used to calculate groundwater withdrawals in IWFM.

The main input module (unit 5) in the IWFM simulation folder includes a variable setting for how water demands are to be calculated, and a flag to set the water supply option. The options selected for this application are to allow IWFM to calculate water use requirements, and to adjust groundwater pumping rates to meet these requirements where surface water supplies fall short. Surface water diversions are calculated using rates prescribed by the model user and are not automatically adjusted. This reflects actual practices in the basin where groundwater is primarily used when and where surface water is not available. In addition, many water users in the basin over irrigate during spring when the surface water supply is plentiful to increase available soil moisture in the dry summer months (Henry, 2010). This would not be reflected if IWFM was basing surface water diversions on crop demand alone. In many cases there is a shortage of surface water available, either due to low streamflow or withdrawals by upstream users. The discrepancy between surface water supply, prescribed diversions, and agricultural demand is quantified in the budget outputs of IWFM. Unit 12 of the IWFM simulation folder specifies that water supply should be adjusted to meet agricultural and urban demands using the criteria discussed previously.

Once the specific water requirement is determined for each subregion (this is calculated based on several formulas described in the crops section of this report), IWFM simulates a groundwater withdrawal distributed among the elements to balance the discrepancy between surface water supply, rainfall, and both agricultural and urban water demands. The balance is primarily dictated by the minimum soil moisture required by the crops in the particular model element, their water use efficiency, and the soil properties associated with that element. In this model application, groundwater pumping is applied when allocated surface water diversions do not meet crop demand as determined by the minimum soil moisture requirement of the specified crops. Given the assumption that each element has an available supply of groundwater the following equation is used by IWFM to determine groundwater pumping rates for each element.
\[Q_{pe} = \frac{Q_{pt} \cdot f_i \cdot (A_{i,ag} + A_{i,ur})}{\sum \{f_i \cdot (A_{i,ag} + A_{i,ur})\}}\]

- \(Q_{pe}\): Pumping from element (M\(^3\)/day)
- \(Q_{pt}\): Total pumping in subregion (M\(^3\)/day);
- \(f_i\): Pumping allocation factor (dimensionless);
- \(A_{i,ag}\): Agricultural area within element i (M\(^2\));
- \(A_{i,ur}\): Urban area within element i (M\(^2\));
- \(n\): Number of element to which pumping is distributed;

(IWFM Theoretical Manual 3.0, 2007)

Associating elements within the model area with particular wells is beyond the resolution of land and water use data currently available. The model could benefit from improved information detailing the location of wells supplying large amounts of irrigation water, along with specification of the areas they supply. Due to a lack of data pertaining to well pumping rates, a maximum pumping rate of 1900 M\(^3\) per day is assumed for all elements in simulation unit 24. Every element is available for groundwater extraction in this model application so the maximum pumping rate is not a limiting factor. With this setup, IWFM simulates the extraction of groundwater to meet crop demand, and the corresponding reduction in groundwater storage and head. Simulation results for the total volume and rate of groundwater pumping are included in the budget section of this report where they can be readily compared to other water use factors in the basin.

4.5 Columbia River Basalt Aquifer Contributions

During the irrigation season, some farms in the Walla Walla Basin rely on water from wells drilled into the CRB aquifer. The locations of all of these wells and the total volume of
water they produce are not known specifically, however they comprise a significant source of irrigation supply in some areas. The contribution from basalt wells is modeled as a water source outside of (in this case below) the model area. The total volume, timing, and distribution of this water are estimated based on information from the WWBWC based on a survey of available well logs and input from knowledgeable parties (figure 4.4). There is a high degree of uncertainty associated with these estimates, and this remains an area where more detailed information could improve the reliability of the model.

Figure 4.4: Areas known to rely on groundwater inputs from CRB aquifer based on personal communication between Rick Henry of the WWBWC and local water users and irrigation managers (Rick Henry, 2010).

Eighty one basalt wells are identified on the pertinent GIS map from WWBWC and their locations are translated into the model by associating each well with the closest node in the model area. These wells are listed as diversions (diversion numbers 763-843) in IWFM simulation unit 25. As with other diversions their flow rates are specified by user input though their source is considered as originating from outside of the model area. All diversions have
associated elements to which they supply water. The elements supplied by the basalt wells are the ones that include a node that is associated with one of these wells. Typically the basalt nodes supply water directly to four to eight elements (figure 4.5).

Figure 4.5: Basalt well locations from WWBWC. Elements that are modeled as receiving direct irrigation inputs are highlighted.

This input will either percolate to groundwater or be used directly by crops, therefore reducing pumping demand. Application of water from the CRB aquifer significantly impacts the water table and groundwater budget for both the modeled and physical system. It is possible that model calibration has a balancing influence between water applied from the CRB aquifer and actual interaction between this aquifer and the suprabasalt sediments. This could occur if the flow into or out of the CRB from the overlying sediments is compensated by the estimation
of irrigation withdrawals from this unit; however the relationship is not possible to quantify.

Total inputs from the CRB aquifer as applied in the IWFM model are summarized in figure 4.6.

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**Figure 4.6**: Estimated monthly total input from CRB aquifer as used in IWFM Walla Walla Basin model. Water is divided evenly among 65 of the 81 wells identified by WWBWC as having a screened interval in the CRB aquifer.

There are several outstanding questions regarding withdrawals from the basalt aquifer that pertain to the water budget for the entire basin.

- What is the total volume and recharge rate of the CRB aquifer?
- Are wells drilled into this aquifer seeing similar declines to wells in suprabasalt material?
- To what degree are the CRB and MPC aquifers hydraulically connected?
- To what degree is this aquifer affected by pumping pressure from outside of the model area?
4.6  **Shallow Aquifer Recharge**

One goal of this modeling effort is the applicability of IWFM as a tool for investigating questions related to aquifer recharge. Aquifer recharge sites are incorporated into IWFM as lakes, with inflow rates, bed thickness, and bed conductivity being directly controlled by user inputs. The three recharge sites are very different in their physical characteristics as well as the management approaches for each site. However, they share the basic principal in which surface water is diverted into a basin during times of high flow and low agricultural demand, where it is then allowed to percolate into the ground. The degree to which these projects serve to increase water table elevation, and the ways in which this effect can be enhanced through management or basin design, are important questions for the future of water management in the Walla Walla basin. To this point all three projects have shown promise in terms of local responses in well levels and spring flows associated with operation at the recharge sites. Following is a brief description of the aquifer recharge sites. Detailed reports on each of the recharge basins is available on the WWBWC website (www.wwbwc.org)

1. Hudson Bay Aquifer Recharge Project: A site managed by the HBDIC and the WWBWC where water is diverted from the White Ditch irrigation canal into rectangular infiltration basins that have been excavated into the quaternary gravel aquifer (figure 4.7). The basins used in this project have been expanded in several phases using several variations of basin construction for a study of infiltration with to basin configuration and construction design. These included using ADS and PVC perforated pipes and several variations of underground tanks intended for stormwater management. The systems have been compared in their infiltrations rates, susceptibility to clogging, and the cost of materials, installation, and maintenance. The development and operation of this site is comprehensively summarized in the report, Aquifer Recharge as a Water Management Tool: Hudson Nay Recharge Testing Site Report (2004-2009), available on the WWBWC website (Bower, Lindsey; 2010). A detailed database of surface and groundwater conditions is currently maintained by the WWBWC. Monitoring wells at this site clearly capture the relationship between flow diverted into the recharge basin and water table movement. The simulation is successful in reproducing these fluctuations (figure 4.8).
Figure 4.7: Detail of HBDIC recharge site from Bower 2010, including monitoring well locations.

Figure 4.8: A graph showing the relationship between recharge site operation corresponding fluctuations in groundwater head at the nearby monitoring well, GW 48. Inflow rate to the recharge site is on the right axis.
2. Locher Road Aquifer Recharge Basin: This site, managed by Gardena Farms Irrigation District, diverts water into an unused gravel quarry in which circular basins have been excavated (figure 4.9). Detailed information about the geologic conditions of the site, and monitoring efforts of nearby wells, and flow response in Mud Creek are available in a detailed report on the Locher Road recharge site by Kevin Lindsey (2007).

![Figure 4.9: Locher road aquifer recharge site, photo from WWBWC website.](image)

3. Hall-Wentland Aquifer Recharge Site: This project recharges the gravel aquifer by flood irrigating a 5 acre field pasture (Figure 4.10). This site there does not have constructed infiltrating basins. Flow volume, infiltration rates, water quality, and the response in nearby wells are the subject of a report prepared by Kevin Lindsey (2009).
An intended application of the IWFM model is to provide a tool for predicting effective locations for future recharge sites with the goal of having sustained enhancement of groundwater resources in the agricultural portions of the watershed. The rate and direction of groundwater flow are determining factors for achieving this goal, and both are accounted for within the scope of these simulations. There are limitations on specific information that can be predicted through modeling. Understanding the resolution to which the model can be used for these predictions is a topic to be addressed in the discussion of model outputs. There are also several factors that complicate attempts to model aquifer recharge. Rooted vegetation and algae growing in the recharge basin develop into a clogging layer that significantly impacts the permeability of the sediment over time. This issue has been addressed periodically by turning the surface sediment with a bulldozer. The effect of the clogging layer on basin permeability has not been quantified; however piezometers installed by the WWBWC in 2009 may yield data to provide insight into this issue. Another factor to consider in aquifer recharge is the development of preferential pathways for subsurface flow.
5 Surface Water

5.1 Surface Water in the Walla Walla Basin IWFM model

Surface water enters the model area as stream inflows, precipitation, and exchange with groundwater in gaining stream reaches or springs. The stream network is divided into 81 reaches based on the locations of inflows, bypasses, and confluences. IWFM has a particular organizational scheme for numbering stream nodes and reaches in which numbers must progress in a downstream direction. Thirty three stream gauges, operated by WWBWC, USGS, and Washington Department of Ecology are the primary sources of stream flow data. In some cases, where gauge data was unavailable, pressure transducers were installed to facilitate reasonable estimations of ungauged streams. The distribution of gauges within the model area is irregular, with some streams having well documented flow rates and others being entirely unmonitored (figure 5.1).
The stream network as represented in this model is a simplification of the actual stream network; however the complete system is functionally represented in terms of connectivity between channels (figure 5.2). IWFM provides several tools for incorporating the features of managed canals and irrigation withdrawals into the model. These are based on bypasses and diversions, specified by the user. Bypasses are distribution points where water is diverted from one channel to another at a controlled rate. The surface water distribution system in the model area is engineered to transport water to locations of demand, in some cases in conflict with the laws of gravity or hydrology. For example, at several locations highlighted in figure 5.2, water is pumped upgradient or piped underneath natural streams. Diversions represent locations where water is withdrawn from the system for agricultural application. Where possible, gauge data is
used to dictate the rates of both bypasses and diversions in the model. Otherwise estimates are based on input from irrigation managers.

Stream channels are characterized in the model by their elevation, channel geometry, bed permeability, and stage-discharge relationships (rating tables). The channels are divided into 81 segments, which are divided at inflow points, end points, and major confluences. Each stream segment is defined in the model preprocessor unit 10 in terms of its upper and lower stream nodes, and the segment into which it flows. In most cases, channel widths were measured in the field and are a component of surface area used to calculate stream gains or losses resulting from interactions with groundwater. IWFM uses the following equation to quantify stream-groundwater interaction.

Figure 5.2: Comparison of physical layout of the stream and canal network (blue) versus the streams as they are incorporated into the model (yellow).
\[ Q_{sg} = C_s \times (\max(H_s, H_b) - \max(H, H_b)) \]

\[ C_s = \left( \frac{k_s}{d_s} \right) \times (L_s \times W_s) \]

Where,

- \( Q_{sg} \): Stream-groundwater interaction (m³ per day);
- \( C_s \): Stream bed conductance (m per day);
- \( H \): Groundwater head at stream node;
- \( H_s \): Stream surface elevation;
- \( H_b \): Stream bed elevation at node;
- \( K_s \): Conductivity of stream bed material at node (m/day);
- \( D_s \): Thickness of stream bed material at node (m);
- \( L_s \): Distance between stream nodes;
- \( W_s \): Channel width at node.

(IWFM Theoretical Manual 3.0, 2007)

It should be noted that this solution assumes stream channel width and conductivity are both constant over a given model run, while it is often the case that these values change as a function of season and channel morphology. In many cases, a value that is correct at a given time will be wrong at another time, regardless of the chosen value; therefore it is often impossible for a given input to be correct for the entire simulation period. This problem affects both the potential accuracy of model input parameters, and the accuracy of physical gauges where flow rates are computed based on a rating curve generated from a limited set of measurements. In this model, stream bed thickness is assumed to have a constant value based on several channel classifications; ‘Walla Walla Mainstem’, ‘large channel’, ‘small channel’.
Stream bed conductivity is a highly sensitive parameter used for calibration, and is a topic discussed in detail later in this report. In cases where a stream is gaining flow from groundwater, i.e. groundwater head is above the stream bed and the stream bed conductivity is greater than zero, the rating table serves as a reference for the flow rate resulting from groundwater seeping into the stream bed (figure 5.3)

Figure 5.3: Illustration of stream-aquifer interactions. Images are from the IWFM Theoretical Manual 3.0 (2007).

Rating tables are defined for every stream node, and were determined directly from WWBWC surface water monitoring records, records from Washington Department of Ecology, USGS, and Oregon Water Resources Department stream gauges wherever possible. In other cases, manual flow measurements were taken at selected field sites, and the Manning equation was applied to estimate additional points. The Manning equation calculates flow velocity based on slope, hydraulic radius, and a stream bed friction parameter known as the roughness coefficient.
\[ V = N \times Rh^{2/3} \times S^{0.5} \]

Where,

\( V \) = average cross sectional velocity (M/second);

\( N \) = Roughness coefficient (dimensionless);

\( Rh \) = Hydraulic radius (Cross sectional area (M^2) / wetted perimeter (M));

\( S \) = 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 that can all be measured directly, and verified by comparing to published values. This can then be coupled with observed evidence of bank full depth and width to estimate additional stage-discharge data points. For several irrigation channel reaches, Cippoletti weirs are used to regulate flow. At these locations, established stage-discharge relationships are available and are input directly into the model as rating tables.

To calculate simulated streamflow IWFM applies a form of the continuity equation. This assumes that for each time step, storage at a given stream node equals zero.

\[ Qin - Qout - Qdiv - Qb - Qsg = 0 \]

\( Qin \): Combined inflows at given node including flow from upstream nodes and tributaries, bypasses, return flow, and runoff

\( Qout \): Flow available to downstream nodes (M^3/day)

\( Qdiv \): Flow withdrawn for other application—generally agriculture (M^3/day)

\( Qb \): Flow bypassed to another node or stream segment (M^3/day)
5.2 Precipitation

It is estimated that 20% of precipitation in the valley percolates to the water table, recharging the gravel aquifer (Petrides, 2008). This rather uncertain value comprises a major source of available groundwater. Surface runoff is periodically a significant factor in the regional hydrologic budget, increasing available surface water and reducing the demand on groundwater when precipitation falls during the growing season.

Precipitation values used in the model originate with daily records from Ag-Weather Net stations at Touchet, College Place, and Walla Walla, Washington (figure 5.4). These values were then interpolated based on elevation, and each subregion in the model was assumed to receive rainfall at a rate based on its respective mean elevations (table 5.1). Every element was considered to receive rainfall at the rate of the subregion in which it lies.
Figure 5.4: Monthly mean rainfall (mm) over the simulation period 2007-2010 at Ag-WeatherNet gauges used for model input. Surface elevation is listed for each station in the legend. Precipitation rates input into the model were calculated for each sub-region by interpolating the between these gauges based on the elevation of the gauges and the mean elevation of the sub-regions.

Table 5.1: Mean elevation for each sub-region used for estimating precipitation in model area.

<table>
<thead>
<tr>
<th>Subregion</th>
<th>Mean elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>336</td>
</tr>
<tr>
<td>2</td>
<td>309</td>
</tr>
<tr>
<td>3</td>
<td>270</td>
</tr>
<tr>
<td>4</td>
<td>212</td>
</tr>
<tr>
<td>5</td>
<td>185</td>
</tr>
<tr>
<td>6</td>
<td>156</td>
</tr>
<tr>
<td>7</td>
<td>138</td>
</tr>
</tbody>
</table>
5.3 Surface Drainage

Surface drainage plays a limited role in the overall hydrologic budget of the model, but can be periodically important with large rain events. It determines stream response to precipitation by defining the area draining to the various channels in the model. This was done using ARC-HDRO tools in GIS though it can be difficult to verify in the field. The model requires every element to be assigned a stream node that will receive runoff from that element. To achieve this I used the ARC-HYDRO ‘flow direction’ and ‘flow accumulation’ tools, which use topographic analysis based on the DEM of the Walla Walla Basin provided by WWBW. The outputs of these tools are then translated from raster data sets into vector data sets and divided into discrete sub-catchments within the model area. The number of catchments is a function of the accumulated number of cells draining to a given point that constitutes a catchment area; in this case a 5000 cell threshold was used, yielding 366 catchments in the model area. Each sub-catchment has an associated ‘drainage point’, and each drainage point, an associated stream node, which is assumed to be the closest non-piped stream node to the given drainage point. Further spatial analysis was done in GIS to determine the sub-catchment for each element based on the location of the centroid of the particular element. The group of elements within a sub-catchment was then considered to drain to a single point, and ultimately to the stream node associated with that drainage point (Figures 5.5 and 5.6).
Figure 5.5: Sub-Catchments (represented by unique colors) are based on topographic analysis in GIS.
Figure 5.6: Detail of sub-catchments, showing elements, drainage lines, drainage points, streams, and stream nodes. Every sub-catchment has a drainage line. Drainage points are associated with the closest stream node, which then receives runoff from the sub-catchment.

5.4 Stream Inflows

Stream flow into the model area is one of the most important factors in model development because it determines the amount of surface water available for distribution within the model. A large degree of error in inflow rate will translate into a large error in model output or a compensating error in model parameters. The mainstem Walla Walla River and tributaries flowing into the model region are included in figure 5.1. The Walla Walla River, originating in the Blue Mountains of Eastern Oregon, enters the model area just east of Milton-Freewater, Oregon, and is the primary surface inflow to the model area. A gauge was installed by WWBWC at the Grove School Bridge in Milton-Freewater in 2007 and has since been used as a direct data source for the rate of inflow in the Walla Walla River. Mill Creek and the Touchet River are the other major inflow sources, though the Touchet confluence is near the outflow point of the model, and therefore its contribution to the regional water budget is limited. Pine and Dry Creeks are the only inflows from the South, converging inside the model boundary.
These drainages have little present or historic data available, though the two streams are known to be both ephemeral and flashy, with flood stages estimated to reach 28 m$^3$ per second (1000 cfs). The Walla Walla District of the U.S. Army Corps of Engineers made an effort to characterize this drainage using a limited data set with intermittent measurements from 1969 through 1986; these estimates included similar peak flows (USACE, 1997) the ones mentioned above. Pine Creek is used as a supplemental source of irrigation water by the HBDIC Irrigation District, and periodically carries some irrigation return flows. Both Pine and Dry creeks, and many of the small tributaries in the model region typically become dry, stagnant, or intermittent by late summer and early fall.

Established gauges provide data for flow into the model area from the Walla Walla River, Touchet rivers, and Mill Creek. The remaining eight inflow locations are ungauged, with little or no historic data available, creating a challenge for model development. Though small ephemeral streams are minor contributors to the regional water budget, replicating their flow conditions can be an important indicator of model performance. Large tributaries, in spite of sparse data records, are important to both model development and water management in the basin. The data scrutiny entailed in the model development process can also lend insight into the contribution of tributaries to the hydrologic budget of the model area, in some cases highlighting areas where significant inputs are overlooked due to limited data. In an effort to fill the data gaps associated with the ungauged inflows, pressure transducers were installed and maintained by WWBWC to record stream depth at the remaining inflow locations. Pressure data was collected from these gauges, recorded on Baro-Troll data loggers, manufactured by In-Situ Inc., at 30 minute intervals, and factoring for barometric pressure, translated into stream depths. Several flow measurements were taken at these locations and entered into the software ‘Table Curve’, fitting a suitable curve generating equation to relate stream depth and flow rate at each particular gauge, to be applied to the transducer data. The gauge at Dry Creek-Oregon was washed out in a flood; the gauge at Pine Creek was also dislodged and then reinstalled, increasing the uncertainty of the data from this gauge because it was not in exactly the same location. The data set resulting from this process, along with the established gauges at the Walla Walla River at Grove School Bridge, Mill Creek at Walla Walla, and the Touchet River at Cummins road, are shown in figure 5.7.
Figure 5.7: Compared inflows to model area over an 11 month period (5/2010 – 4/2011). Note that Mill creek has 2 gauge location included on this chart. They are the DOE gauge in upstream in Walla Walla and the Transducer gauge installed to record data for this modeling effort.

The Washington Department of Ecology (DOE) gauge in Mill Creek at Walla Walla, Washington is significantly upstream from the model area, so an additional gauge was installed in Mill creek near Detour road, close to the confluence with the mainstem Walla Walla River. Initially these two gauges showed a very similar flow rate, though by mid-summer they had diverged, with flow at Walla Walla significantly lower than downstream at Detour road, likely due to irrigation return flows. In late October of 2010, the gauge at Detour road was washed away by high water.

It is interesting to note that the pattern of flow in the Garrison Creek and Dry Creek (Washington), both flowing into the Walla Walla from the north is more similar to the Touchet
River than the Walla Walla. A logical explanation for this may be that the Touchet River also originates from the north while the Walla Walla River originates from the southeast. The Pine and Dry (Oregon) creek drainages are south of the model area, though the data from these gauges is insufficient to find a pattern that can be associated with any of the other streams. Stone and Birch creek are very low flow and Woodward canyon primarily carries agricultural return flow, though it also floods occasionally.

Incorporating the data from the gauges installed by WWBWC-OSU resulted in several complicating factors. These data records began with transducer installation in May of 2010, while the model was developed with data from 2007 through 2009. To estimate unknown inflows I looked for a consistent proportional relationship between the small tributaries and the flow records in the Touchet River. Data from the transducer gauges was used to establish the relative magnitude of these inflows. Where there was not enough data to make this sort of estimate, particularly in the case of the Pine Creek drainage, a mass balance approach was applied, using the gauges in the mainstem Walla Walla River along with known inflows and diversions to estimate the inflow from these streams. This approach does not account for water withdrawals and groundwater interaction in these channels within the model area.

Altogether, the group of transducers installed by the WWBWC-OSU team for this project can be considered good indicators for wet versus dry conditions in these streams, and the relative magnitude of the smaller tributaries. Specific flow rate estimates have a large margin of error due to uncontrollable circumstances. The magnitude and distribution of error is a topic to be addressed later in this report. Improving estimates of the Pine Creek drainage would be particularly valuable for future improvements to the model and an improved understanding of the basins’ hydrologic budget.

5.5 Irrigation

The region represented in this model includes three irrigation districts, the Hudson Bay Development Company (HBDIC), the Walla Walla River Irrigation District (WWIRD), and Gardena Farms Irrigation District (GFID). The WWIRD and HBDIC irrigation districts are both supplied by a
diversion from the Walla Walla mainstem into the Little Walla Walla Canal. Water is distributed between the two districts via a network of canals and pipelines, many originating at a structure in Milton Freewater commonly known as ‘the Frog’; several lateral pipelines are also used to supply water to farmland. The GFID is served by the Gardena canal (also referred to as the Burlingame Canal), supplied by a diversion structure in the Walla Walla River at Beet road.

Highly permeable streambeds are a factor that must be accounted for in the ability of irrigation districts to meet their water user demands. The Little Walla Walla Canal is an example where gauge data can be used to give good estimates of seepage losses between the headgate of the diversion from the Walla Walla River and the gauged branches at the Frog (figure 5.8).

---

**Figure 5.8**: Estimated seepage loss from the Little Walla Walla Canal between the point of diversion on the Mainstem River and ‘the Frog’ in Milton-Freewater, Oregon. Seepage in this canal reach can be estimated from the difference between the gauged flows represented by the red (upstream) and blue (downstream) lines on this graph. 1 M³ per second = 35.3 cfs.

*Combined gauge estimate includes estimated flows for Milton ditch and East Crockett Branch canal.
The issue of canal seepage has led to an ongoing effort to convert earth lined canals into pipelines, in an attempt to reduce seepage losses. This has a direct cost in terms of the expense of pipe installation, and the unintended consequence of reducing an important source of groundwater recharge. Quantifying the relationship between irrigation demands, stream leakage rates, and groundwater levels is an important objective of this modeling effort, and will be addressed in greater detail in the discussion of model outputs and scenarios. The WWBWC and Army Corps of Engineers have both attempted to measure the seepage rate of some irrigation canals in the basin (Baker, 2010) (USACE, 1997). The mean daily gains and losses of stream reaches as calculated in the model are shown in figure 5.9. Springs are generally gaining as would be expected, while other canals are primarily losing. The mainstem Walla Walla River alternates between gaining and losing reaches. These results generally concur with the seepage analysis published by the WWBWC (Baker, 2009). It should be noted when scrutinizing this map that the seepage rates are an annual average, though many of the canals are not operated through the winter, and therefore their seepage occurs over the six to eight months in which they are in use.
Figure 5.9: Mean seepage for model area streams over the four year simulation period, in meters per day over the channel bed area as calculated by IWFM. Blue streams indicate a net gain from groundwater, red, orange, yellow are losing, while green is neutral, in some cases indicating piped sections.

All streams and canals within the model were assigned to one of eleven irrigation regions. Each of the three primary irrigation districts is considered an irrigation region. The other regions include spring fed channels, the Mud Creek drainage, small tributaries, and the Walla Walla mainstem. The regions as they are defined in the model are shown in figure 5.10.
Figure 5.10: Irrigation regions as considered for the IWFM model. The HBDIC, WWRID, and GFID irrigation districts have gauged inputs. The other regions used estimates and personal communication with irrigation managers and WWBWC personnel to determine flow rates and timing.

The primary irrigation districts are gauged at their respective headgates, and several of the canal branches are also gauged. Many of the tertiary canals, however, are not gauged and estimates incorporated into the model are based on consultation with irrigation district managers, generally as a proportion of flow diverted from the source channel. Gauges are subject to varying degrees of error due to field conditions. The gauges maintained by WWBWC have been assigned reliability ratings of 1 to 4 (1 being the highest). These ratings were considered during the process of making model adjustments, generally by disregarding unreliable gauge data where it appeared to conflict other gauges.

Within the irrigation districts, seepage, runoff, and return flows are calculated by the model based on input data and hydrologic parameters. Bypasses are determined by gauge data.
wherever possible as previously discussed. Figure 5.11 shows the locations of bypasses in the model area and table 5.2 summarizes their data sources; specific input data is included in appendix B.

Figure 5.11: Locations where water is diverted from one channel to another, referred to as bypasses, as incorporated in the Walla Walla Basin IWFM model. Numbers correspond to the bypass numbers in table 5.2.
Table 5.2: Summary information for all bypasses in the model. Bypass flow rates are calculated using the formulas listed in the chart.

<table>
<thead>
<tr>
<th>Bypass #</th>
<th>Export-upstream node</th>
<th>from segment</th>
<th>Import-downstream node</th>
<th>to segment</th>
<th>Formulas - Information source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13</td>
<td>WWR</td>
<td>250</td>
<td>16 LWW</td>
<td>OWRD Little Walla Walla gauge</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>1 WWR</td>
<td>84</td>
<td>2 East side pipeline</td>
<td>est-see irrigation worksheet</td>
</tr>
<tr>
<td>3</td>
<td>90</td>
<td>2 East side pipeline</td>
<td>108</td>
<td>3 East side pipeline</td>
<td>est-50% of flow</td>
</tr>
<tr>
<td>4</td>
<td>107</td>
<td>2 East side Pipeline -end</td>
<td>123</td>
<td>5 WW mainstem</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>5</td>
<td>268</td>
<td>16 Frog</td>
<td>599</td>
<td>36 FORD</td>
<td>1.05*wwbwc gauge 205-bypass 11</td>
</tr>
<tr>
<td>6</td>
<td>269</td>
<td>17 Frog</td>
<td>1197</td>
<td>51 White ditch</td>
<td>OWRD White Ditch gauge</td>
</tr>
<tr>
<td>7</td>
<td>274</td>
<td>17 Frog</td>
<td>298</td>
<td>18 Crockett</td>
<td>WWBWC gauge 207+206</td>
</tr>
<tr>
<td>8</td>
<td>303</td>
<td>18 Crockett</td>
<td>560</td>
<td>35 W Crockett</td>
<td>WWBWC gauge 207</td>
</tr>
<tr>
<td>9</td>
<td>352</td>
<td>2 East Little Walla Walla R</td>
<td>487</td>
<td>32 Wells ditch</td>
<td>est-Hall Wentland recharge site flow or 30% LWCI</td>
</tr>
<tr>
<td>10</td>
<td>407</td>
<td>26 Walla Walla mainstem</td>
<td>2081</td>
<td>76 Gardena Farms diversion</td>
<td>GFID diversion gauge at Beet Road</td>
</tr>
<tr>
<td>11</td>
<td>600</td>
<td>36 Frog (via West Ford)</td>
<td>1284</td>
<td>52 Milton Ditch</td>
<td>15% WWRID (May-August), 7% WWRID (September-April)</td>
</tr>
<tr>
<td>12</td>
<td>629</td>
<td>36 ford</td>
<td>955</td>
<td>46 Mud creek</td>
<td>gauge-wwbwc 301</td>
</tr>
<tr>
<td>13</td>
<td>760</td>
<td>39 WWR</td>
<td>811</td>
<td>40 Lowden lateral</td>
<td>est-35% of GFID</td>
</tr>
<tr>
<td>14</td>
<td>818</td>
<td>40 Lowden lateral</td>
<td>877</td>
<td>41 Lowden ditch</td>
<td>est-50% of bypass 13</td>
</tr>
<tr>
<td>15</td>
<td>922</td>
<td>41 End Lowden Lateral</td>
<td>1149</td>
<td>49 Mud Creek</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>16</td>
<td>1214</td>
<td>51 White ditch</td>
<td>1304</td>
<td>53 Powell-Pleasantview</td>
<td>est-7% of White ditch</td>
</tr>
<tr>
<td>17</td>
<td>1219</td>
<td>51 White ditch</td>
<td>1352</td>
<td>54 Umapine Ditches</td>
<td>est-50% of White ditch after bypass 16</td>
</tr>
<tr>
<td>18</td>
<td>1283</td>
<td>51 Pine creek</td>
<td>1837</td>
<td>69 White reservoir</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>19</td>
<td>1303</td>
<td>52 End Milton ditch</td>
<td>1307</td>
<td>53 Powell-Pleasantview</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>20</td>
<td>1361</td>
<td>54 White ditch</td>
<td>1445</td>
<td>56 Highline Canal</td>
<td>est-40% of bypass 17</td>
</tr>
<tr>
<td>21</td>
<td>1394</td>
<td>54 Huffman ditch</td>
<td>1428</td>
<td>55 Huffman Pipeline</td>
<td>est-20% of flow</td>
</tr>
<tr>
<td>22</td>
<td>1399</td>
<td>54 Huffman ditch</td>
<td>1673</td>
<td>61 Huffman pipe</td>
<td>based on WWBWC gauges 408-410</td>
</tr>
<tr>
<td>23</td>
<td>1409</td>
<td>54 Huffman pipe</td>
<td>1701</td>
<td>64 Johnson pipe</td>
<td>est-50% of flow</td>
</tr>
<tr>
<td>24</td>
<td>1444</td>
<td>55 Huffman ditch</td>
<td>1507</td>
<td>56 Highline Canal</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>25</td>
<td>1508</td>
<td>56 Highline tailout</td>
<td>2148</td>
<td>76 Gardena canal</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>26</td>
<td>1878</td>
<td>69 White reservoir outflow</td>
<td>1923</td>
<td>70 Pine creek</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>27</td>
<td>2237</td>
<td>76 Gardena canal</td>
<td>2356</td>
<td>79 North lateral Gardena canal</td>
<td>All remaining flow</td>
</tr>
<tr>
<td>28</td>
<td>491</td>
<td>32 Wells ditch</td>
<td>0</td>
<td>32 Hall-Wentland recharge site gauge</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>1226</td>
<td>51 White ditch</td>
<td>0</td>
<td>51 HBDIC recharge site gauge</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>2126</td>
<td>76 Gardena canal</td>
<td>0</td>
<td>76 Locher road recharge site gauge</td>
<td></td>
</tr>
</tbody>
</table>

The remaining factor in the water budget is withdrawals for irrigation, which are referred to in the model as diversions. To create flexibility in the model, every third stream node is listed as a potential diversion point, unless it is the top or bottom of segment. These points can be conceptualized as individual taps that can be turned on or off. Each diversion is...
controlled by the stream segment and irrigation district in which it lies. Using the model input worksheets (see appendix B) entire stream segments can be turned on or off, controlling every diversion within that segment. For finer tuning, individual diversions can be switched on or off in an overwrite column. This allows diversion allocation to be weighted within a segment, because withdrawals may occur disproportionately within a stream segment, particularly a longer one. Each irrigation region is assigned a daily flow rate for the entire model period (figure 5.12). The input worksheets count the number of diversions switched on for each irrigation region, and divide the total flow in the region by that number. The resulting number is the prescribed flow rate for the individual diversions (figure 5.13).

Figure 5.12: Total flow for Irrigation regions as considered for the Walla Walla Basin IWFM model. Spring fed channels and small tributaries are also defined as irrigation regions but not considered to be in use, therefore they are not included on this graph. 1 M³ per second = 35.3 cfs.
Figure 5.13: Flow rate per diversion in model. Individual diversion rates are calculated by dividing the total flow in the irrigation region by the number of diversion points turned on in the given region.

If a stream is dewatered and cannot deliver the prescribed diversion, the diversion is simply not met and this is accounted for as a diversion shortage in the model output stream and diversions budgets. If this results in crop requirements going unsatisfied through surface water withdrawals, then the model automatically simulates groundwater pumping to meet the demand. This results in an important similarity between simulated and actual water allocation in that surface water is the first choice source for irrigation, and groundwater is used when it is not available.

Currently, all elements in the model have the potential to receive irrigation flow. This is accomplished by assigning each element a diversion from which it can receive irrigation. This was done using spatial analysis tools in GIS to determine the closest diversion to each element, resulting in each diversion supplying a group of typically 40 to 60 elements, resulting in a pattern illustrated in figures 5.14 and 5.15. It should be noted that if a diversion is switched off the associated elements do not receive irrigation.
Figure 5.14: A depiction of the areas irrigated by each stream segment. Colors represent groups of elements that are irrigated by the channel segment that flows through each color block.

Figure 5.15: Detail of stream diversion points (yellow) and their associated areas of irrigation. Each block of uniquely colored elements represent the area irrigated by the diversion point within it, provided the diversion is turned on.
The model would benefit from fine tuning the location of diversion points, as well as the areas receiving irrigation water from specific diversions, and the timing and flow rates of these diversions. This information could be obtained with more detailed inputs from irrigation managers, otherwise gauge data is the best available information source on which to base estimated diversion rates.

5.6 Springs

A crest of natural springs has historically occurred within the model area north of Milton-Freewater, though many of these have run dry or become intermittent as groundwater levels have declined (Figure 5.16).

![Figure 5.16: Locations of historic springs, aquifer recharge sites, and selected surface gauges. The White Ditch is highlighted.](image)
Flow rates in these springs are an observable and measureable indicator of the dynamics of surface water-groundwater interaction. Some springs have also proven to be highly responsive to irrigation and aquifer recharge. Generally, groundwater levels peak in the spring and are at their lowest point in the fall. The effect of irrigation is to generate flow in springs in late August and September due to canal seepage and percolation from farmland. This is a difficult effect to replicate in the simulation because these flows are likely to be highly sensitive to local irregularities in subsurface conductivity due to heterogeneity beyond the resolution of available geologic data. Spring flow is also very sensitive to channel bed elevation. Water level and spring bed elevations were measured by WWBWC and OSU personnel in 2009 using a Magelllan Pro-Mark 3 GPS unit with a resolution of better than 1 centimeter; however the ground surface in the model is based on a 10 meter resolution DEM, which is the primary limitation on identification of spring emergence in the model. Simulating flow in springs is an excellent indicator of model performance because it represents a directly measureable correlation between field measurements and simulated conditions for both groundwater and surface water, provided that the effect of irrigation on spring flow can be accounted for. Stream bed elevations are entered for every stream node in the model, enabling an improved level of resolution with regard to stream-groundwater interactions. Simulation results at surface gauges and spring fed channels were variable, with greater correlation in cases where spring flow appears to be associated with water table fluctuation as opposed to springs that flow during times of high irrigation rates. Simulation outputs at several gauged springs are reviewed later in this report, following an explanation of the data analysis methodology used for this project.

The spring at the headwater of Johnson Creek has proven to be responsive to aquifer recharge operations at the HBDIC recharge site (Bower, Lindsey; 2010). This spring had not flowed in decades before water was diverted into this basin, but has since re-emerged periodically when the recharge site is in use (figure 5.17).
Figure 5.17: Johnson Creek before and after HBDIC recharge site operation. Images are from Bower and Lindsey; 2010.

Figure 5.18 highlights both the response of groundwater level to recharge site operation and the difficulty of simulating that response. The gauge at well 46 shows a strong correlation to the HBDIC recharge site and the IWFM outputs capture this reasonably well. The more subtle and delayed response observed in Johnson creek (fed by Johnson spring) is not well captured by the model at this point. The low flow rates in springs can be especially difficult to simulate because there is little margin of error. If the simulated water table is too low, modeled flow can be entirely absent at the spring location. In some cases checking a point downstream from the spring can account for this flow emerging down gradient from where it is expected. Updated data from WWBWC for Johnson spring should lend further insight into the models’ performance in this particular area.
Figure 5.18: Gauged and simulated response to inflow at HBDIC recharge site. Flow rates at Johnson spring are multiplied by 10 to highlight relationship to flow into HBDIC recharge basin. Groundwater elevation at monitoring well 46 is shown on the right axis.
6 Land and Water Use

6.1 Land use in IWFM

This section describes the urban, agricultural, and riparian areas of the portion of the Walla Walla Basin covered in this model. Of particular importance is the distribution of crops, their associated water requirements, and the typical soil characteristics of the region. The distribution of land use was compiled by surveys by WWBWC personnel (figure 6.1).

Figure 6.1: Land use map of model area provided by WWBWC. Subregions are outlined to show how they correspond to land uses.
The land uses above are simplified into 16 categories with the areal coverage of each defined for all 7 sub-regions (figure 6.2). Crop demand is calculated for each subregion based on these inputs and the characteristic water use for each crop as discussed in the following section of this report. Groundwater pumping is determined for each element as a function of element area and the proportion of urban and agricultural land uses within that element, and their respective water requirements. This input is defined in unit 13 of the IWFM simulation folder which broadly categorizes land within each element as agricultural, urban, riparian, and native vegetation. These values are determined for the model region with GIS spatial analysis. Water channels are included with riparian areas, industrial zones and roads are lumped with urban areas, and fallow pasture considered as being native vegetation.

![Image of land use allocation for IWFM Walla Walla Basin model](image)

**Figure 6.2:** Land use allocation in the model area by subregion. Alfalfa, pasture and wheat are the most prevalent crop types.
6.2 Urban and Domestic Water Use

Milton-Freewater, Oregon, with a population of approximately 6500 people is the primary urban area within the model and its primary water source is the CRB aquifer ([www.mfcity.com](http://www.mfcity.com)). Urban and domestic water consumption was estimated for model inputs based on average per capita water consumption, area of model sub-region, and population density. U.S. Census Bureau statistics were used to estimate the respective populations within each subregion of the model (table 6.1). Estimates for the rural portion of the model area were based on the 2000 U.S. census for Walla Walla and Umatilla counties, with the urban populations and land area as subtracted from the total values. The remaining figures were used to calculate the population density of the non-urban areas of these counties, and USGS figures were used to estimate per capita water use. Subregion 2 of the model area corresponds to the city of Milton Freewater for which census statistics were directly available. The other subregions were assigned population numbers based on their total area and the estimated rural population density within the county.

Table 6.1: Population statistics and per capita water use estimates applied to the model area. Population centers are subtracted from county population statistics to obtain rural population density for counties included within the model ([US Census Bureau, 2000](https://www.census.gov)).

<table>
<thead>
<tr>
<th>Per capita water use</th>
<th>100 gallons per day (USGS, 2005)</th>
<th>People per KM²²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Umatilla County (excluding Umatilla, Pendleton, and Hermiston, OR)</td>
<td>3.6</td>
<td></td>
</tr>
<tr>
<td>Walla Walla county (excluding Walla Walla and College place, WA)</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Milton Freewater, OR</td>
<td>1329</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model subregion</th>
<th>Area (KM²²)</th>
<th>Estimated population</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3.9</td>
<td>5480</td>
</tr>
<tr>
<td>3</td>
<td>28.5</td>
<td>102</td>
</tr>
<tr>
<td>4</td>
<td>80.3</td>
<td>286</td>
</tr>
<tr>
<td>5</td>
<td>55.9</td>
<td>296</td>
</tr>
<tr>
<td>6</td>
<td>55.7</td>
<td>295</td>
</tr>
<tr>
<td>7</td>
<td>6.3</td>
<td>33</td>
</tr>
</tbody>
</table>
The estimate of 0.378 M$^3$ (100 gallons) per person per day was considered a baseline value which was assumed to have significant seasonal variation. The figure was increased by 50% from July through September to account for domestic landscaping, and decreased over the peak winter months. These estimates are summarized in figure 6.3.

![Figure 6.3: Estimated municipal and domestic water use withdrawn from gravel aquifers for each model subregion. Subregion 2 is the city Milton-Freewater, Oregon; the largest population center in the model area. The majority of the city’s water supply comes from wells in the Columbia Basalt aquifer, and is therefore accounted for with the diversions associated with inputs from this source.](image)

6.3 Agricultural Water Demand in IWFM

Agricultural water demands are computed by IWFM as a function of crop water consumption and irrigation efficiency. It is assumed that some water designated for irrigation is lost to deep percolation and some to evaporation. These are respectively designated as recoverable and non-recoverable losses and set by the model user in unit 25 of the IWFM simulation folder. Efficiency is related to soil properties and irrigation style as reflected by user input data. This is in turn calculated based on a formula for the consumptive use of applied water (CUAW) necessary to sustain optimum agricultural conditions as determined for each
subregion. The following series of equations are used by IWFM to calculate agricultural demand while supply is dictated by user inputs and settings.

\[ D_{ag}^{t+1} = \frac{CUAW^{t+1}}{Eff_{sa,avg}^{t+1}} \]

\[ CUAW_{t+1} = \frac{(Dr^{t+1}\theta_{min}^{t+1} + ET_c^{t+1}\Delta t - (Dr^{t}\theta_{rp}^{t} + Ip^{t+1}\Delta t))}{\Delta t} \]

\[ Eff_{sa,avg}^{t} = \frac{CUAW^{t}}{AW^{t}} = \frac{CUAW^{t}}{(CUAW^{t} + Dp + Rf)} \]

Where,

\( D_{ag} \): Agricultural water demand (M/day);

\( CUAW \): Consumptive use of applied water, calculated by subregion (M/day);

\( Eff_{sa,avg} \): Crop weighted average seasonal application efficiency (dimensionless);

\( \theta_{min} \): Minimum soil moisture requirement (M/M);

\( ET_c \): Evapotranspiration rate under standard conditions (M/day);

\( Dr \): Thickness of root zone (M);

\( \theta_{rp} \): Available soil moisture in storage from previous time step (M/M);

\( Ip \): Infiltration from precipitation (M/day);

\( AW \): Applied water (M/day);

\( t \): Time;

\( Dp \): Deep percolation that is not reused (M/day);

\( Rf \): Return Flow that is not reused (M/day).

(IWFM Theoretical Manual 3.0, 2007)
6.4 **Crop Water Consumption**

Evapotranspiration (ET) accounts for the majority of water consumption in agriculturally productive areas requiring irrigation, such as the Walla Walla Basin. Transpiration rates differ by crop with respect to growing season, root depth, and water uptake efficiency. These factors are all specified in model inputs based on values in the FAO 56 (Food and Agriculture Organization of the United Nations) reference manual for ET estimation (Allen et al, 1998). The daily ET also varies with weather conditions and antecedent soil moisture. The data sources for obtaining daily ET measurements are the same Ag-Weather net stations where precipitation is recorded at Walla Walla, College Place, and Touchet Washington. The stations measure air temperature, wind speed, relative humidity, and solar radiation, and apply these parameters to the Penman Montieth equation to calculate a reference ET value. Reference ET refers to the ET rate of a specified plant, in this case grass, expressed in mm per day. Reference ET is then adjusted for each crop within the model region using a crop coefficient, a value used to derive the ET rate of a given crop in comparison to the reference ET. The crop coefficients used in the model are also based on those published in the FAO 56. These values vary seasonally and by crop, with typical growing season for Kimberly Idaho being used as a reference for climate conditions in the Walla Walla Basin. Table 6.2 shows seasonal crop coefficients and growing season length adapted from the estimates in FAO 56. Greater detail for these inputs is included on the ‘Crops’ worksheet in appendix D.

\[ \text{ET}_c = \text{ET}_o \times K_c \]

Where,

\( \text{ET}_c \): ET rate for specific crop (M/day);

\( \text{ET}_o \): Reference ET-grass (M/day);

\( K_c \): Crop Coefficient (dimensionless).
Table 6.2: Seasonal crop coefficients and growing periods used to generate daily ET estimates in the model. The first 13 categories are defined by the model user and the last 4 categories are specified by IWFM.

<table>
<thead>
<tr>
<th>Crop Coefficients</th>
<th># of days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop</td>
<td>Initial Planting</td>
</tr>
<tr>
<td>Alfalfa-hay</td>
<td>April</td>
</tr>
<tr>
<td>Apples</td>
<td>March</td>
</tr>
<tr>
<td>Pasture</td>
<td>March</td>
</tr>
<tr>
<td>Grapes</td>
<td>May</td>
</tr>
<tr>
<td>Cherries</td>
<td>March</td>
</tr>
<tr>
<td>Row crops (see onions in FAO 56)</td>
<td>October-January</td>
</tr>
<tr>
<td>Nursery; equal to orchard</td>
<td>March</td>
</tr>
<tr>
<td>Grass lawn</td>
<td>March</td>
</tr>
<tr>
<td>Wheat; Non-irrigated (winter wheat)</td>
<td>October</td>
</tr>
<tr>
<td>Wheat; irrigated (35-45 lat)</td>
<td>March-April</td>
</tr>
<tr>
<td>Domestic rural (see turf grass in FAO 56)</td>
<td>March-October</td>
</tr>
<tr>
<td>Orchards (see peaches in FAO 56)</td>
<td>March</td>
</tr>
<tr>
<td>Pastoral land management</td>
<td>March</td>
</tr>
<tr>
<td>City (includes roads, industrial)</td>
<td>March-October</td>
</tr>
<tr>
<td>Native vegetation; fallow fields</td>
<td>March-October</td>
</tr>
<tr>
<td>Riparian areas, water channels (see deciduous trees in FAO 56)</td>
<td>March</td>
</tr>
<tr>
<td>Bare soil (equal to native vegetation)</td>
<td>March-October</td>
</tr>
</tbody>
</table>

The ET output derived from the above formula is illustrated for several crops and land types in figure 6.4. This chart shows the rate of estimated ET for subregion 4, the largest of the model subregions. Reference ET, like precipitation, was interpolated between the three closest gauges with regard to elevation. A rate was determined for each subregion using mean elevations to characterize each subregion.
Figure 6.4: Selected ET rates (mm/day) for the four year (2007-2010) simulation period.

It can be noted from figure 6.4 that non-irrigated wheat tends to have the highest peak ET rate due to the deep roots that enable it to survive without irrigation, though it quickly declines due to senescence. Alfalfa has relatively low water demand and a fast growth cycle enabling 3 harvest cycles per year, explaining why it is the crop of choice for much of the model region, particularly the driest areas.

6.5 Soil Characteristics

Soil data was collected using NRCS soil surveys available on the internet to determine values for the physical soil properties in ‘root zone parameters’ section of IWFM simulation.
folder unit 7. The parameters specified are field capacity (measures of the capacity of soil to retain water), porosity (measures potential storage volume in the vadose zone), SCS curve number converted to metric units in accordance with Dogrul (2008)(corresponding to runoff potential), and hydraulic conductivity.

The survey data was acquired by defining each model sub-region as an area of interest for which a soil map was produced. Each map has a corresponding list of soil types present with qualitative and quantitative information about their physical and hydrologic properties. Further analysis was based on soil types that covered 4.5% or more a given subregion. This simplified the data analysis process by eliminating roughly half the soil types while still including most of the areal coverage. Weighted averages were taken based on coverage area, to determine parameter values 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 published in Ward and Trimble, 2004. Agricultural is the dominant land use classification with the exception of sub-region 2 which covers the town of Milton-Freewater. Table 6.3 summarizes the soil parameters values used in the model.
Table 6.3: Soil properties used in model based on compiled data from NRCS web soil survey. Curve numbers are converted to metric in model input in accordance with Dogrul (2008), though here they remain as published for reference purposes.

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

Water stored in soil is a significant component of the hydrological budget. The budgets from this simulation reveal that soil is generally near its minimum moisture requirement because irrigation rates are determined from crop demand, and are therefore similar to evapotranspiration rates except in times of heavy rainfall. This is evident in the soil water budget included in the ‘water budgets’ section of this report. The following conservation equation is used by IWFM to calculate the volume of water is soil storage. The terms in the equation are user defined (i.e. thickness of root zone) or calculated based on user inputs (i.e. actual crop evapotranspiration).
\[ \frac{\partial D_r \theta_r}{\partial t} = I_{fp} + I_{aw} - ET_{cadj} - D_p \]

Where,

\( D_r \) = Thickness of root zone (M);

\( \theta_r \) = Soil moisture in root zone (M/M);

\( I_{fp} \) = Infiltration of precipitation (M/day);

\( I_{aw} \) = Infiltration of applied water (M/day);

\( ET_{cadj} \) = Actual crop evapotranspiration (M/day);

\( D_p \) = Deep percolation (M/day);

\( t \) = time.

(IWFM Theoretical Manual v3.0, 2007)
7 Simulation Output Data Analysis

7.1 IWFM Data Output controls

The development of the IWFM model of the Walla Walla Basin hinges on the compilation and processing of data for model inputs. Model outputs are then compared to this data to guide further revision and finally to quantify components of the hydrological system in terms of budgets and make predictions for hypothetical scenarios based on model outputs. This requires scrutinizing the degree and distribution of error in model outputs for both surface water and groundwater.

IWFM includes an input module (unit 10 in the simulation folder) in which the user enters the groundwater and stream nodes for which well time series and stream hydrographs are desired. There are options to specify the time step of the outputs and the aquifer layers for which to print groundwater head. These hydrograph outputs are the basis for assessing model performance. Data is compiled and assessed in terms of root mean squared error, mean relative error, and correlation coefficient. The details of processing and analyzing simulation outputs for groundwater and surface water are given below.

7.2 Groundwater Output Analysis

IWFM produces an output that shows groundwater head in each aquifer at every node of the model region; this can be useful for investigating simulation outputs where well data is not available, however the output file is very large and not ideal for quantitative evaluation of performance. For quantitative analysis simulation outputs must be compared to recorded data from wells for the points of where the wells were located. The result of subtracting the simulated water level from the recorded water level at a given point in time is referred to as the residual. A negative value of the residual means the simulation is too high and a positive value means the simulation is too low.

The model produces an output text file of hydrographs at the nodes specified by the user. In this case these are the nodes corresponding to the 64 wells in the model area for which
there is data available, though several of these wells were excluded from data analysis due to unreliable or sparse data (i.e. one or two measurements). This output can copied and pasted onto the ‘Groundwater Results’ page of the model analysis sheet where it is converted to monthly averaged data and compared to the entire set water table elevation data (also converted to monthly averages). The data is then reflected in the ‘Groundwater analysis’ worksheet which includes a column for observed data while the monthly averaged simulated data automatically appears in the next column while the residuals and squared residuals are calculated in the following columns. The first columns of the sheet list important information such as the well identification and date. Graphs of observed versus simulated data are also included for each well and updated automatically when new data is applied. The complete model outputs and data processing worksheets are included as appendix E of this report.

Statistics summarizing the overall results of the simulation output that is pasted on the results page are compiled on a worksheet entitled ‘Summary Data’. This sheet consists of columns listing statistical outputs for each individual well. Each well has a mean residual and correlation coefficient associated with it. The groundwater outputs for the entire simulation are summarized by the calculation of a standard deviation for all squared residuals which can be considered as a mean error, a mean of the correlation coefficients for all the gauges, and a mean of the mean residuals at each gauge. The latter of these values is flawed because high and low values gauges can cancel each other out, and it is biased by the uneven distribution of wells. It can only be considered as a general indication of whether the simulated water table is too high or low, or to give a general sense of the effect of a particular adjustment during calibration. Nash-Sutcliffe efficiency is also listed for reference but is not a metric particularly well suited to the evaluation of this model’s performance. This formula compares the model residual to the residual between observed value and a mean observed value for the well in question. The issue with it is that the uncertainty of elevation and aquifer thickness data is greater than the range of water table variability at a given point. For this reason, an average groundwater head elevation frequently gives a closer estimate at a given point than simulated output, though it captures none of the temporal behavior of the water table. The output is included in the analysis sheet in case it can be applied in future iterations of the model.
7.3 **Surface Water Output Analysis**

The analysis of surface water outputs is very similar to that of groundwater. The hydrographs are printed for selected nodes that correspond to gauges in the model area. The nodes, gauges, and monthly average flow rate are listed in columns on the ‘Surface Water Analysis’ worksheet included in appendix E. Once the hydrograph outputs are copied and pasted onto the ‘Surface Water Results’ page, monthly average flows are calculated and appear in a column for simulation values in the appropriate row, specified by gauge identification and date. Graphs of gauged versus simulated flow rates appear adjacent to each listed gauge.

Summary statistics are also calculated in a set of columns on the summary data worksheet. Statistics for each gauge and the simulation as a whole are included. Each gauge has an associated correlation coefficient, and the mean correlation coefficient for all the gauges is used to generate a representative value for the entire model. Each gauge also has a mean residual and a mean flow rate. The residual is divided by the flow rate and multiplied by 100 to calculate the mean residual at that gauge as a percentage of flow so that large and small streams can be compared to each other. The absolute values of these percentages are also listed and their sum is divided by the number of gauges. The resulting value is the mean percent error for all gauges. Nash-Sutcliffe efficiency is again listed for surface water gauges and again a disclaimer is attached to this value: In the case of surface water gauges the Nash-Sutcliffe efficiency is deceptively high because it is dominated by gauges with the highest flow, i.e. the mainstem Walla Walla River. The model tends to have the best outputs in the mainstem river, while the gauges where the simulation has a high degree of error often occur where flow is very low, so these results appear inconsequential in the this term.
8 Model Calibration and Validation

8.1 Hydrological Model Calibration Theory

The calibration of a hydrological simulation such as the IWFM Walla Walla Basin model is a process of seeking the best possible representation of the physical characteristics of the model region and parameter values that compensate for the entrained errors. Physical conditions must constitute the guidelines of calibration in order to have a credible outcome; however the structure of the model and limitations of available data ensure that the model cannot be entirely accurate. Gupta et al. (1998) argue that there is a point at which increased data collection will not benefit the modeling effort and instead suggests a multi-objective approach to calibration. They elaborate on this by making the point that having “informative data” is more important than having a large volume of data. This suggests it may be wise to assess the areas where the available data is lacking in case a few representative measurements are available or there is information from a comparable site that can be used to determine a baseline value to begin adjustments. The goal of calibration is to find a set of parameters that minimize model error for the given data set and can be validated by applying them to a different data set for the same model, while maintaining model performance. This objective requires a strategy that acknowledges the limitations of hydrological modeling and employs a systematic approach to parameter adjustment. This can be complicated by the problem of equifinality.

Beven (2006) points out that in models with many parameters, outputs that best fit the observed data may be produced by more than one set of input variables. This may be due to errors in input data, parameter uncertainty, or model structural uncertainty. One way that some modelers avoid this problem is to create an optimization function which systematically adjusts parameters toward a best fit result, while providing an estimated margin of error. This process often requires imposing assumptions or constraints on the model inputs that may not reflect physical conditions. Structural errors in the model stemming from the numerical solutions may also be a significant factor that is not accounted for in the calibration process. The result of these considerations is that optimization may cause the modeler to ignore
permutations of parameter sets that produce simulations that are well within the range of model error (Beven, 2006).

For this model a multi-objective optimization approach was employed for calibration. This was based on an example described in Blasone et al. (2006) in which the authors calibrated a model for both rainfall-runoff response and groundwater head using an aggregate optimization function \( F_{\text{aggr}} \) that weighted the error contributions of these factors with regard to mean squared error (MSE).

\[
F_{\text{aggr}}(\theta) = w^r \text{MSE}_r(\theta) + w^w \sum \text{MSE}_w(\theta)
\]

Where,

\( F_{\text{aggr}} \): Aggregate optimization value;

\( \theta \): Parameter vector;

\( w^r \): River runoff weight;

\( w^w \): Groundwater level weight.

(Blasone et al, 2006)

The above equation was used as a starting point for developing an objective function for the calibration of the Walla Walla Basin model. It was modified by applying it to outputs at surface water and groundwater gauges respectively and incorporating several other analysis metrics into the calibration process. For groundwater, standard deviation for the entire set of model residuals was considered to indicate the magnitude of error for groundwater head elevation in terms of meters. Correlation coefficient is a metric used to show the relationship of trends in the simulated outputs to observed data independent of their respective heads. Excel uses the following equation to produce a correlation coefficient value between -1 and 1; if
this value is above .5 it is considered a strong correlation, below .2 is a weak correlation, and a negative value means there is no correlation (Cohen, 1988).

\[
\text{Correlation Coefficient (X,Y)} = \sqrt{\frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2\sum(y - \bar{y})^2}}
\]

\(X, Y\) : Two arrays of numbers with the same numbers of values

It was apparent during calibration that some wells showed strong correlation between observed and simulated conditions while having significant differences in groundwater head. At other wells simulated heads matched the range of observed heads but seasonal variability was unsynchronized. These issues may originate from several factors including geologic heterogeneity not accounted for in the model inputs or localized irrigation practices creating mounded regions of the water table that are not apparent in the simulated output. It may also be that the characteristics of specific wells such as their depth, cones of depression in the surrounding water table, or localized clogging in the aquifer were not captured in the simulation.

For surface water similar statistics were used guide calibration. Correlation coefficient was applied to the surface gauges, and the error at each gauge was also considered as a percentage of the recorded flow at that gauge; a metric known as mean relative error (MRE) (Du et al., 2009). This was applied to account for the wide range of discharge volumes in different channels, the range of errors could not reasonably be considered in terms of flow volume alone.
\[
\text{MRE} = \frac{\sum_{i=1}^{n}(Pi - Oi)}{\sum_{i=1}^{n}(Oi) * 100}
\]

Where,

MRE : Mean relative error;

P : Predicted flow rate;

O : Observed flow rate.

(Bing et al., 2009)

To calibrate this model based on the factors described above, I developed an objective function in which these four criteria were scaled such that they each had the same range between their best and worst values. This entailed using an excel worksheet listing all simulation trials in the rows and the outputs values for the criteria described above listed in columns. The best and worst values among the entire set of simulations was identified for each of the analysis metrics to define the range of output values. The standard deviation of well gauges and MRE of surface gauges were then transformed by subtracting their values from 10 and 100 respectively so that the goal would be to maximize each value. The range from each analysis criterion was then scaled by dividing it by the range of the transformed standard deviations to determine a weight for each metric. Each analysis metric from a given simulation output was then multiplied by its associated weight; at this point all four of the metrics were scaled so that they had the same range of values. The scaled mean correlation coefficient for groundwater was multiplied by 1.2 to give this metric an extra influence in determining the best simulation. This was because of the error entrained in model development that was assumed to originate from the 10 meter DEM used to define surface elevations. This appeared to manifest itself in some gauges as a vertical offset such that a particular gauge may have a strong correlation between observed and simulated data but significant vertical error. The multiplier was applied to make this type of error less influential than cases where there was a poor
correlation between temporal trends of observed and simulated values. The objective function was applied to the results of each simulation trial using the following equation:

\[(10 - \text{GWSD}) + \text{GWCC} \times \text{GWCC}_w + (100 - \text{MRE}) \times \text{MRE}_w + \text{SWCC} \times \text{SWCC}_w\]

Where,

- \(\text{GWSD}\): Standard deviation of residuals at groundwater gauges (weight is 1);
- \(\text{GWCC}\): Mean correlation coefficient of groundwater gauges;
- \(\text{GWCC}_w\): Weight associated with GWCC;
- \(\text{MRE}\): Mean relative error of surface water gauge as a percentage of observed flow;
- \(\text{MRE}_w\): Weight of MRE for surface water gauges;
- \(\text{SWCC}\): Mean correlation coefficient of surface water gauges;
- \(\text{SWCC}_w\): Weight of SWCC.

In this equation groundwater standard deviation and surface water MRE are transformed using the same method that was applied for the scalar adjustment of the analysis metrics. With this transformation the goal of calibration is to maximize each term in the objective function.

### 8.2 Parameter Sensitivity Analysis

The model development process requires numerous input parameters for which few physical measurements are available. All of these have the potential to be considered
calibrating parameters; however it is not feasible to calibrate all of them due to time limitations. The first step of calibrating the Walla Walla basin model was to determine the sensitivity of numerous parameters so that the calibration effort could be focused where it would have the greatest impact. This was done by selecting 25 parameters that were initially estimated in the model development stage and testing the impact of increasing and decreasing each parameter individually. Each parameter was adjusted to the upper and lower limit of an assumed range, with care taken to balance these adjustments so that the high and low values were evenly distanced from the baseline. In a few cases initial adjustments caused convergence errors, so the degree of change was decreased in order to run a complete simulation. The most sensitive parameters for surface water and groundwater are listed in table 8.1 and a graphical overview of the relative sensitivity of all parameters tested is depicted in figures 8.1 and 8.2. The values used for these tests and a complete set of results are included as appendix I of this document.

Table 8.1: Most sensitive parameters for groundwater and surface water as determine by sensitivity analysis. This ranking was determined by scaling analysis metrics so that they had the same range of values and adding the absolute value of their degree of change from the baseline model.

<table>
<thead>
<tr>
<th>Groundwater</th>
<th>Surface Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MPC hydraulic conductivity</td>
<td>1 Stream bed conductivity</td>
</tr>
<tr>
<td>2 Stream bed conductivity</td>
<td>2 Fraction of recoverable loss</td>
</tr>
<tr>
<td>3 QC specific yield</td>
<td>3 Fraction of deep percolation</td>
</tr>
<tr>
<td>4 Fraction of recoverable loss</td>
<td>4 Irrigation fraction high</td>
</tr>
<tr>
<td>5 MPC vertical conductivity</td>
<td>5 Irrigation re-use factor</td>
</tr>
<tr>
<td>6 Irrigation re-use factor</td>
<td>6 Fraction of non-recoverable loss</td>
</tr>
<tr>
<td>7 MPC specific storage</td>
<td>7 Vadose zone hydraulic conductivity</td>
</tr>
<tr>
<td>8 QC hydraulic conductivity</td>
<td>8 Vadose zone porosity</td>
</tr>
<tr>
<td>9 Vadose zone hydraulic conductivity</td>
<td>9 Vadose zone thickness</td>
</tr>
<tr>
<td>10 Fraction of deep percolation</td>
<td>10 Root Zone porosity</td>
</tr>
</tbody>
</table>
Figure 8.1: Sensitivity of simulated groundwater outputs to parameters. Correlation coefficient represents the mean value from 63 wells and is scaled to have the same total range as the standard deviations. Parameters were tested by increasing and decreasing each one. In some cases, this caused a convergence error in the simulation, in which case the trial was retried with a lesser adjustment.
Figure 8.2: Sensitivity of simulated groundwater outputs to parameters. Correlation coefficient represents the mean value from 35 surface gauges and is scaled to cover the same total range as the values of mean relative error. Parameters were tested by increasing and decreasing each one. In some cases, this caused a convergence error in the simulation, in which case the trial was retried with a lesser adjustment.
It should be noted from these charts that the values are derived by subtracting the output criteria from the simulation with adjusted parameters a baseline version of the model. For standard deviation a positive value indicates that the adjusted parameter improved the model output. Correlation coefficient is the opposite where a higher number is desirable, so an improved simulation will yield a negative value when subtracted from the original version. The results of the sensitivity analysis clearly show that hydrologic conductivity of the MPC aquifer is the dominant parameter for standard deviation, while correlation coefficients are most sensitive to specific yield in the QC aquifer and the conductivity of stream beds. Specific storage and hydrologic conductivity of the MPC aquifer also have significant influence on correlation coefficients. For surface water stream bed conductivity and thickness were the most sensitive parameters, however these are directly related in the solution the streamflow continuity equation. For example if a stream bed thickness is doubled the flow through it will be reduced by half; if the conductivity is then doubled the exchange in that stream segment will be back to its original value. For this reason, it would not be productive to calibrate both variables. In this model stream bed thickness was considered a constant and conductivity was used as a calibrating parameter. Other parameters that showed to be sensitive for surface water outcomes were the fraction of recoverable loss (the amount of water from agricultural diversions that is assumed to percolate to groundwater) and the fraction of water in the vadose zone that becomes deep percolation.

Based on the results of the sensitivity analysis the calibration was performed by primarily using MPC aquifer hydrologic conductivity and stream bed conductivity, as well as adjusting the volume of diversions by irrigation region when necessary to balance other changes. Specific yield of the QC aquifer, specific storage in the MPC aquifer, the fraction of recoverable loss from diversions, the fraction of deep percolation from the vadose zone, and the conductivity of the vadose zone were used as secondary calibration parameters. Their respective values were adjusted within boundaries determined by literature review after significant changes were made to the primary parameters to improve overall simulation outcomes where possible.
8.3 Calibration of Selected Parameters

Calibration of the IWFM Walla Walla Basin model entailed an iterative approach to adjusting the selected calibration parameters, attempting to push the values toward the best overall fit between observed and simulated values. Often a changed value would improve the model output at one location while increasing the error at another. It was helpful to recognize trends in the adjustment process, such as increasing MPC hydrological conductivity would yield lowered groundwater head while decreasing the conductivity would have the opposite effect (figure 8.3).

![GW 28](image)

**Figure 8.3:** The effect of adjusting hydraulic conductivity from 16 to 45 m/day in the MPC aquifer during model calibration as observed at monitoring well GW 28 March 2007 through Dec 2009.

Stream bed conductivity was first estimated by WWBWC seepage analyses (Baker, 2009), and then calibrated using the stream segments as defined in the model. The goal was to tune simulation outputs with observed hydrological conditions. Increasing stream bed conductivity generally raised groundwater elevation and lowered stream flow; however in gaining stream reaches stream flow could increase dramatically with a more permeable channel
bed. In addition, varying hydraulic conductivity in some cases changed the condition of a stream from gaining to losing or vice versa.

The process of calibrating the conductivity of the MPC aquifer brought about significant complications because of the sensitivity of this parameter, coupled with the fact that there were some discrepancies where the model was too high and some where it was too low. In regions where closely spaced wells had residuals with opposing signs it was particularly difficult to adjust the model productively. The circled area on the right in figure 8.4 is an example in which simulated groundwater head at the wells upgradient was too high and the simulation output at the wells immediately downgradient was too low. Any attempt to compensate for one problem, if successful, exacerbated the other one. The opposite problem occurred in the vicinity of the HBDIC recharge site and immediately downgradient from it. The higher wells had positive residuals (simulated water table was too low) and lower wells had negative residuals because the simulated water table was too high.

Correlation coefficients were also used to guide calibration, both for particular areas and for the model as a whole. Some wells that showed poor correlation to simulation outputs may have been affected by pumping or other factors not accounted for in the model. The final mean correlation coefficient values for the wells used in model calibration are depicted in figure 8.5.
Figure 8.4: Wells used for model calibration are depicted with colors corresponding to their mean residual in the calibrated model (observed-simulated groundwater head). These residuals are also interpolated with inverse distance weighting to show trends in model error using the same color bar for residuals from the simulation output. Several areas are highlighted where closely spaced wells have opposing discrepancies, presenting a challenge for calibration.
Figure 8.5: Wells used for data analysis with points colored corresponding to mean correlation coefficient from the calibrated model. These values are also interpolated using inverse distance weighting with the same color gradient corresponding to the interpolated values.

The calibration process was centered on systematically adjusting the hydraulic conductivity of the MPC aquifer, the specific yield of the QC aquifer, and the conductivity of stream beds by segment. During this process I also periodically retested the secondary calibration parameters and reset the initial conditions based on model spin up. The parameter values reached through the calibration process are shown in table 8.2.
Table 8.2: Values of calibration parameters used in the model after completing calibration adjustments. Parameters with the highest sensitivity are listed as primary parameters and less sensitive parameters are referred to as secondary parameters. It is also specified if the parameter primarily affects groundwater outputs (GW), surface water outputs (SW), or both.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sensitivity Category</th>
<th>Calibrated Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC Hydraulic Conductivity</td>
<td>Secondary (GW)</td>
<td>90 Meters/day</td>
</tr>
<tr>
<td>MPC Hydraulic Conductivity</td>
<td>Primary (GW)</td>
<td>24 Meters/day</td>
</tr>
<tr>
<td>QC Specific Yield</td>
<td>Secondary (GW)</td>
<td>0.07</td>
</tr>
<tr>
<td>MPC Specific Yield</td>
<td>Primary (GW)</td>
<td>0.07</td>
</tr>
<tr>
<td>QC Storage Coefficient</td>
<td>Secondary (GW)</td>
<td>0.01</td>
</tr>
<tr>
<td>MPC Storage Coefficient</td>
<td>Secondary (GW)</td>
<td>0.00001</td>
</tr>
<tr>
<td>QC Anisotropy factor</td>
<td>Secondary (GW)</td>
<td>3</td>
</tr>
<tr>
<td>MPC Anisotropy factor</td>
<td>Secondary (GW)</td>
<td>8</td>
</tr>
<tr>
<td>Fraction of Recoverable loss</td>
<td>Secondary (GW, SW)</td>
<td>0.18</td>
</tr>
<tr>
<td>Fraction of Deep Percolation</td>
<td>Primary (GW)</td>
<td>0.55</td>
</tr>
<tr>
<td>Vadose Zone Conductivity</td>
<td>Secondary (GW)</td>
<td>0.3 Meters/day</td>
</tr>
<tr>
<td>Stream Bed Conductivity</td>
<td>Primary (GW, SW)</td>
<td>0 to 3 Meters/day*</td>
</tr>
</tbody>
</table>

*see appendix B for specific values by steam segment

8.4 Model Validation

Once a computer simulation model such as this one has been developed and calibrated, an important question remains. Are the parameters derived from the calibration process applicable only to fit the original data set used model development, or can they be used in a predictive sense for broader applications? The process of model validation is intended to address this question, establishing the applicability of the model for predicting future conditions given various climatic or management scenarios. In a distributed model such as this one, it is important to note that the model should only be considered valid for parameters that have been explicitly validated (Refsgaard, 1997). Therefore some of the budget predictions from this model should be regarded with skepticism in spite of the validation for the model as a whole.

It is reasonable to anticipate a slight increase in model error in the validation process; however the degree should give some indication of the robustness of the model or lack thereof.
In the case of this model the validation was accomplished by applying the parameters established through calibration with 2007 through 2009 data to the same model setup using 2010 data. This is referred to as a split-sample test. Boundary conditions were derived in the same manner as described earlier. The results of this effort are shown in table 8.3.

Table 8.3: Summary table of composite statistics for both the calibrated and validated model outputs. The ‘reliable gauges’ category disregards gauges assigned a WWBWC grade 4 rating. The increase in standard deviation and decrease in correlation coefficient both represent a decline in model performance, whereas the decrease in mean relative error for surface water gauges indicates an improvement over the validation period.

<table>
<thead>
<tr>
<th>Groundwater composite summary</th>
<th>Calibration period only (2007-2009)</th>
<th>4 year simulation period</th>
<th>Validation period only (2010)</th>
<th>% Change: Calibration vs. Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation (meters)</td>
<td>3.18</td>
<td>3.23</td>
<td>3.39</td>
<td>6.5</td>
</tr>
<tr>
<td>Variance</td>
<td>10.12</td>
<td>10.45</td>
<td>11.45</td>
<td>13.1</td>
</tr>
<tr>
<td>Mean Correlation Coefficient</td>
<td>0.631</td>
<td>0.592</td>
<td>0.475</td>
<td>-24.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Surface Composite Water Summary</th>
<th>Mean Correlation Coefficient (all gauges)</th>
<th>Mean Correlation Coefficient (reliable gauges)</th>
<th>Mean Relative Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.648</td>
<td>0.716</td>
<td>26.6</td>
</tr>
<tr>
<td></td>
<td>0.628</td>
<td>0.69</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>0.570</td>
<td>0.622</td>
<td>9.3</td>
</tr>
</tbody>
</table>

These results show the expected trend that the model is on the whole somewhat more accurate for the period it was calibrated for compared to the validation period, though the 2010 data still produced results that were not dramatically different than the data set from 2007 through 2009. The performance metrics were varied, ranging from a 24.8% decline in performance for the groundwater correlation coefficient to a surprising 65% improvement in the mean relative error in surface water gauges. One issue affecting the groundwater gauges is that 10 of the 61 wells used for data analysis have data sets that begin in August or September of 2009. All of these wells then have full 2010 data sets, so it is likely that their influence is
disproportionately strong over the validation period compared to the calibration period. It would benefit future efforts to revise this model to incorporate these wells more fully into the calibration process as they accounted for the three largest declines in correlation coefficient for the validation period, as well as the largest improvement. The improvement in the mean relative error at surface water gauges may reflect uneven distribution in a limited number of the largest simulation errors effectively dominating this term.

8.5 Error

A conceptual summary of the sources of error in a mathematically based hydrological model is a topic addressed by Gaganis and Smith, (2006). These begin with the limitations entailed in the simplification of natural systems for the purpose of modeling. The process of parameterization and the representation of physical systems in model space both limit the representation of heterogeneity; three dimensional processes are often incorporated with one or two dimensional representations. Several processes may be lumped within the mathematical model structure, or phenomena such as weathering or channel migration may be missed altogether in a model, though significant in reality (Gaganis and Smith 2006). In a recent study Clark and Kavetski (2009) concluded that errors associated with numerical solution schemes used in hydrological modeling were often more significant than model structural errors. This could either increase error in the model output or actually compensate for errors in parameterization, showing deceptively good model performance. In fact merely the order of operations a model uses in its numerical solution scheme can have a significant effect on the final outputs. This is because it is necessary for a model to calculate processes using a sequence of equations while the actual processes occur simultaneously (Clark and Kavetski, 2009). One example where this may apply to IWFM is that bypass flows are calculated before diversions in the continuity equation as it is applied to each segment, though these two factors can occur independently (Dogrul, 2008).

Practically every source of data required to develop a hydrological model has an associated margin of error. With this in mind, it may be impossible to fully quantify the degree
of error in input data in a model such as this one; however understanding the sources of error is an important step. In this section I will attempt to specify some particular areas of uncertainty related to input data. The influence of error in parameters is proportional to the sensitivity of the parameters, and may also have a component of seasonality or be scale dependent. For example, rainfall is interpolated over the model area, and should be considered an estimate though it is based on measurements. This estimate is likely to be nearly accurate in most cases; however, in large storm events the degree of error and its impact on model results are simultaneously elevated. This is also affected by other parameters such as curve number which determines the portion of rainfall that becomes runoff with regard to soil type. The overall impact of these values is small; however these parameters should be recognized as imperfect estimations. The same can be said for crop water use and soil characteristics. These are important aspects of this model because agriculture is the primary source of water demand; however there are limits that must be applied when adjusting specific inputs where the specific conditions of a site are unique and a comprehensive data set is not available.

Heterogeneity within an aquifer and uncertainty of thickness and extent of the geologic units in the model area contribute significantly to uncertainty within the model. It is stated in the geologic assessments used to develop the model that there is significant interbedding between the MPC aquifer and the less conductive MPF layer. This would result in an effective hydraulic conductivity that would vary spatially as well as with regard to the scale of focus. There are also likely to be geologic features not included in the model because they have not been well characterized by any studies to date. Some wells used for data analysis are shallower than the total depth of the aquifer. These wells may be affected by boundaries such as clay lenses, or other regions with increased hydraulic resistance that cause them to be sensitive to piezometric lines that are not representative of the aquifer as a whole. It is noted in a paper by Refsgaard (1997) that using a single value of hydraulic conductivity in a groundwater model is a major simplification; however, he also notes that variable aquifer thickness still results in a gradient of transmissivity. Without additional field data the net error of piezometric heads may not be improved (Refsgaard, 1997). It is necessary to consider the anisotropic properties of an aquifer when incorporating it into a model. In the sensitivity analysis this did not appear to be a particularly sensitive parameter, however, the ratios of horizontal to vertical conductivity
applied were 3, 8, and 8 for the three QC, MPC, and MPBC aquifer layers respectively. The values were based on an interpretation of the geologic descriptions in Lindsey (2007) and calibration.

The 10 meter horizontal resolution of the DEM used to determine surface elevation may have also contributed significantly to model error because surface elevation serves as a reference for the upper and lower elevations of the two aquifers, as well as their interface, translating into a direct impact on water table elevation and groundwater flow. These are several of the explanations proposed for the magnitude and variability of error in the model. It is a possibility that the physical conditions of the MPC aquifer would be better represented by a gradient of hydraulic conductivity rather than a single value.

There is precedent for calibrating a hydrological model by applying spatial variability to the most sensitive parameters. In a study of the Ter basin in Spain, Marce et al. (2008) discretized the watershed into zones based on slope, lithology, and land use, and considered their calibration parameters with regard to these zones. They used a multi-objective function for calibration and concluded that spatial variation of parameters with regard to lithology and land use improved model predictions for stream discharge; slope was not sensitive in this regard (Marce et al., 2008). They also noted that incorporating additional complexity increases uncertainty, so a spatially variable parameterization must be physically correlated to be justified. It is worth noting that IWFM has the capability to apply calibration using parametric nodes, in which nodes can be grouped by selected attributes for calibration. This was not used in this model application because of the spatial inconsistency of available data inputs. Model subregions also provide a built in means of applying spatial variability to soil characteristics, evapotranspiration, and precipitation.

As an experiment in the calibration process, I developed an approach of adjusting hydraulic conductivity of the MPC aquifer using a gradient based on the spatial distribution of mean residuals at groundwater gauges. This effort involved estimating a maximum and minimum value of conductivity for the MPC aquifer, and using these as the limits for the conductivity gradient. The mean residual values were taken from the best version of the model to that point and then interpolated using the inverse distance weighting tool in ARCMAP GIS.
The results were similar to those shown in figure 8.6. The interpolated value was then extracted at every node in the model area and assigned a corresponding value along the assumed gradient of hydraulic conductivity in the MPC aquifer.

This method was determined to be more of a means of compensating for errors entrained in model development than being representative of the physical properties of the aquifer. This process resulted in an improvement in terms of reducing the total standard deviation in simulation results, though the adjustments were slightly detrimental to the overall correlation coefficient. Due to the uncertainties of input data, a simpler model structure is preferable to a more complex one. For this reason the final version of the model uses a single value of conductivity rather than a gradient.

Stream flows are measured by a network of gauges that use rating tables to translate channel depth to flow rate. The Manning equation was used to complete the rating tables for the transducers installed for this project. A rating curve will generally change seasonally as vegetation in and around the channel grows and is then washed out. Streams may also change course, or in the case with canals, debris may clog a pipe or screen causing ponding that is later incorrectly interpreted as high flow. Rating curves are also unreliable for flood events, though there is frequently not an adequate substitute to measure these flows. In this model, trouble with the transducer gauges in Mill, Pine, and Dry Creeks necessitated the use of a mass balance approach for estimating these important inflows. If there was error in the gauge records from the mainstem Walla Walla River it could have been hidden by this process while translating to incorrect estimates for these inflows.

An important note about this issue is that it affects both input data and the recorded data to which model outputs are compared. There may in fact be cases where the model is more accurate than the gauge records, and large discrepancies at surface gauges must be considered in light of this possibility. An example of this is at the Tum-a-lum Bridge gauge in the Walla Walla River, downstream from the model inflow point at Grove School Bridge (figure 8.6). The stream gauge at Tum-a-lum Bridge is known to have had periodic problems, though the precise timing of these issues in not documented, therefore the WWBWC data was not edited for use in the model. Data from a downstream gauge at Pepper Bridge is well aligned with the
Grove School Bridge gauge, so in this case the periods of questionable data from the gauge at Tum-a-lum Bridge gauge can be interpolated from the two other gauges. Based on this analysis, the discrepancy at the Tum-a-lum gauge for May and June 2008 and early 2009 was overlooked during model calibration (figure 8.7).

![Figure 8.6: Location of the gauges in the Mainstem River compared in the example. It is apparent from their respective hydrographs that there are several periods for which the Tum-a-lum gauge is not reliable.](image)
Figure 8.7: Monthly averaged data from 3 gauges in the Walla Walla River. The Tum-a-lum Bridge gauge should show a flow rate that is equal or slightly greater than Pepper Bridge. The inconsistencies on this graph point to suspect data at Tum-a-lum Bridge in May, 2008 and January through March, 2009.

The surface water gauges managed by the WWBWC have limitations in how regularly they can be maintained and the frequency of flow measurements that can be taken to update rating curves. These types of problems are inevitable and have been addressed by WWBWC personnel by devising a simple gauge rating system to be considered when working with the data from these gauges. During the calibration of this model these ratings were taken into account when adjusting diversions and stream bed conductivity to reflect gauge data. The ratings assigned to surface water gauges are included in appendix I.

Error in a regional model such as this one originates from numerous sources; however it is collectively reflected in the residuals of model outputs, in some cases with a spatial or temporal correlation and in other cases with an outstanding residual at a particular gauge. At times, errors may compensate for each other; in fact the process of model calibration may promote this outcome as much as it promotes the parameter values reflecting physical conditions.
9 Gauge Output Examples

9.1 Gauge Data Summary

This section provides several representative examples of field data and simulation outputs compared at selected locations (figure 9.1). Error bars for groundwater graphs are set at +/- the root mean squared error (RMSE) for the given well. Surface water gauges shown are primarily those at spring locations, as these are of particular interest in this modeling effort. In addition results are shown for the gauge on the Walla Walla River at Touchet, Washington, the closest gauge to the model outflow. Mean relative error (MRE) and correlation coefficient are reported for each surface water gauge shown. Daily data was used to capture the subtleties of stream flows. Error bars are not shown for surface gauges because they obscure the data lines, making the graph illegible. All groundwater and surface water gauge outputs are included in appendix E.

Figure 9.1: Location of all groundwater wells and surface water gauges shown in section 9.2.
9.2 Groundwater Gauges

Well 33 (figure 9.2) is representative of the central region of the simulation area, not controlled by boundary conditions. Over the period of March through July of 2010 the simulation does not follow the trend of observed data. This discrepancy is repeated in the results from many wells in this area for this time frame. There was high rainfall over this time period, and the simulation has a spike in deep percolation to groundwater corresponding rise in the water table that is not shown in observed data.

![GW 33](image)

*Figure 9.2: Simulation output for GW 33. The RMSE for this well is 0.76 meters and the correlation coefficient is 0.58. Error bars are +/- the RMSE.*

Well 63 (figure 9.3) is an example of a site where there is a significant degree of vertical error between the recorded and simulated water table, however a strong degree of correlation. There are many sites in the model with similar outputs. This well also follows the trend of the previous example in that it overestimates the rise in the water table in the spring of 2010.
Figure 9.3: GW 63 has a RMSE of 5.4 meters and a correlation coefficient of 0.76. Error bars are +/- the RMSE.

The following example, monitoring well 93 (figure 9.4) is in a region with generally sparse data due to low gauge density. The well is likely influenced by both pumping and percolation from farmland in the GFID. The simulation captures the trends and water table elevation at this well, but appears to smooth the peaks and valleys of the hydrograph.

Figure 9.4: GW 93 has a RMSE of 1.35 meters and a correlation coefficient of 0.79. Error bars are +/- the RMSE.
Well 106 (figure 9.5) is at a significant location in the model, near the downgradient end, making it representative of the overall trend of groundwater fluctuation over the simulation period. It is likely influenced by exchange with the Mainstem River, agricultural activities, and boundary conditions.

Figure 9.5: GW 106 has a RMSE of 1.51 meters and a correlation coefficient of 0.78. Error bars are +/- the RMSE.

Well 108 (figure 9.6) shows poor correlation between observed and predicted water table elevations. The steep drops over the spring time indicate that this well is likely affected by pumping that is not captured in the simulation. Predicted groundwater levels peak in spring for this well, as is the case for most of the wells in the model area and the boundary conditions, while gauged data shows steep declines in groundwater head over the spring. That said, the annual mean depth to the water table, and the annual variations in water table height are very well captured.
Figure 9.6: GW 108 has a RMSE of 1.93 and a correlation coefficient of -0.13.

Well 113 (figure 9.7) shows a strong correlation in terms of the timing of water table fluctuations, however it does not cover as great an annual range. The simulated values are consistently above the recorded groundwater elevation, though they are particularly high in late summer as the modeled water table does not drop as dramatically as the recorded data indicates. They may be a case of pumping effects or indicate an area of the model in need of further calibration.
Figure 9.7: GW 113 has a RMSE of 2.2 meters and a correlation coefficient of 0.93.

9.3 Surface Water Gauges

Springs represent a challenge for modeling, as they require the water table to breach the stream bed, while generating a realistic flow rate. Spring flows were a focus of calibration as they are an easily observable connection between surface water and groundwater. Big Spring, WWBWC gauge 218 (figure 9.8) is the largest spring in the model area and one of few that flows year round.
Dugger Spring (figure 9.9) is known to flow primarily when the White Ditch is operating, presumably due to seepage from the canal. White Ditch is shown in the graphic above with 60% of the gauged flow rate. This is to account for a significant portion of the water in the canal that is diverted upstream. It is interesting to note that both the gauged data and flow rate predicted at this location by IWFM have considerably stronger correlations to the flow rate in White ditch than they do to each other.
Figure 9.9: Dugger Spring is the headwater of Dugger Creek. It has a MRE of 60.4% and a correlation coefficient of -0.07 between recorded and predicted data. The correlation coefficient obtained comparing the recorded data to the White ditch data is 0.22 and comparing the simulated data to the White Ditch yields a 0.55 correlation coefficient.

Little Mud Creek (figure 9.10) has also been speculated to gain water when White Ditch is operating. It may also gain from the distributary canals that are supplied by White Ditch. The simulation appears to concur with this hypothesis, while the gauge data also indicates this could be the case. These relationships are supported by the fact that these springs tend to flow in late summer, when ambient groundwater elevation is near its minimum and there is a high rate of irrigation.
Figure 9.10: Simulated and observed flows in the Little Mud Creek. Flow in the White ditch is also shown, corresponding to the right axis, to show the correlation between ditch operation and flow in Little Mud Creek.

The closest gauge to the model outflow is the USGS gauge at Touchet, Washington (figure 9.11). This is an important gauge because it indicates whether the surface water portion of the model is balanced in terms of net imports and exports compared to documented data. The balance is very good at this gauge, as it is at the majority of the mainstem gauges. This is partly due to the mass balance approach that was used to calibrate historic inflows from ungauged tributaries. This is particularly evident at during peak flows. Low flow periods were generally balanced through the process of model calibration.
Figure 9.11 Simulated and observed flows for the Walla Walla River gauge at Touchet, Washington from January 2007 to December 2010. Note that this graph uses a log scale because of seasonal variability of flow rates.
10 Water Budgets

10.1 Groundwater Budgets

The available supply of groundwater is an issue of central importance to the water management in the Walla Walla Basin. Estimating a sustainable usage rate is a primary incentive for creating this model. This section reviews hydrologic budget estimates from the calibrated model. The complete set of budgets is included as appendix F.

Figure 10.1 shows the total groundwater budget broken down into its specific components over a four year period. Extraction through pumping is clearly dominant, though inputs from streams are also significant. These are usually a positive input into the aquifer system, though there are periods in late winter and spring when the model shows streams to be collectively gaining from groundwater, which is indicated by a negative value on this graph. This condition does not persist after the onset of irrigation season when permeable canals begin carrying water. There is a consistent inflow from percolation from the soil, which adds up to the largest individual component, as is shown in figure 10.1.
Figure 10.1: Groundwater budget calculated by the model broken into its components in meters per day from 2007 through 2010. Total storage in the aquifers corresponds to the right hand axis. The ‘Total inputs’ term is the sum of the fluxes other than pumping. It should be noted that this includes losses from the aquifer from gaining stream reaches and water flow out of the model boundary. All data is displayed using a two week running average.

It is clear in figure 10.1, that groundwater pumping is a dominant factor in the total flux of groundwater in and out of the model area. When pumping ceases in late fall at the end of the growing season, there is a period of aquifer replenishment. The trend of total storage follows the net inputs as would be expected. These net inputs include some the negative terms associated with boundary outflow and groundwater discharge into gaining stream reaches, primarily in the Walla Walla River.

Figure 10.2 compares the total annual average of the components of the groundwater budget as calculated by this model. It should be noted that while ‘deep percolation’ (36.3% of total inputs) and ‘recharge from agriculture’ (25.6%) are terms that always add to the
groundwater storage, ‘gain from streams’ (18.5%) and ‘boundary inflow’ (14.9%) can be either negative or positive, as is shown on the previous chart. This accounts for their net contribution being less than the first two terms though they have a greater volume of flux. The three recharge sites combine to contribute 4.7% of the inputs to aquifer storage, with the majority of this coming from the HBDIC recharge site. Though this is a relatively small amount of the total, eliminating this source would increase the deficit between inputs and outputs by 64%.

Figure 10.2: A comparison of the annual average of the terms in the groundwater budget in millions of M$^3$ per day.

The total inputs amount to 93% of the extraction from pumping. To investigate this estimated decline, the simulation data can be compared to the historic data from monitoring well GW 18, shown in figure 1.3. This well had an average water table elevation of 222.98 meters above sea level over 10 measurements in 1950. Over 6 measurements taken from May, 2010 to February, 2012 the water table averaged 219.94 meters above sea level; a decline of 3.04 meters in 63 years, or 4.8 centimeters (1.9 inches) per year. The estimated decline can be most directly calculated by subtracting the beginning storage volume from the ending storage volume and dividing the result by the land area. This yields a predicted decline of 0.24
centimeters of water per year, which can then be divided by the drainable porosity (specific yield) of 0.07 used in the model (this was a calibrated term) to calculate the predicted decline in groundwater level. The result is 3.4 centimeters per year, which shows a correlation to the observed data at monitoring well 18 that is well within the expected margin of error (a nearly identical result is obtained from monitoring well GW 19).

In light of this information, it should be noted that ‘Total storage’ is a term that combines the volume of the three aquifers in the model, and therefore includes the uncertainties of volume, conductivity, and storativity associated with each one. The term does not include the QF and MPF strata because they are not considered aquifers. These layers may hold water some water, and given the volume of the MPF formation (the largest in the model), this could constitute a significant degree of error associated with this term.

10.2 Stream Budgets

The collective hydrologic budget for all streams shows that the ‘gain from groundwater’ term is generally negative as the majority of streams in the model are losing water (figure 10.3). This term mirrors the ‘gain from streams’ term in the groundwater budget. Agricultural diversions account for 14% of total inflows to the model; however this number is much greater in the summer when flows are at their lowest. Of this water, 1.8% returns to stream channels after percolating through soil, indicating over-irrigation. 2.1% of the total inflows seep to groundwater; however this number is over 20% in some irrigation canals, the gaining sections of the mainstem Walla Walla River account for the lower net value in the final budget.
Figure 10.3: Hydrological budget for all streams in the model area. The total inflows and outflows are shown on a log scale on the right axis to highlight the periods of discrepancy, corresponding to withdrawals for irrigation. Data is shown with a two week running average.

Figure 10.4 shows a representative reach of the Walla Walla River. This reach is primarily gaining groundwater. It supplies the GFID via the Gardena canal, accounting for the large seasonal bypass flow. As with most of the Mainstem River, runoff and return flow are minor factors. The following graph, figure 10.5, shows a typical canal segment. This reach has no inflow because it supplied by a bypass, as shown by the negative value for bypass flow (water bypassed out of the reach would be positive, as in the figure above). Diversions closely mirror the bypass rate, and when there is outflow it is generally due to surface runoff or return flows. Seepage losses to groundwater are significant, approaching 20% during irrigation season.
Figure 10.4: Budget for a stream reach on the mainstem Walla Walla River (model reach 39). This is a gaining reach, and also includes the diversion point for the Gardena Canal. The diversion rates for all mainstem reached are roughly estimated due to lack of data. Data is shown using a two week running average. Inflow and outflow are on the right axis.
Figure 10.5: Water budget for White Ditch (model reach 51), a primary distributary canal in the model area. There is no inflow or outflow. Water is delivered via a bypass, corresponding to the negative values for bypasses. There is some return flow and loss to groundwater approaches 20%. Data is shown with a two week running average.

10.3 Crop and Soil Budgets

The budget for agricultural water use is an important simulation output. Figure 10.6 shows that surface diversions and groundwater pumping combine to meet agricultural demands. Surface diversions are dominant in the early part of the growing season, and then exceeded by pumping as stream flows decline over the summer. Surface water diversions actually exceed agricultural demand in early spring as farmers in this area typically over apply water to increase soil moisture for the dry summer. Pumping is initiated in IWFM by the minimum soil moisture required for plants, so applied water and ET closely follow the total agricultural requirement; with ET being slightly higher due to water use by uncultivated plants and non-irrigated wheat. Direct precipitation also constitutes an important source of water, annually totaling 31% of the total agricultural requirement, though much of this falls outside of the growing season.
Figure 10.6: Agricultural water budget as calculated by IWFM. Data is shown using a two week running average.

Agricultural diversions and precipitation are the inputs of water into the soil layer. Once the water is in the soil storage, it can either be transpired by plants, percolate to groundwater, return to a stream, or remain in the soil. The rate of infiltration into the soil is associated with evapotranspiration because water is applied during the growing season at the rate it required by plants to maintain adequate soil moisture. It also mirrors the pattern of rainfall when it occurs. Deep percolation and runoff occur in proportion to precipitation events, as this is the primary time when excess water is available (figure 10.7).
Figure 10.7: Water budget for soil as calculated by IWFM, shown in cm per day per unit land area. Data is shown using a two week running average.
11 Scenarios

11.1 Scenario overview

The model was used to test several scenarios reflecting proposed water management strategies. These scenarios included an increased inflow and operational period for the Locher Road aquifer recharge site, running canals through the winter, and the proposed lining of canals in the HBDIC and WWRID irrigation districts. The Locher road recharge site has typically been operated for period of 20-40 days at about 0.04 M$^3$ per second (1.5 cfs). It has recently been expanded from .25 acres to 2.5 acres. The first scenario entails a significant increase of water diverted into this recharge site. This is then compared to an alternative recharge strategy, specifically to run water through the permeable canals throughout the winter to all their seepage losses to recharge groundwater. These two scenarios are then combined into a third scenario.

The final scenario addresses the proposal to convert canals into pipelines which is currently taking place. It is promoted as a solution to the issue of canals leaking water, making it more difficult for irrigation districts to meet their water user demands. A concern about this is the potential unintended consequence of depriving the underlying aquifers of an important source of recharge, specifically the water that seeps out of the canals (Petrides, 2008). It is known that some of the springs in the area west of Milton-Freewater primarily flow when canals are operating, likely a response to this leakage factor (personal communication, Will Lewis of WWBWC). In light of the proposals to line these canals, I have used the model to simulate piping the WWRID and HBDIC irrigation districts. This was done by converting the stream bed permeability for all canals in the respective districts to zero. Figure 11.1 serves as a reference map for the scenarios discussed below.
Summary of scenarios

Scenario 1 “16 Fold Increase (Four fold increase in recharge, four times longer)”: In this scenario the Locher road recharge site was operated at the 0.2 M$^3$ per second for every day that the GFID was running at least 1.13 M$^3$ per second (40 cfs) through the Gardena canal. In this scenario, the site was operated for an average of 132 days per year over the four year simulation period.

Scenario 2 “Running canals through winter”: The second scenario involved running all of the major canals in the model area from December through February, regardless of agricultural demand, to see the effect on groundwater levels due to seepage. The flow rates used for canals in this scenario were determined by taking 40 percent of the average flow rate in May, when canals are near peak operation.
Scenario 3 “Running canals through winter and increasing inputs to Locher road”: Scenarios one and two were combined.

Scenario 4 “Lining canals in the HBDIC and WWRID irrigation districts”: Stream bed conductivity was changed to zero meters per day throughout the HBDIC and WWRID irrigation districts. These canals are highlighted in figure 11.1.

11.2 Discussion of Scenario Results

In the ‘16 fold increase’ scenario, the Locher Road recharge site is operated for 397 days over the entire simulation period. The resulting plume is concentrated around and the recharge site and declines with distance, the net effect is a 10.7 centimeter mean increase in groundwater elevation (figure 11.2). It should be noted that the area around the lower Gardena canal has a slightly lower water table than in the validated model because water diverted into the recharge site is not available at the end of the canal, reducing seepage in this area. The following scenario diverted 1.13 m$^3$ per second into the Little Walla Walla Canal, which was then distributed through the HBDIC and WWRID irrigation districts. The rate of bypasses was based on 40 percent of the average rate for May, and sustained from December through February, however no extra water was being withdrawn for diversions other that those already allocated in the model and excess flow returned to the mainstem Walla Walla River at a downstream location. An additional 0.85 m$^3$ per second was diverted into the Gardena Canal, and again, the excess returned to the river south of Touchet, near the model outflow. It is apparent from figure 11.3 that the benefit of increased groundwater storage was more widely dispersed by operating the canals through the winter than in the scenario of increased inputs to Locher Road. When operating the canals through the winter, the water table declines slightly in the area immediately adjacent to the Walla Walla River because the water diverted into the canal network reduces seepage in this area. The mean increase in groundwater head for all model
nodes was 10.7 centimeters in this scenario when compared to the validated model, the same as in the first scenario. Combining the conditions of these two scenarios resulted in a net gain in aquifer storage over the simulation period, with the distribution of increased water table elevation reflecting a combination of the previous scenario outputs. The output after 4 years is illustrated in figure 11.4.

Figure 11.2: Plume after 4 years of increased input to Locher Road recharge site. This figure illustrates the change of water table elevation in comparison to the validated model.
Figure 11.3: Predicted effect on the water table that would result from diverting 1.13 m$^3$ per second (40 cfs) through the Little Walla Walla Canal to be distributed through the HBDIC and WWIRD irrigation districts as well as 0.85 m$^3$ per second (30 cfs) through the GFID.
Figure 11.4: Predicted change in water table elevation after 4 years resulting from the scenario in which inputs to the Locher Road SAR site are increased by a factor of 16 and canals are operated through the winter months.

The scenario of lining canals resulted in a significant decline in groundwater elevation over the region where the pipes are located, while some additional water reaches downstream from the pipes, and seeps through the channel beds, resulting in a slightly increased water table in this region (figure 11.5). Declines of over 3 meters are predicted in the central region of the canal network, while increases of up to 0.5 meters are predicted downstream from the end of the piped reaches. The overall effect through 4 years of simulation was an average decrease of 37.4 centimeters per model node, or 9.4 centimeters per year, though an increase of summer flows in the Mainstem River due to return flows from water that previously seeped through the canal beds. It is likely that some of the water saved due to this increased efficiency would be used by downstream water users who currently receive surface water only occasionally. Water budgets show that groundwater is the dominant source of water for irrigation needs while low flows in the Walla Walla River are a critical factor for salmon habitat. These are both important considerations that are affected by the canal lining scenario.
Figure 11.5: Change in groundwater elevation resulting from converting the canals of the HBDIC and WWRID irrigation districts into pipelines after 4 years of simulation.

In figure 11.6 the impact of the various scenarios is depicted by subtracting discharge values from the validated model at a point in the Walla Walla River, just above the confluence with the Touchet River, from the simulated discharge resulting from scenario conditions. A positive value indicates the scenario leads to an increase in flow and a negative value indicates reduced stream flow. This figure shows that the flow in the Walla Walla River increases over the summer months in the piping scenario because water that does not seep through the canal beds returns to the Mainstem River in the current model setup. Another possible outcome would be for water that previously seeped from canals to reach downstream users and be used in additional agricultural diversions. The water table decline associated with this strategy may ultimately make it unsustainable by increasing the cost of groundwater pumping and accelerating the decline of aquifer storage. Operating canals through the winter and increasing flow into Locher road both yield modest improvements to summer flows. The former of these
scenarios results in an apparent spike in flow when the canals begin to receive extra water in winter. This is because a pulse of water runs through the canal system and back into the mainstem, essentially taking a shortcut to the point of analysis. Subsequently, the discharge declines because of the diverted water that seeps through the canal bed and does not reach this point. This type of analysis using IWFM can be used to inform a strategy for increasing aquifer storage over winter so that additional water can be left instream over the summer.

Figure 11.6: Predicted impact of simulated scenarios on discharge in the Walla Walla River. This graph depicts the difference of flow in the Walla Walla River near Touchet, Washington.

Little Mud Creek illustrates the variability of the scenarios tested with the model on a small stream, sensitive to irrigation canal seepage, as is evident in the simulation results for the scenarios shown in figure 11.7. Maintaining canal flow through the winter causes the model to predict flow increases of about 50 percent, while piping the irrigation districts results in dramatically reduced flow. Increasing the inputs to Locher road recharge site, about 4 kilometers away, appears to have a small effect on the simulation outputs for this location.
Monitoring well 31 was selected to provide a specific comparison of the various scenarios for groundwater head because it is located near the center of the model area (see figure 11.1) and is also subject to influence from canal seepage. The Locher Road recharge site is 2.2 kilometers away from this well. The validated model has a strong correlation at this well, of 0.89, though a high RMSE of 4.6 meters. Figure 11.8 shows the impact of each scenario in terms of the difference in groundwater head compared to the validated model. The results correlate with those in the previous graphs. Running canals through the winter yields a predicted increase in the water table of up to 1 meter after 4 years of simulation. The recharge site scenarios yield a more modest increase in groundwater head and piping canals causes the model to predict a drop in groundwater elevation of approximately one meter after four years, with some seasonal variability.
Figure 11.8: Comparison of the effects of the four simulated scenarios at monitoring well 31.

Figure 11.9 compares the components of the groundwater budget in the various scenario conditions in terms of their respective differences from the budget outputs of the validated model. The pipe installation scenario results in a decline in total storage associated with decreased inputs from streams. It is interesting to note that the decline in seepage is somewhat offset by reduced pumping, increased boundary inflow (due to a steeper gradient of groundwater head), and increased deep percolation. Predictably, the scenarios of increased input to the Locher road recharge site, and running canals through the winter, both yield a net increase in aquifer storage when compared to the validated model. Figure 11.10 shows the mean annual trend in water table elevation over the simulation period. The validated model shows an annual decline of 0.24 centimeters of water in aquifer storage while annual declines in water table elevation of 0.79, 0.04, and 0.07 centimeters are predicted for the ‘Piped canals’, ‘Locher Road increase’, and ‘Canals Running though Winter’ scenarios respectively. The
scenario in which these two recharge sources are combined results in an overall net increase in aquifer storage of 0.12 centimeters per year.

Figure 11.9: Total changes from the validated model for the predicted groundwater budget in response to applied scenarios after 4 years of simulation. ‘Total inputs’ refers to the sum of the first five categories.
These budgets warrant further investigation with the goal of developing a sustainable water management strategy. This may include additional aquifer recharge sites or operating canals when there is available water, regardless of agricultural demand. There appears to be a possibility that the aquifer could be stabilized while providing the water needed for agriculture and leaving additional water in the Walla Walla River over the dry summer months to improve instream habitat. An important question to address from these simulated findings is how they translate to real world conditions. Can a unit of water infiltrated into the aquifer over the winter be correlated to a unit of water left in the river over the summer?
12 Recommendations

This model provides a reasonable balance between complexity of representation and the knowledge of the system being represented. The observed dynamics of the system were well captured by the model, typically within the range of uncertainty of the base data. While this study points out that there is opportunity to improve the model, there are also limiting factors to address if such an effort is to be undertaken. Incorporating additional complexities is necessary to improve the representation of the hydrology of the Walla Walla Basin in this model application; however it must be kept in mind that the complexity of a natural system cannot be accounted for in a computer simulation, and what we have represented here may come close to using the full extent of presently available knowledge. Additional research for the purpose of improved modeling is likely to be expensive, so careful planning of field work coupled with an understanding of IWFM is needed to assure the effort is productive. Based on this I have created a list of recommendations and outstanding questions, and categorized them into several groups.

Model Setup

1. Incorporate parametric nodes

   The physical system represented in the model has some characteristics that occur repeatedly, but in an irregular pattern. For such situations, IWFM has the option of grouping elements with common characteristics as ‘parametric nodes’. Parameters sets can then be adjusted by parametric nodes, giving the user an additional means of refining the model during calibration. This feature could be particularly useful for representing heterogeneity of the aquifers and the area adjacent to the main stem Walla Walla River, where the channel creates a more dynamic morphology compared to the rest of the model area.

2. Recalibrate with 2010 data included
As was mentioned in the validation section of this report, 10 of the 63 wells used for data analysis have data sets dating back to August, 2009 or later. This is likely to have affected the calibration process by underrepresenting these wells. Now these wells have complete data sets through 2011 which could be used to improve calibration and/or the validation of the model.

Hydrogeology

3 Identify Problem Areas in Simulated Outputs

Some areas of the model area were persistently discrepant with observations during the calibration process. This could be due to the conditions of specific wells where data was collected, mischaracterization of the aquifer, particularly with regard to thickness, or error in surface elevation originating from the 10 meter DEM. One notable area is around monitoring wells 11 and 13 (see the circled area on the right in figure 8.4). These wells had little monthly variation, and were consistently 6+ and 8+ meters low in simulation outputs throughout the calibration process. Using a high resolution GPS device to compare model elevation inputs to well elevations would be an effective method of checking data accuracy. Reviewing well logs for with regard to drilling depth, assumed aquifer depth, and evidence of irregularities such as clay lenses could reveal important information that would improve the model. Areas where there are closely spaced wells with conflicting errors (water table too high versus water table too low) are points that would demand attention first.

4 Is it appropriate to characterize the MPF unit as an aquitard?

It is stated in the geology report by Kevin Lindsey that this unit primarily consists of silt and clay deposits; however it is interbedded to an unknown extent with the overlying MPC unit that consists of more permeable conglomerate material. He also states that this unit appears to yield water in several wells, though it is not clear if these are wells in the model area (Lindsey, 2007). Currently the unit is considered an aquitard based on personal communication with WWBWC hydrogeologist Rick Henry. Given the volume of material in the MPF strata, this characterization could have a significant impact on the
overall storage and transmissivity of the aquifers in the model. It is worth considering whether the MPF layer is appropriately representing in the model framework.

5 Characterizing the MPBC strata

The MPBC unit is characterized as an aquifer within the model based on the description in Lindsey (2007). There is no inflow defined for this unit because of its limited spatial extent and poorly understood conditions. A subsurface inflow being defined for the MPBC unit would increase the flow crossing the model boundary, though it is unclear by how much and therefore may only add unnecessary complication. It is also unclear, if the MPBC unit is appropriately considered an aquifer, whether it is a confined or unconfined aquifer. Wells in the MPBC unit, particularly ones near the model boundary, could provide an important source of information to address these questions. Identifying the source of recharge for this unit would also provide insight that could improve its representation in the model.

Surface Water and irrigation

6 Measure Pine and Dry Creeks

Pine and Dry creeks, which converge within the model area, are the primary tributaries to the Walla Walla River from the south, and are known to range annually from entirely dry to significantly large streams. They are also used as a supplemental source of irrigation by the HBDIC. There is currently no gauge on these streams, and historical records are limited to a few measurements over the past 60 years. We attempted to install gauges on these streams but they were washed out. It would be very helpful for characterizing these channels to measure them on a regular basis, noting when they are dry, and to make an attempt to quantify their flow during a flood stage. To simplify this, the measurements could be made for their combined flow below their convergence.

7 Document Irrigation Distribution
Many of the branches in the canal network are ungauged and therefore associated flows could only be estimated for this model. This is particularly true in the Lowden laterals and off of the Gardena canal below its intake from the Walla Walla River. Periodic measurements or improved communication with irrigation managers would provide useful information for characterizing canal flows and associated irrigation diversions.

8 Water Used Directly from the Walla Walla River and Tributaries
Some water users are located directly on the Walla Walla River, and perhaps lower Pine Creek. The amount of water that these people withdraw from these streams is not known, and coarsely estimated in the model. Identifying these users or attempting to quantify their rate of water use would lead to a more accurate representation of surface water distribution in the model.

9 Review Mud Creek Area and Associated Model Inputs
The simulation outputs for Mud Creek show high levels of return flow (graphs are not shown in this report). This indicates over irrigation and may indicate a problem with the gauge that dictates the rate water is diverted from Ford Canal to Mud Creek. Specifically, this is WWBWC gauge 301 (rated a 3 on the gauge rating scale). It is also possible that land use could be mischaracterized in this region, causing an underestimate of ET.

Soil

10 Soil Sampling
Sampling for porosity, thickness, and field capacity of the soil layer at representative locations to verify or enhance the NRCS data would be a relatively inexpensive means of incorporating additional field data into the model. These are not particularly sensitive
parameters, but collectively do impact simulation and account for a significant flux of water.

Data Analysis

11 Review the Budgets

Though this was an integral part of the calibration process, budget outputs from the model give great detail and can provide specific insights where the model is performing well or needs improvement. This can be more informative than an overall statistical metric because it can highlight specific issues in terms of water fluxes, allocation, or spatial distribution that are missed by analyzing the model with an objective function alone.

12 Review Daily Data Sets

The model was developed using monthly averaged data for stream gauges and wells. In some cases anomalous measurements in the daily data sets were undoubtedly missed (the some were discovered and removed). These can cause issues in both the source data and the data set used for analyzing model outputs, therefore additional review, particularly by somebody well informed about current and historic conditions would benefit the overall accuracy of the model.

Scenarios

13 Testing the model

As ongoing changes in water management are implemented in the Walla Walla Basin the model can be tested by applying these changes and comparing the simulated results to field observations. If the model outputs continue to be valid, further scenarios should be applied with discreet goals such as stabilizing the amount of aquifer storage and increasing summer low flow conditions in the Walla Walla River.
13 Conclusion

The modeling yielded a representation of the hydrologic conditions in the subsection of the Walla Walla Basin that had performance suitable for the purposes for which it was developed. On the whole the model had a good correlation to observed data with a root mean square error of 3.2 meters and a mean correlation coefficient of 0.59 at groundwater gauges and .63 at surface water gauges, the mean relative error for surface water gauges is 22%. There are particular areas and gauges that are suspect of providing erroneous data for reasons such as error in surface elevation or aquifer thickness. All of the applied scenarios demonstrate a logical systemic response to the alterations they represent. At this point the model is a useable tool, to be employed with appropriate caution, for informing water management planning in terms of regional scale issues. We emphasize that it does not have the resolution to address questions of a localized nature (e.g., farm-by-farm groundwater elevation). It is capable of showing trends in the response of groundwater and surface water systems to alterations in water resource management, essentially allowing the exploration of alternative management scenarios through computer simulations. The model should not be used for predicting precise flow rates or the groundwater level at a specific point for a specific time, except where inputs are tightly constrained, such as near a boundary or gauged bypass.

The model was applied to 4 scenarios based on current issues in the Walla Walla Basin. These included increasing flow into the Locher Road aquifer recharge site, converting the canals of the HBDIC and WWRID irrigation districts into pipelines, and running the canal network through the winter in order to take advantage of its permeability as a source for aquifer replenishment. The model consistently produced results that followed the patterns expected with these alterations. Increasing flow at the Locher road recharge site produced a steady plume of mounding in the water table emanating from the recharge site, which appeared to increase with time. The piping scenario produced a decline in spring fed streams such as Little Mud Creek and a water table decline of over one meter in the primary agricultural region. Year round canal operation led to increased discharge in spring fed streams and increased water table elevation throughout the model area. The scenario combing the use of canal beds as recharge sources with increased input to Locher road recharge site was the only scenario that
resulted in a net increase in aquifer storage over the simulation period. This demonstrates the models’ utility as a tool for estimating the requirements for sustainable water management. It could also be a starting point for developing a strategy to increase summer flows in the Walla Walla River by supplementing irrigation with additional groundwater without depleting the aquifers over the long term.

The model can be improved with continued revision; there are numerous details where additional information could yield improvements in the representation of the physical system enabling a more refined calibration. It would be important to focus this effort on the more sensitive parameters. Surface elevation, aquifer thickness, hydraulic conductivity, and stream bed permeability have been identified as characteristics that are coarsely applied in this version of the model and would be appropriate choices for efforts to either verify or improve upon current input data. Other factors such as the fraction of irrigation water that reaches the water table, or the reuse of irrigation runoff, could be the subject for future research that could improve this model and potentially be applied to other regions also facing limited water supplies.

Every effort has been made to make the application of this model transparent and input worksheets with applied data sets are included as appendices to this document. IWFM does not have a dedicated user interface, so the input worksheets have been designed so that data is formatted for direct input into the FORTRAN modules used by the model. This is intended to enable future users of this model to understand the data sources and data processing methods used in model development, and facilitate future application and revision of this model.
References


