

August 28, 2015

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RE: Walla Walla Basin Integrated Water Flow Model Development and Calibration Report

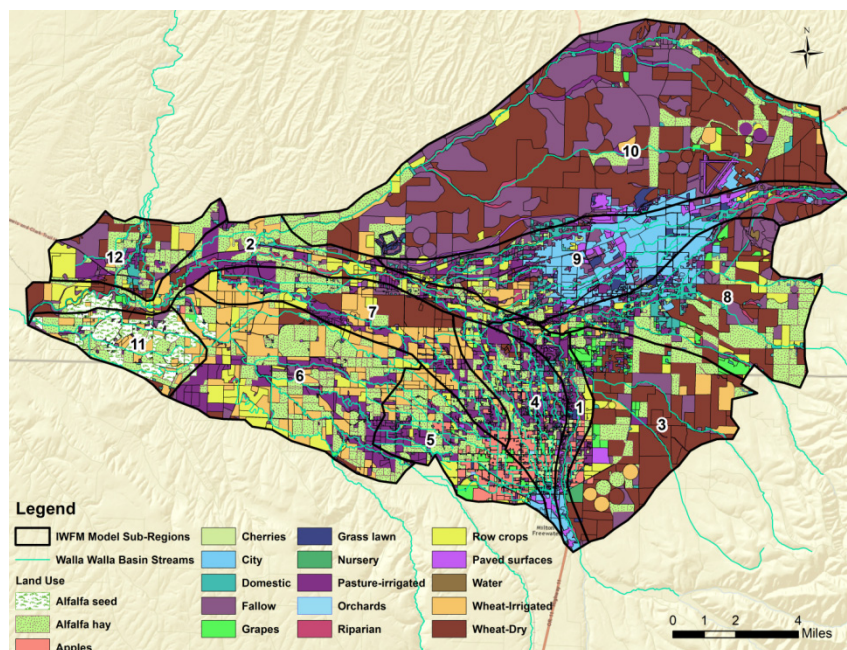
Dear Steven,

Enclosed please find the Walla Walla Basin Integrated Water Flow Model development and calibration report. This report addresses comments from your draft report review. Should you have any questions, please do not hesitate to give us a call.

Sincerely,



Jason Keller, R.G.
Senior Hydrogeologist



Walla Walla Basin Integrated Water Flow Model: Model Development and Calibration

Prepared for:
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Walla Walla Basin Integrated Water Flow Model: Model Development and Calibration

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EXECUTIVE SUMMARY

The Walla Walla Basin Watershed Council (WWBWC) and Walla Walla Watershed Management Partnership have initiated the Walla Walla Basin Integrated Flow Enhancement Study, which seeks to enhance stream flows while maintaining the long-term viability of water supplies for irrigated agriculture, residential, and urban use. Through the study, water management scenarios are being evaluated to meet established streamflow and water supply goals.

A calibrated hydrological model is an effective tool for evaluating the potential impacts of proposed water management scenarios on hydrological conditions in the basin. To this end, GeoSystems Analysis, Inc. in collaboration with the WWBWC has developed a calibrated surface water – groundwater finite element numerical model. The basin model utilizes the code Integrated Water Flow Model (IWFM), developed by the California Department of Water Resources Bay-Delta Office. The IWFM code was selected for this application due to its robust treatment of surface water – groundwater interactions and capability of calculating agricultural water demand based on climate and land use data. Furthermore, the IWFM code has been used successfully for a sub-region of the Walla Walla Basin.

The basin model was developed utilizing data sources to define basin geology, precipitation, groundwater and surface water conditions, land use classification, agricultural and urban demand, and soil properties. The model boundary was defined by the areal extent of the alluvial basin deposits and encompasses the land surface and five sedimentary geologic units that overlay the Columbia River Basalt formation within the Walla Walla Basin. Overall, the model encompasses 239 square miles and extends to a maximum depth of 940 feet below ground surface. The model area was divided into 12 sub-regions based on physical characteristics or management entities, allowing for focused evaluation of water use and available resources for each sub-region.

Surface water data from 53 stream gauges and groundwater elevation data from 97 monitoring wells were collected and processed, providing the basis for surface water inflow and groundwater boundary conditions. The stream gauge and monitoring well data also formed the data set against which the model was calibrated and validated.

Model calibration was performed by primarily adjusting horizontal saturated hydraulic conductivity of the sedimentary units, stream bed conductivity, non-recoverable loss rate (evaporation), and recoverable loss rate (percolation from soil to groundwater) in an iterative manner and evaluating the fit between observed and simulated groundwater elevation and surface water flow. Model calibration was based on data for years 2007 through 2009, 2011, and 2013 while data sets for years 2010 and 2012 were reserved for model validation. Calibration results

were evaluated based on several metrics: root-mean-squared-error (RMSE), correlation coefficient and mean error for groundwater elevation and mean relative error and correlation coefficient for surface water flow.

The calibrated model RMSE for groundwater was 10.85 ft with a correlation coefficient of 0.71. Mean groundwater elevation error represented 0.19 percent of the mean total groundwater storage, supporting that the overall groundwater budget predictions are a reasonable indicator of available groundwater resources. Surface water gauges were divided into six gauge series, with calibrated model results for the larger rivers and streams considerably more accurate than the irrigation networks consisting of numerous small canals and springs. Correlations coefficients for the gauge series ranged from 0.99 for the Touchet River gauge to 0.35 for the Mud Creek gauge series. Mean relative error ranged from 10 percent for the Touchet River gauge to 130 percent for the HBDIC-Pine Creek gauge series.

Applying the calibrated model to the validation data set did not significantly change the statistical agreement between the measured and predicted groundwater elevations. Surface water fit was more affected by including the validation data set, though the model fit was improved for several of the gauge series. The statistical metrics between predicted and measured groundwater elevations were similar for the calibration and validation data sets, indicating that the calibrated model predicts the physical processes that affect groundwater elevation. Statistical metrics for predicted and measured surface water flow generally were similar or improved when including the validation data set.

Calibration model hydrological budget outputs indicate that agricultural water application is in excess of agricultural water demand due to inefficiencies in irrigation delivery and over application of surface water in the late fall and spring to store water in the unsaturated zone. Groundwater is the primary source of irrigation water over the summer months. During these months groundwater extraction exceeds groundwater recharge and inflow from the model boundaries and concurs with the simulated decline of groundwater storage. Streams are gaining from groundwater on the whole; however, some individual reaches, and entire sub-regions, lose water to channel seepage.

Groundwater recharge from managed aquifer recharge (MAR) in the HBDIC sub-region helped to offsets groundwater losses from groundwater pumping and increased return flows to streams, indicating that MAR can offset aquifer storage losses. The potential for MAR to contribute to basin wide goals for conjunctive use of surface water and groundwater resources hinges on the optimization of MAR facility location and recharge volumes. The calibrated Walla Walla Basin

model serves as a tool to further evaluate MAR in the basin in addition to analyzing water use, resource availability, and management alternatives that can form the development of a water management strategy that both meets requirements for instream flow and provides water for irrigators.

1.0 INTRODUCTION

The Walla Walla Basin is located in a semi-arid region of Eastern Washington and Oregon (Figure 1), receiving an average of 17 inches of annual rainfall, primarily over the winter and spring months. Low summer flows in the Walla Walla River are known to be limiting to fish passage and are associated with seasonally high stream temperatures that degrade fish habitat (Mendel et al., 2005). An agreement between local irrigation districts and federal and state regulators in 2000 established a minimum flow of 25 cubic feet per second (cfs) in the Walla Walla River below the outtake to the Little Walla Walla canal and 18 cfs below the Gardena Canal outtake, with the objective of promoting viable habitat for endangered fisheries (Mahoney et al., 2011).

Channel seepage in both the mainstem Walla Walla River and over much of the canal network causes inefficiency in the delivery of irrigation water. Ongoing efforts to convert permeable canals into pipelines have improved irrigation efficiency; however, this practice deprives the underlying aquifers of an important source of recharge (Scherberg, 2012). The reduction in recharge from canal seepage comes at a time when groundwater resources are being increasingly relied upon to meet water demand as less surface water is available due to minimum stream flows. This has exacerbated a gradual decline in the groundwater table that has been documented in the Walla Walla Basin since 1950 (Patten, 2010).

The Walla Walla Basin Watershed Council (WWBWC) and Walla Walla Watershed Management Partnership have initiated the Walla Walla Basin Integrated Flow Enhancement Study, which seeks to enhance stream flows while maintaining the long-term viability of water supplies for irrigated agriculture, residential, and urban use. Through the study, water management scenarios are being evaluated to meet established streamflow and water supply goals.

A calibrated hydrological model is an effective tool for evaluating the potential impacts of proposed water management scenarios on hydrological conditions in the basin. To this end, GeoSystems Analysis, Inc. in collaboration with the WWBWC has developed a calibrated surface water – groundwater finite element numerical model. The basin model utilizes the code Integrated Water Flow Model (IWFM), developed by the California Department of Water Resources Bay-Delta Office (CDWR-BDO) (Dogrul, 2013). The IWFM code was selected for this application due to its robust treatment of surface water – groundwater interactions and capability of calculating agricultural water demand based on climate and land use data. Furthermore, the IWFM code has been used successfully for a sub-region of the Walla Walla Basin (Scherberg, 2012).

This report describes the process of model development and calibration; describing how physical conditions are represented within the model framework and data sources used (Section 2.0),

calibration methods (Section 3.0), and calibration results and hydrological budgets (Section 4.0). The calibration model input files are provided in Appendix A.

2.0 MODEL DEVELOPMENT

2.1 Model Domain

The Walla Walla Basin model encompasses a three dimensional domain defined by the areal extent and thickness of the alluvial sediments deposited over the Columbia River Basalt (CRB) formation within the Walla Walla Watershed (Figure 1). The CRB formation is considered to be an impermeable lower boundary for the purposes of this model, an assumption which is consistent with the conclusions of Lindsey (2007). The model encompasses 239 mi² and extends to a maximum depth of 940 ft below ground surface (bgs).

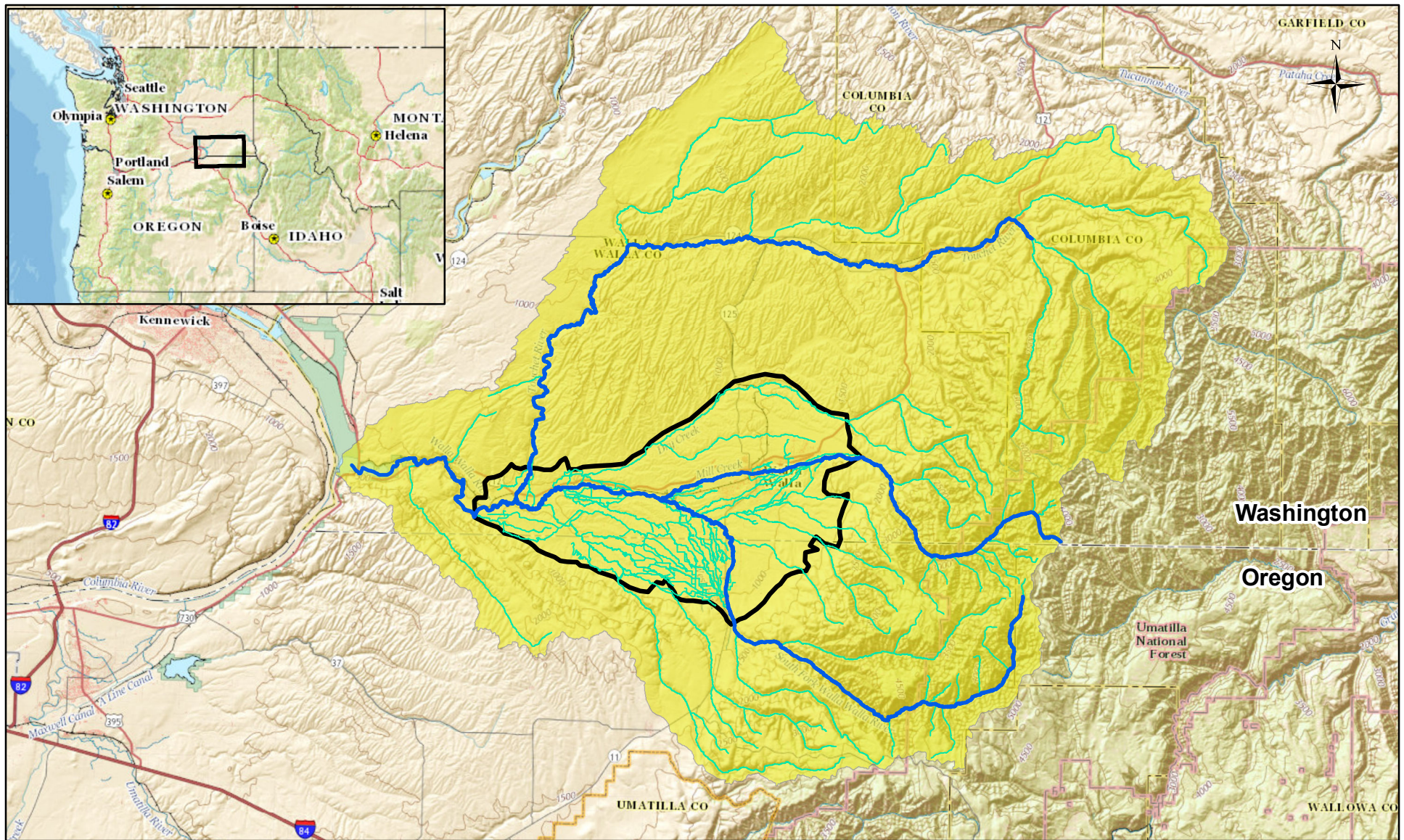
The model is bounded by the Blue Mountains to the east, the Horse Heaven Hills to the south and southwest, and the Palouse Slope to the north and northwest. The model includes the basin population centers of Walla Walla, WA, College Place, WA, and Milton-Freewater, OR (Figure 2). Outside of these urban areas the primary land use is agricultural. The model domain includes the Walla Walla River and its perennial and intermittent tributaries.

2.2 Model Grid

The model grid was generated using the IWFM Mesh Generator tool available on the CDWR-BDO website (<http://baydeltaoffice.water.ca.gov/modeling/hydrology/IWFM/>). The model framework is based on a grid of 16,215 triangular finite elements (Figure 3). Each of these elements covers an area of approximately ten acres. The vertices of these elements are referred to as nodes, of which there are 8,294 in the model. The points of intersection of streams and canals across nodes are defined as stream nodes (Figure 3).

To ensure that the model streams were topographically correct, the Mesh Generator output was modified using ArcMap GIS to snap stream nodes within the model to actual stream locations identified in the National Agriculture Imagery Program 2006 stream coverage.

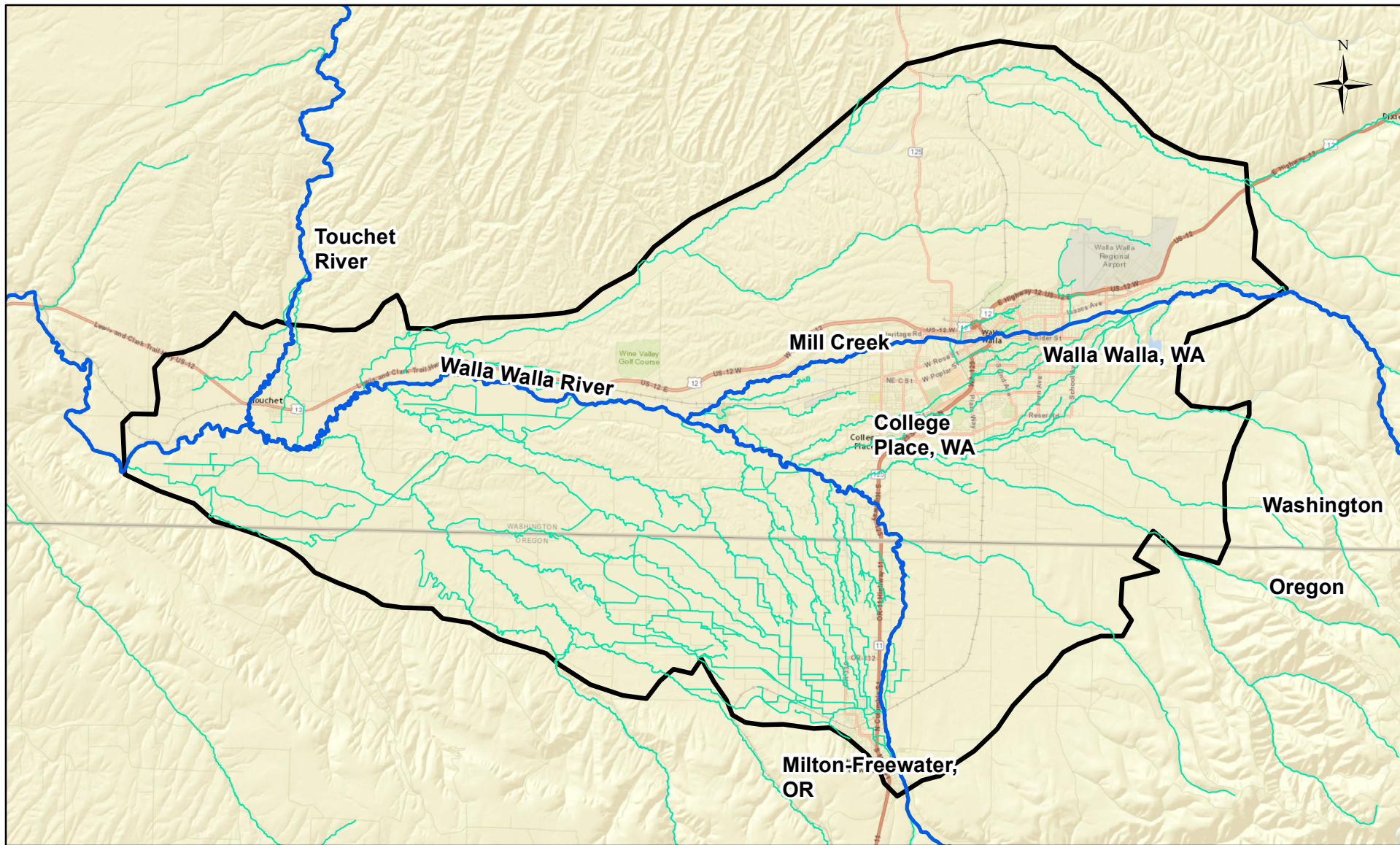
Stream nodes are further sub-divided into stream segments, which are defined to represent physically distinct stream reaches based on points of origin and points of convergence, or flow out of the model area. There are 1,506 stream nodes in the model and 91 stream segments. All features within the model are defined spatially within this framework as are model inputs such as boundary conditions, climate conditions, and water demand. Complete definitions of model elements, nodes, and stream nodes are provided in Appendix B.



Legend

- Walla Walla Basin
- Walla Walla Basin Rivers
- IWFM Model Boundary
- Walla Walla Basin Streams

Figure 1. Walla Walla Basin and Basin model boundary

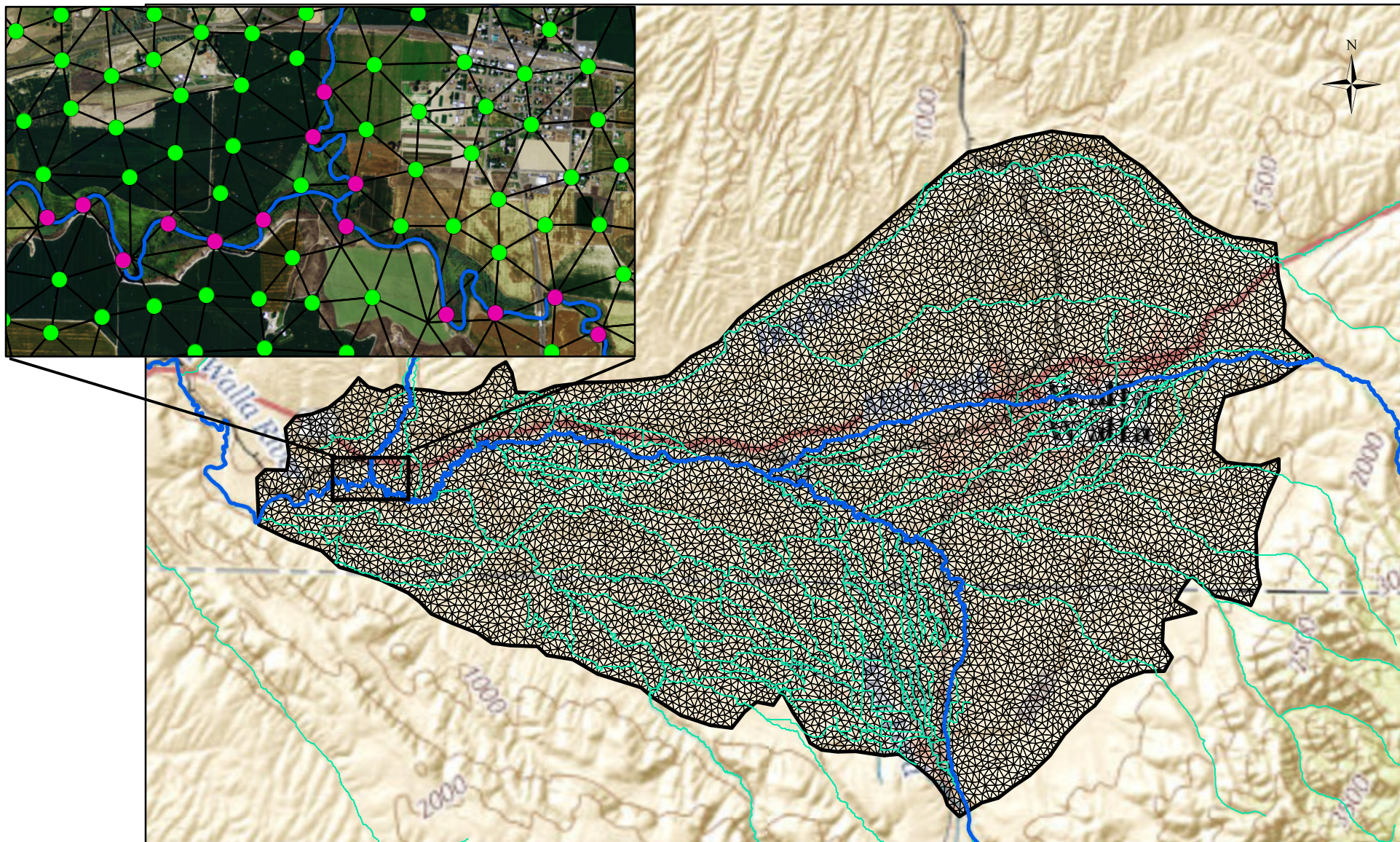


Legend

- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- IWFM Model Boundary

0 2.5 5 10 Miles

Figure 2. Walla Walla Basin model domain



Legend

- 2015 IWFM Model Boundary
- IWFM Model Nodes
- Walla Walla Basin Rivers
- IWFM Model Elements
- IWFM Stream Nodes

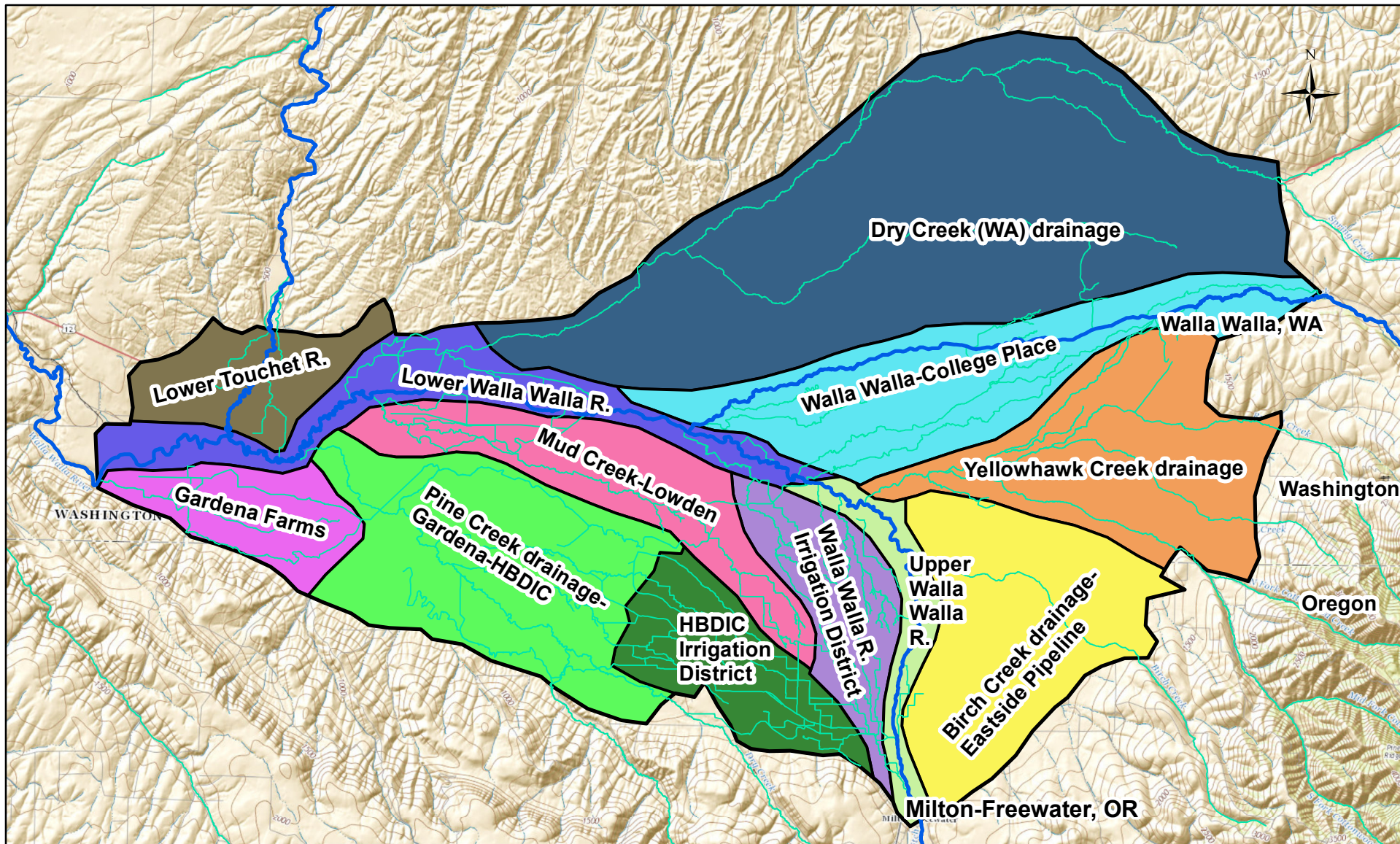
Figure 3. Walla Walla Basin model element, node, and stream node distribution

2.3 Model Sub-Regions

The model is divided into 12 sub-regions based on predominant physical characteristics or management boundaries (Figure 4). Model sub-regions allow for model outputs that provide the hydrological budget for each sub-region, in addition to the hydrological budget for the entire model domain. Model sub-region boundaries were defined based on consultation with the WWBWC and approximate irrigation district boundaries, Walla Walla – College Place urban area, reaches of the Walla Walla River, and drainage boundaries for several tributary streams. For convenience, the sub-regions are each assigned a unique name and number, as defined in Table 1.

Table 1. Walla Walla Basin model sub-region name and number

Sub-region Number	Name
1	Upper Walla Walla River
2	Lower Walla Walla River
3	Birch Creek Drainage-Eastside Pipeline
4	Walla Walla River Irr. District
5	HBDIC Irr. District
6	Pine Creek drainage-Gardena-HBDIC
7	Mud Creek-Lowden
8	Yellowhawk Creek drainage
9	Walla Walla-College Place
10	Dry Creek (WA) drainage
11	Gardena Farms
12	Lower Touchet River



Legend

- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- 2015 IWFM Model Boundary

Figure 4. Walla Walla Basin model sub-regions

2.4 Geologic Framework

The model domain encompasses the land surface and five sedimentary geologic units that overlay the CRB formation within the Walla Walla Basin. The sedimentary depositional patterns result from historic flooding and channel migration of the Walla Walla River within its valley.

Every node has an associated land surface elevation originating from a ten meter digital elevation model provided by the WWBWC. The thickness of each underlying stratigraphic layer is defined for every node, with these values determining the top and bottom elevations of the aquifer layers as well as the lower model boundary. The hydrogeological characteristics of the strata are specified in the model parameters unit of the model inputs and discussed in Section 4.1.

The thickness of the stratigraphic layers as input into the model is based on structure contour and isopach analyses from Lindsey (2007) with some modification to address anomalies that were identified while formatting the geologic data for incorporation into the basin model. Collectively, the sedimentary units are thickest in the central portion of the model area and comprise a thin layer around the perimeter (Figure 5).

The geologic units included in the model are briefly described in the following sections in order of shallowest to deepest. Refer to Lindsey (2007) for a detailed description and mapping of the regional geology. Appendix B provides a complete summary of stratigraphic thickness at all model nodes.

2.4.1 *Quaternary Fine Unit*

The Quaternary Fine (QF) unit, also referred to as the Touchet Beds, is the upper strata represented in the model. It consists of layers of fine loess and silt deposited by eolian processes and flooding. It is not highly conductive to water, though it is not considered a confining unit. The QF unit primarily occurs on ridges and topographically high areas and is not found in the stream channels of the model area (Figure 6).

2.4.2 *Quaternary Coarse Unit*

The Quaternary Coarse (QC) unit, referred to by Newcomb (1965) as “new gravels”, primarily consists of uncemented coarse gravels of which the extent and thickness have been significantly affected by post-depositional erosion from streams (Figure 7). The unit is an unconfined and highly conductive aquifer.

2.4.3 Miopliocene Coarse

The Miopliocene Coarse (MPC) unit, referred to as “old gravels” in Newcomb (1965), consists of variably cemented sand and gravels distinguishable from the QC unit by the presence of basalt clasts and a clay matrix that gives it a red-brown to yellow-brown appearance. The MPC unit comprises the aquifer with the greatest water bearing capacity within the model and supplies the majority of groundwater used for agricultural purposes. It is hydraulically continuous with the overlying QC unit (Figure 8), though less conductive.

2.4.4 Miopliocene Fine

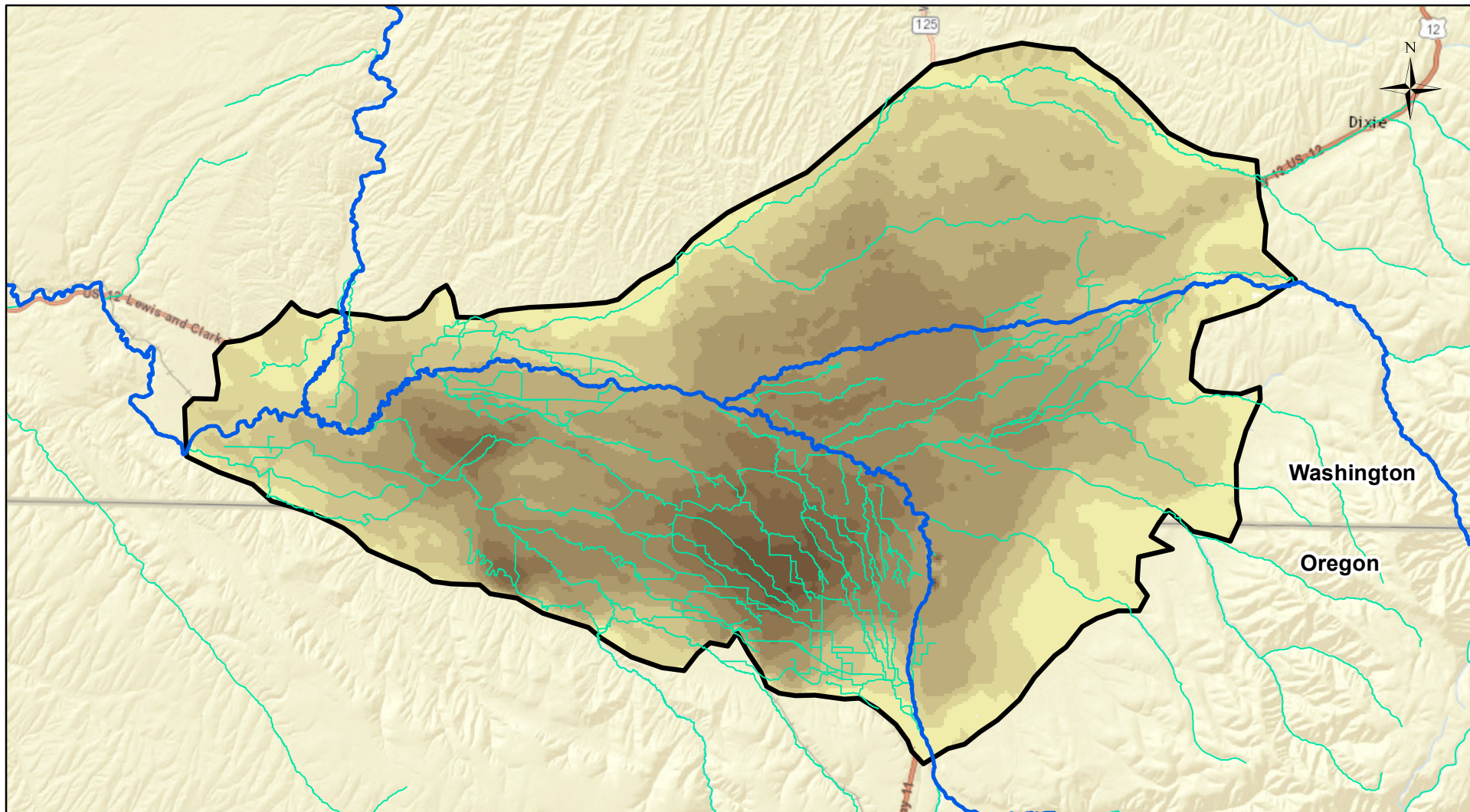
The Miopliocene Fine (MPF) unit is primarily found below the MPC unit, though there is a significant degree of interbedding between the layers. It consists of silt, clay, sandy-clay, and sandy mud, and typically has blue, green, brown, or yellow appearance. Like the MPC unit, the MPF unit has variable thickness due to material being redistributed by channel migration (Figure 9). Due to the interbedding of the Miopliocene strata, areas of gravel may be present within the MPF unit, some of which appear to yield a usable groundwater supply. For this reason the MPF unit is represented as an aquifer in the model though it is believed to be far less conductive than the MPC unit and has a lower water bearing capacity.

2.4.5 Miopliocene Basal Coarse

The Miopliocene Basal Coarse unit (MPBC), where it is present, lies directly above the CRB. It is distinct from the other Miopliocene units, consisting of arkosic-micaceous sands deposited by an ancestral river flowing from the north. It is incorporated into the model as an aquifer, capable of storing and transmitting water. It is currently mapped in five distinct patches, up to 90 meters thick in places, though it is absent over much of the model area (Figure 10). Characterization of the MPBC unit is difficult due to the fact that few wells are deep enough to document it. It is possible that the unit is more extensive than is currently known.

2.4.6 Columbia River Basalts

The CRB formation consists of numerous layered basalt flows, some of which function as confined aquifers. The top of this unit is considered to be the lower boundary of the model and is not included in the model domain; however the aquifers are a source of municipal water supplies and used to supplement irrigation water. These practices serve to connect the CRB and alluvial aquifers as leakage from municipal water distribution systems and excess water applied for outdoor use in urban and domestic areas percolates into shallow groundwater.



Legend

- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- IWFM Model Boundary

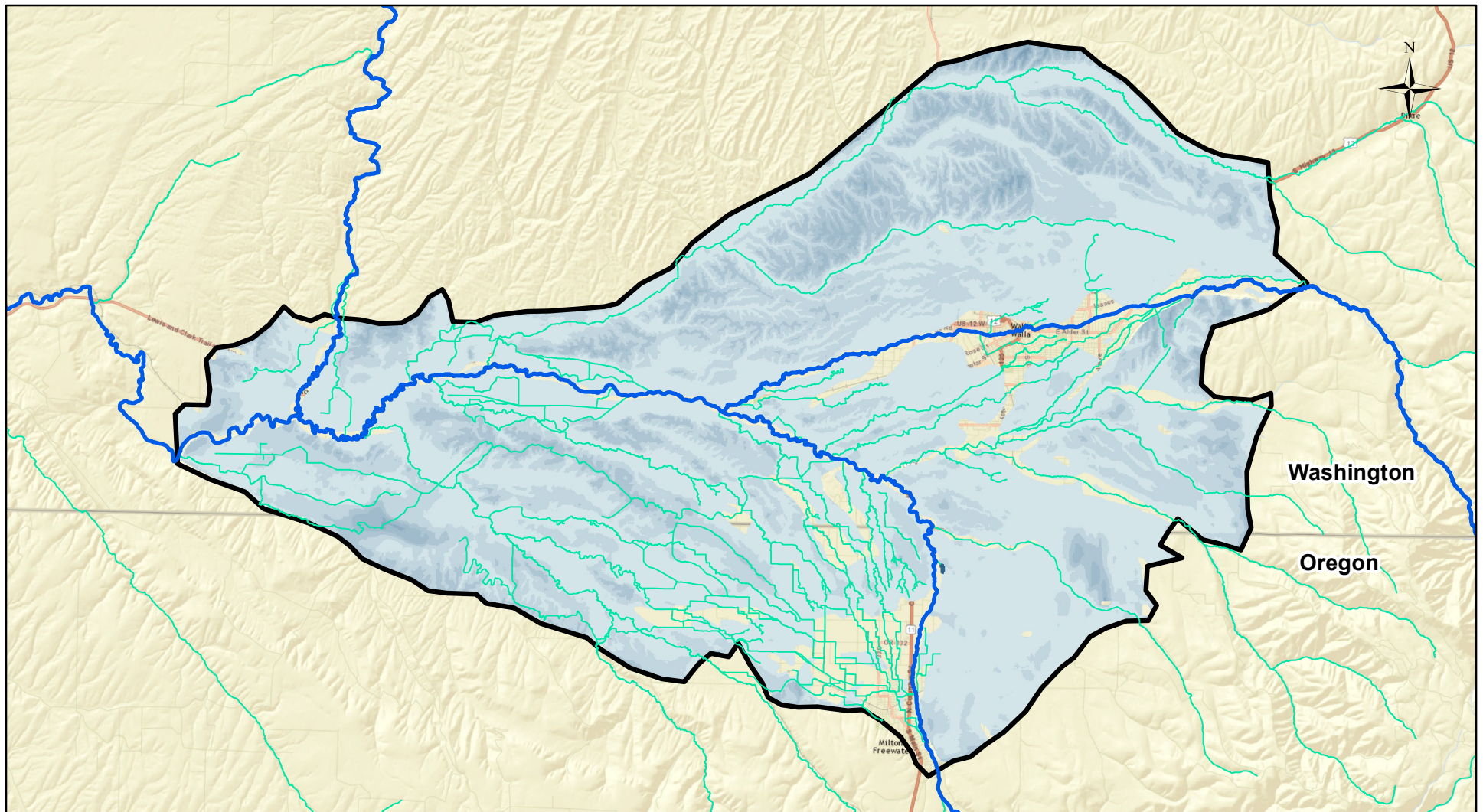
Total thickness of alluvial deposit (feet)

- 0 - 100
- 101 - 200

- | | | | | | | | |
|---|---|---|---|---|---|---|---|
| 201 - 300 | 301 - 400 | 401 - 500 | 501 - 600 | 601 - 700 | 701 - 800 | 801 - 900 | 901 - 1,000 |
|---|---|---|---|---|---|---|---|

0 2.5 5 10 Miles

Figure 5. Thickness of subsurface materials in the Walla Walla Basin model domain (depth to Colubia River Basalts)



Legend

- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- IWFM Model Boundary

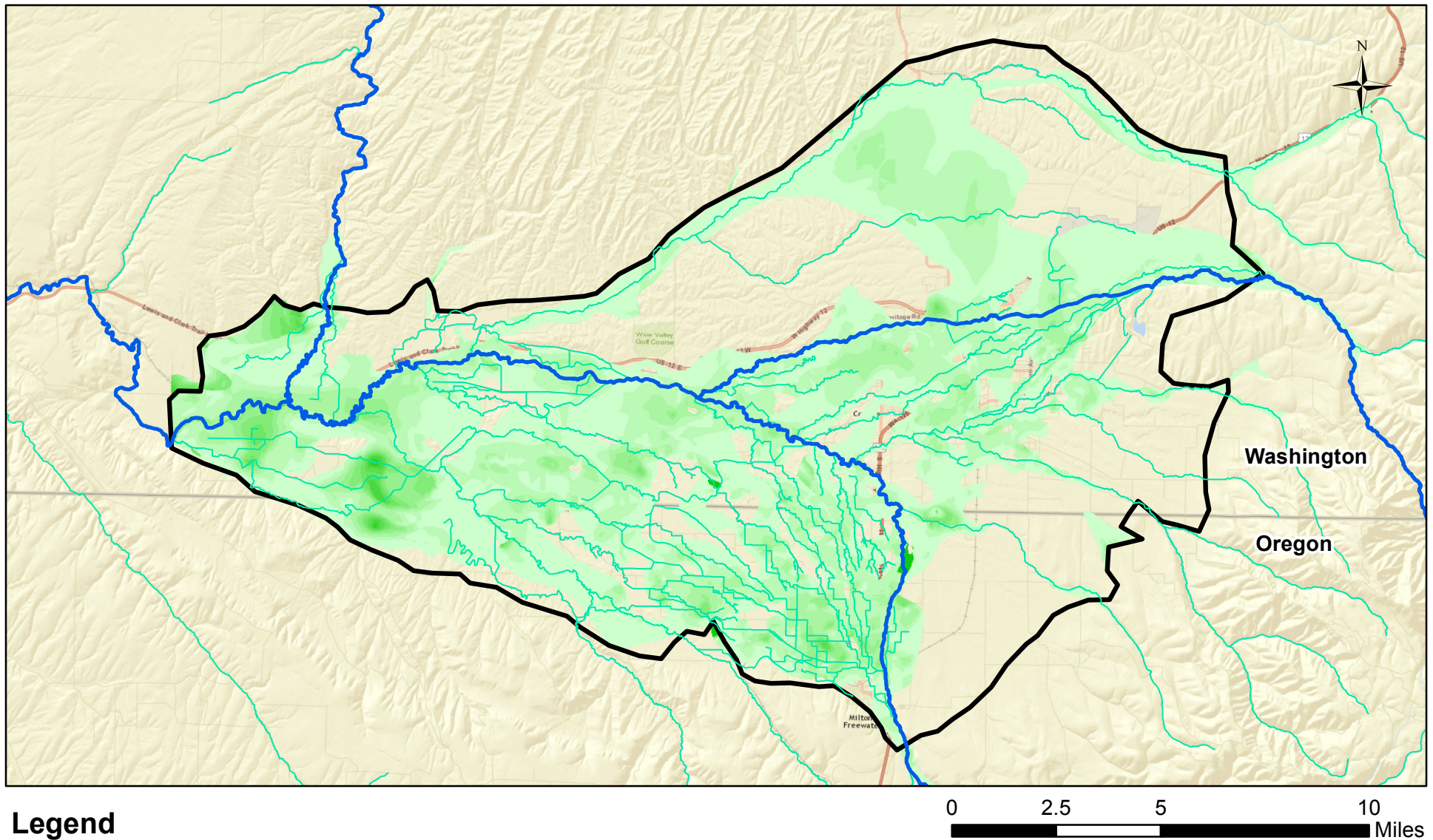
Thickness of QF unit (feet)

- 0 - 40
- 41 - 80

- | | | |
|---|---|---|
| 81 - 120 | 201 - 240 | 321 - 360 |
| 121 - 160 | 241 - 280 | 361 - 400 |
| 161 - 200 | 281 - 320 | 401 - 440 |

0 2.5 5 10 Miles

Figure 6. Thickness of Quaternary Fine unit in the Walla Walla Basin model domain



Legend

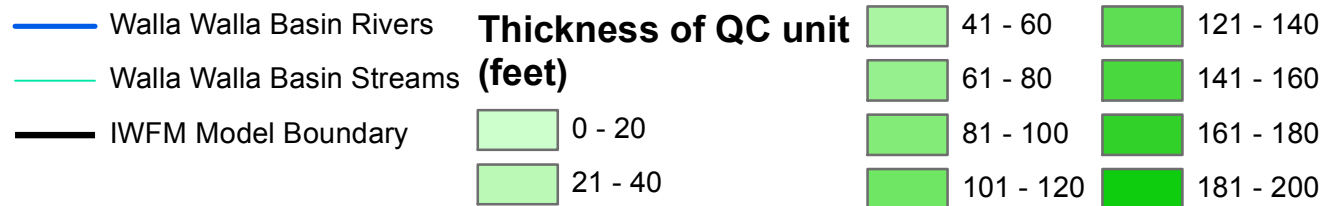
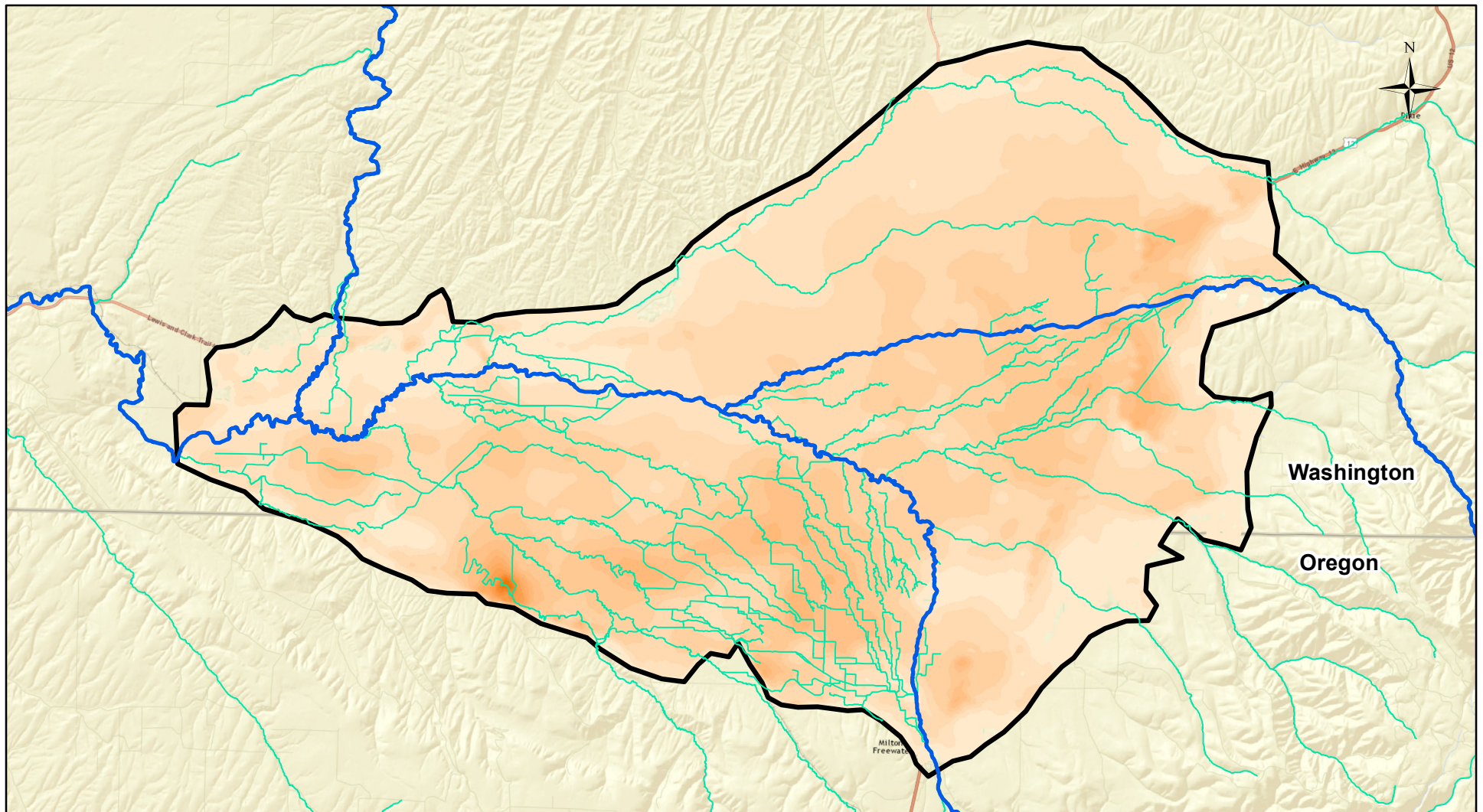


Figure 7. Thickness of Quaternary Coarse unit in the Walla Walla Basin model domain



Legend

- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- IWFM Model Boundary

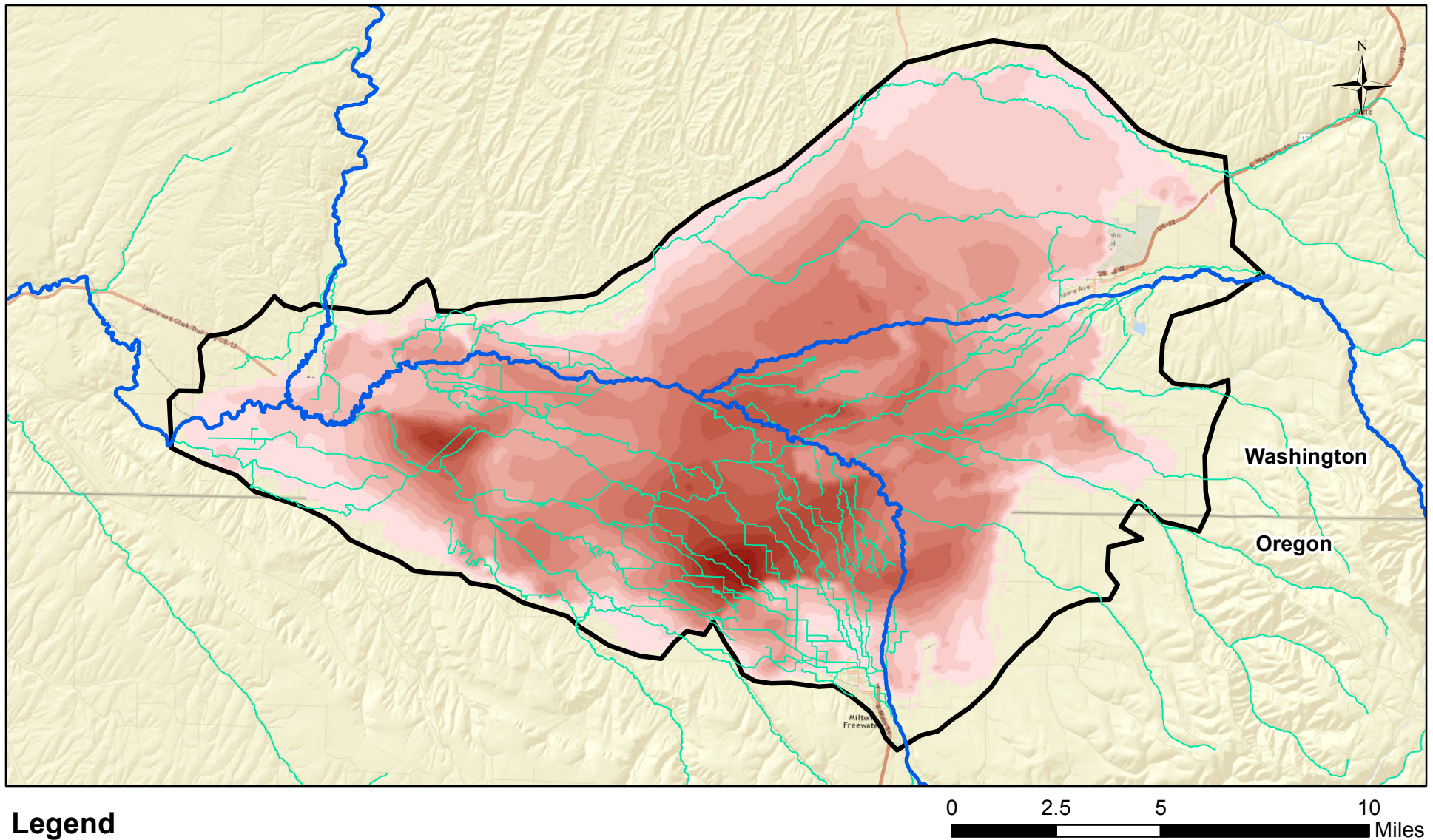
Thickness of MPC unit (feet)

- 0 - 50
- 51 - 100

 101 - 150	 301 - 350	 501 - 550	 701 - 750
 151 - 200	 351 - 400	 551 - 600	 751 - 800
 201 - 250	 401 - 450	 601 - 650	
 251 - 300	 451 - 500	 651 - 700	

0 2.5 5 10 Miles

Figure 8. Thickness of Miopliocene Coarse unit in the Walla Walla Basin model domain



Legend

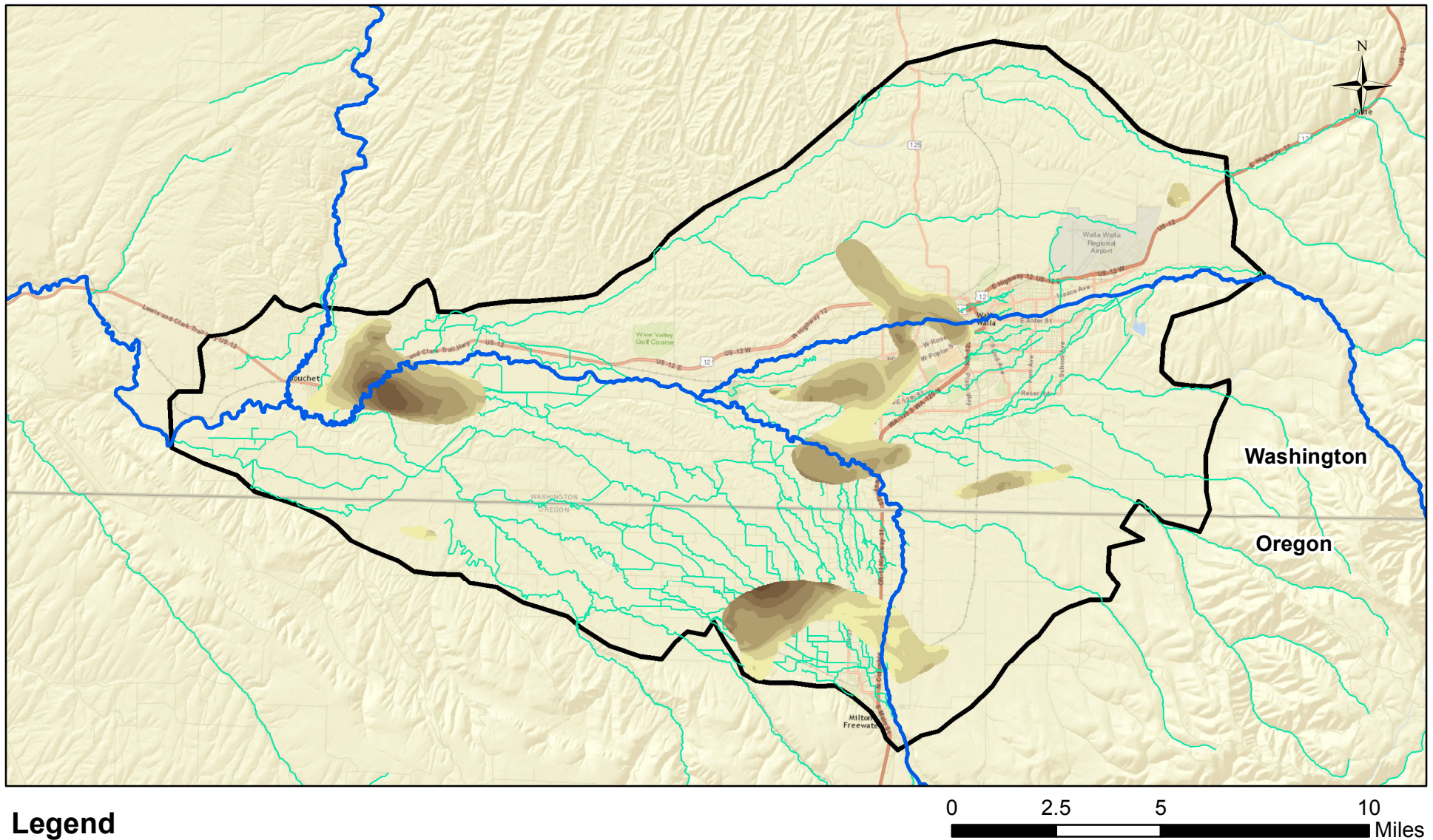
- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- IWFM Model Boundary

Thickness of MPF unit (feet)

- 1 - 50
- 51 - 100

 101 - 150	 301 - 350	 501 - 550
 151 - 200	 351 - 400	 551 - 600
 201 - 250	 401 - 450	 601 - 650
 251 - 300	 451 - 500	 651 - 700

Figure 9. Thickness of Miopliocene Fine unit in the Walla Walla Basin model domain



Legend

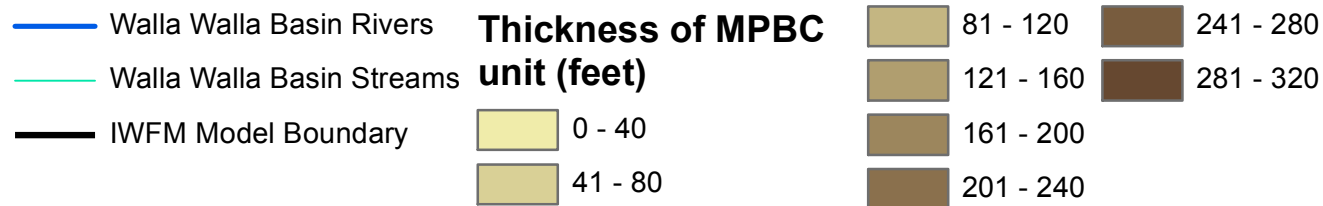


Figure 10. Thickness of Miopliocene Basal Coarse unit in the Walla Walla Basin model domain

2.5 Groundwater

Groundwater within the model occurs within the four lower sedimentary units, as described in the preceding section, with the majority of the total groundwater volume being in the MPC aquifer. Groundwater is an important source of water for irrigation and feeds springs within the basin, some of which provide off channel habitat and thermal refuge for juvenile salmonids (Wolcott, 2010). Groundwater declines jeopardize these benefits and are therefore an important consideration for water management within the basin.

2.5.1 Groundwater Boundary Conditions

A specified head boundary condition was used to estimate lateral groundwater inflow into the model area. Groundwater elevation data was obtained from a collection of 97 monitoring wells within the model area. These wells are actively monitored by WWBWC personnel with data collected at intervals that range from hourly to quarterly (Patten, 2010). Some wells have groundwater elevation data records that go back over 50 years whereas others have only recently been added to the WWBWC groundwater monitoring program.

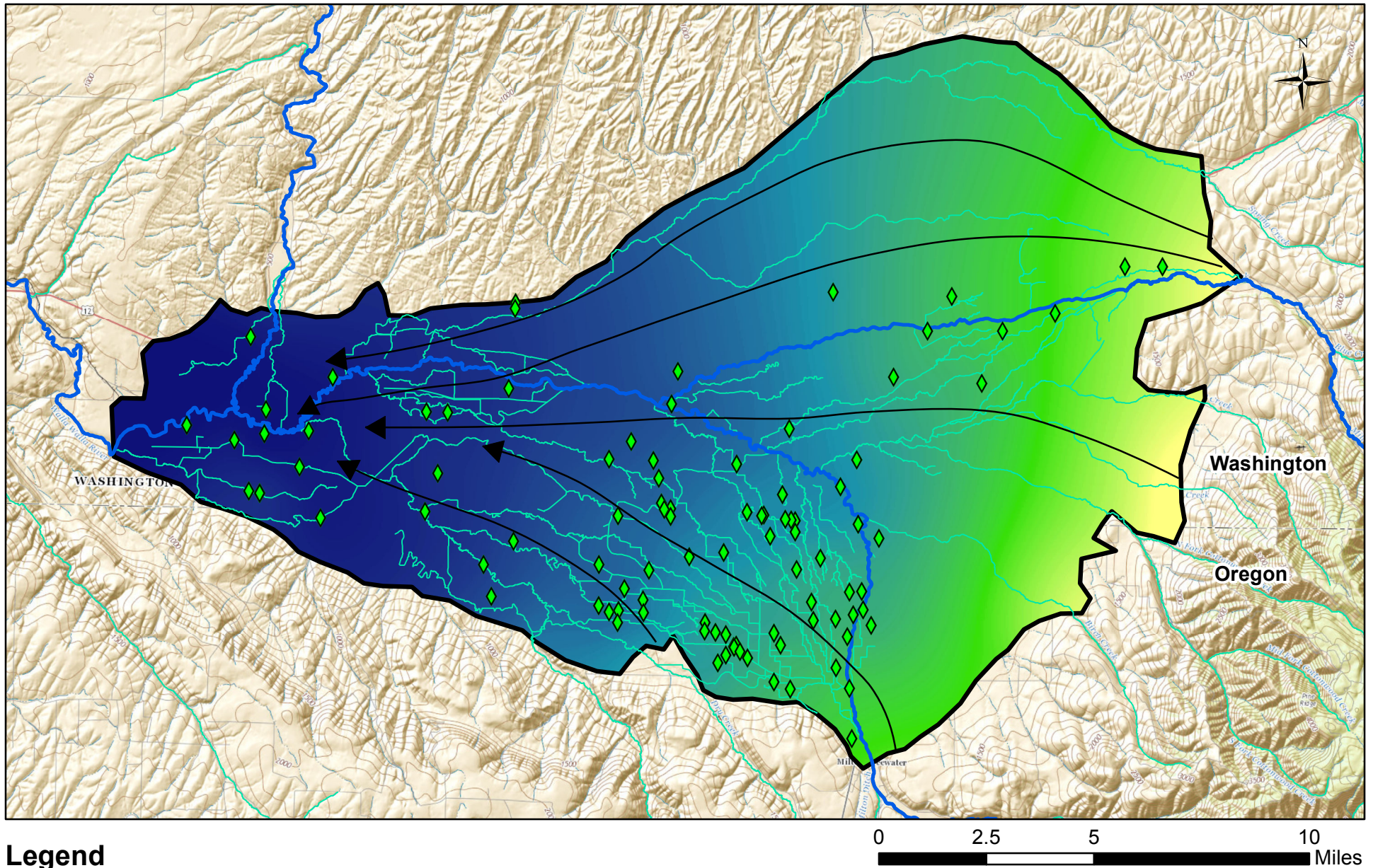
Monitoring wells were assigned data quality ratings from one through four, with one being the highest data quality rating. Data quality ratings were based on the number of groundwater elevation measurements during the model development period (2007 through 2013), the consistency of the measurements, and the presence of an identifiable pattern in groundwater elevation change, both seasonally and in comparison to nearby wells. Data from monitoring wells that were determined to have a rating of four were not used for generating boundary conditions or for model calibration; this eliminated seven wells from the input data set. Data from the remaining wells was processed to determine a monthly average groundwater elevation. A spline interpolation of the monthly average groundwater elevations was performed in ArcGIS to project estimated monthly groundwater elevations over the model area.

Some monitoring wells lacked groundwater elevation data over single or multiple months, creating inconsistency in interpolated groundwater elevation because of inconsistent input sources. This necessitated generating groundwater elevation estimates for monitoring wells with missing data. Groundwater elevation estimates at the monitoring wells was done by assuming a linear regression between measured data points in instances where a missing month of data had groundwater elevation measurements available for the neighboring months. If consecutive months of groundwater elevation data were missing, the groundwater elevation was taken to be the average historic groundwater elevation measured at that well for the given month.

Interpolated groundwater elevations were developed for the 84 months that were the focus of model development (Figure 11). The measured and interpolated basin wide groundwater hydraulic gradient was generally from east to west throughout the year.

Interpolated monthly groundwater elevation values were extracted from the points along the model boundary using ArcGIS tools. The resulting groundwater elevation data set was assumed to represent groundwater head along the model boundary for the fifteenth day of each month, and a linear interpolation was then performed to estimate groundwater elevation along the boundary for each day to satisfy the daily time step input of the model. Where groundwater elevation was below the elevation of a given aquifer, it was assumed that no boundary inflow occurred within that aquifer.

The thin layer of aquifer material along the northern and eastern portions of the model boundary limits groundwater inflow at these areas. As a result, the model is relatively insensitive to the groundwater boundary conditions along the northern and eastern model boundary, limiting the effect of possible errors associated with the sparse monitoring well data that is available in the northern and eastern portions of the model area (Figure 11). Interpolated monthly groundwater elevations along the model boundary and daily groundwater boundary conditions assigned in the model are provided in Appendix C.



Legend

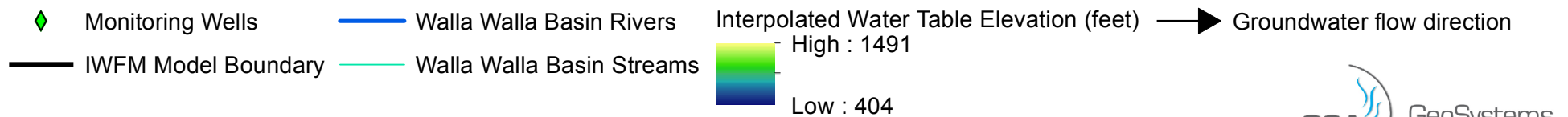
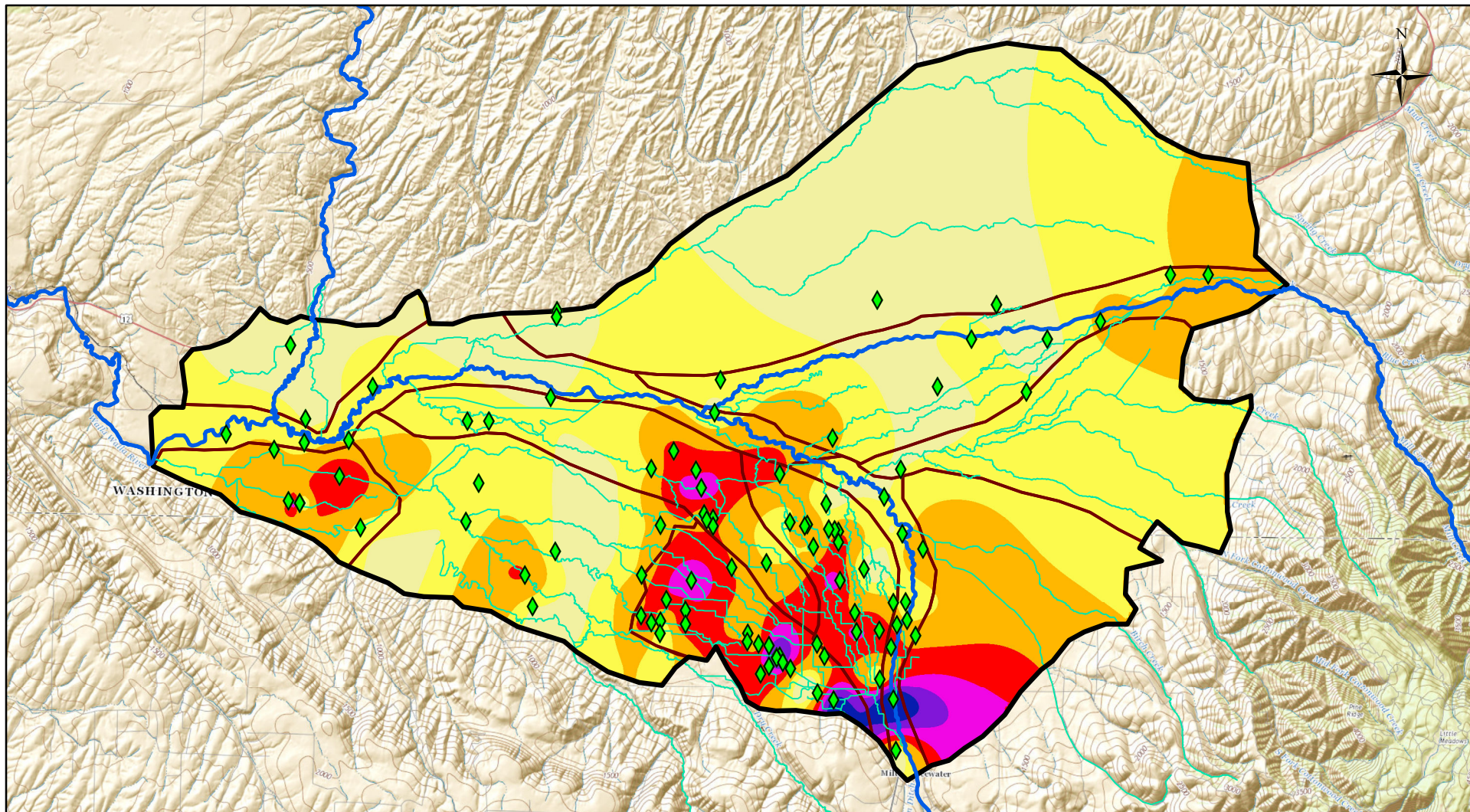


Figure 11. Example of interpolated water table for May, 2007 generated for determining boundary conditions using data from selected monitoring wells.

2.5.2 Groundwater Pumping

Groundwater pumping from the alluvial aquifers is calculated by the model based on the difference between agricultural demand and applied water from surface water and the CRB wells. To estimate the distribution of alluvial aquifer pumping within the model, the standard deviation of measured groundwater elevation for each well was interpolated over the model area (Figure 12). A low groundwater elevation standard deviation implies small temporal changes in groundwater elevation, implicating little or no groundwater pumping was occurring within the monitoring well's measurement area. Elements with an interpolated groundwater elevation standard deviation of less than 0.2 m were considered to not be influenced by alluvial aquifer pumping, and model settings were adjusted accordingly so that pumping would not be simulated in those areas. The remaining model elements were assumed to have the potential to supply groundwater from the alluvial aquifer to meet the remaining agricultural demand.

Groundwater pumping from the CRB aquifer is known to occur at locations within the model boundaries (Figure 13); however, pumping volumes are not known. Estimates for CRB aquifer pumping were based on the difference between the calculated water demand and the amount of surface water applied. Within each sub-region, this difference is then multiplied by a factor between 0.0 and 0.4 based on the number and distribution of CRB wells in the sub-region relative to the water demand in that sub-region, and based on consultation with irrigation district managers. Estimated pumping from the CRB wells is specified in the model inputs using a daily time step. Complete processing of data used for estimating pumping from the CRB aquifer is provided in Appendix D.



Legend

- IWFM Model Boundary
- Walla Walla Basin Rivers
- ◆ Groundwater Monitoring Wells
- Walla Walla Basin Streams
- IWFM Model Sub-Regions

Well data Standard Deviation (feet)

0 - 1

1 - 2

2 - 4

4 - 6

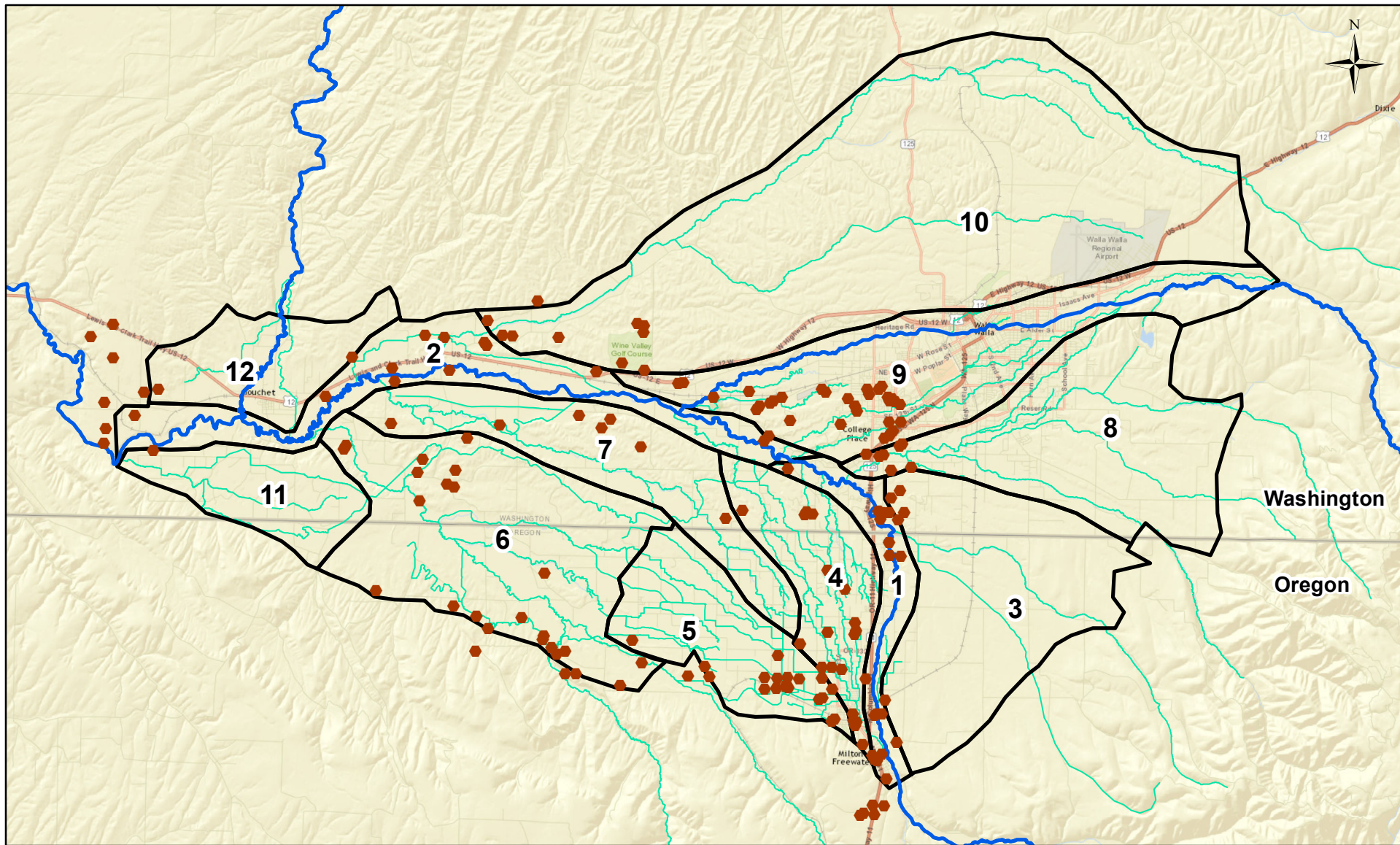
6 - 8

8 - 10

> 10

0 2.5 5 10 Miles

Figure 12. Interpolated Standard Deviation of 2007 through 2013 groundwater elevation data collected at monitoring wells.



Legend

- Walla Walla Basin Rivers
- Walla Walla Basin Streams
- CRB Well locations
- IWFM Model Sub-Regions

Figure 13. Locations of wells know to draw water from the Columbia River Basalt (CRB) aquifer system.

2.6 Surface Water

The primary Walla Walla Basin model surface water inflow is the rivers and streams that cross the model boundary as they flow out of the mountains and toward the basin floor. Additionally, surface water – groundwater interactions significantly affects flows in many stream reaches. To a lesser extent, return flows of treated wastewater from the metropolitan areas serve as a surface water inflow. Within the model a network of canals distribute water for irrigation purposes. Model surface water outflow is restricted to where the Walla Walla River crosses the western model boundary.

Gauge data was used wherever possible to estimate the distribution of river, stream, and canal flows within the basin. A majority of these gauges are managed by the WWBWC, while others are managed by the United States Geological Service (USGS), Oregon Water Resources Department, and Washington Department of Ecology. These gauges have been grouped by the WWBWC into six series based on the location, water body, and management entities (Figure 14). Where gauge data was not directly available, surface water flows and diversion rates were based on the records of the most applicable upstream or downstream gauges or from consultation with irrigation district management personnel and WWBWC. All surface water gauge data used in the model is included in Appendix B.

Stream physical and hydraulic parameters were assigned generally by segment type. All stream nodes were assumed to have properties that align with their segment type unless information is available to warrant a variation. For example, the piped reach on the otherwise permeable Gardena canal. Stream bed conductivity, stream bed elevation relative to surface elevation, wetted perimeter of the channel, and stage-discharge relationship were all defined based on the segment type associated with a stream node. Segment types for all model stream nodes are shown in Figure 15. Segment types and rating tables used in the model are included in Appendix B.

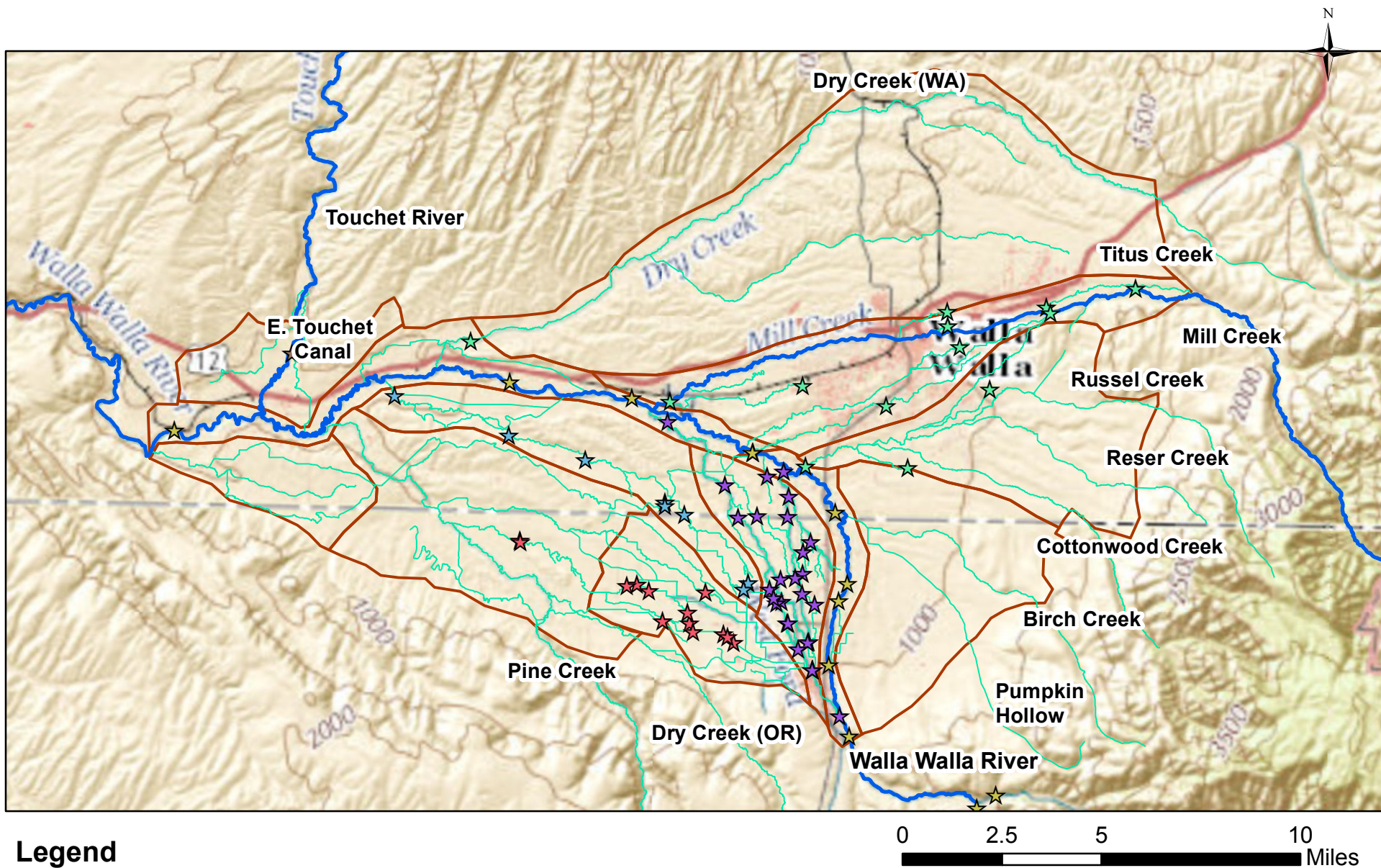
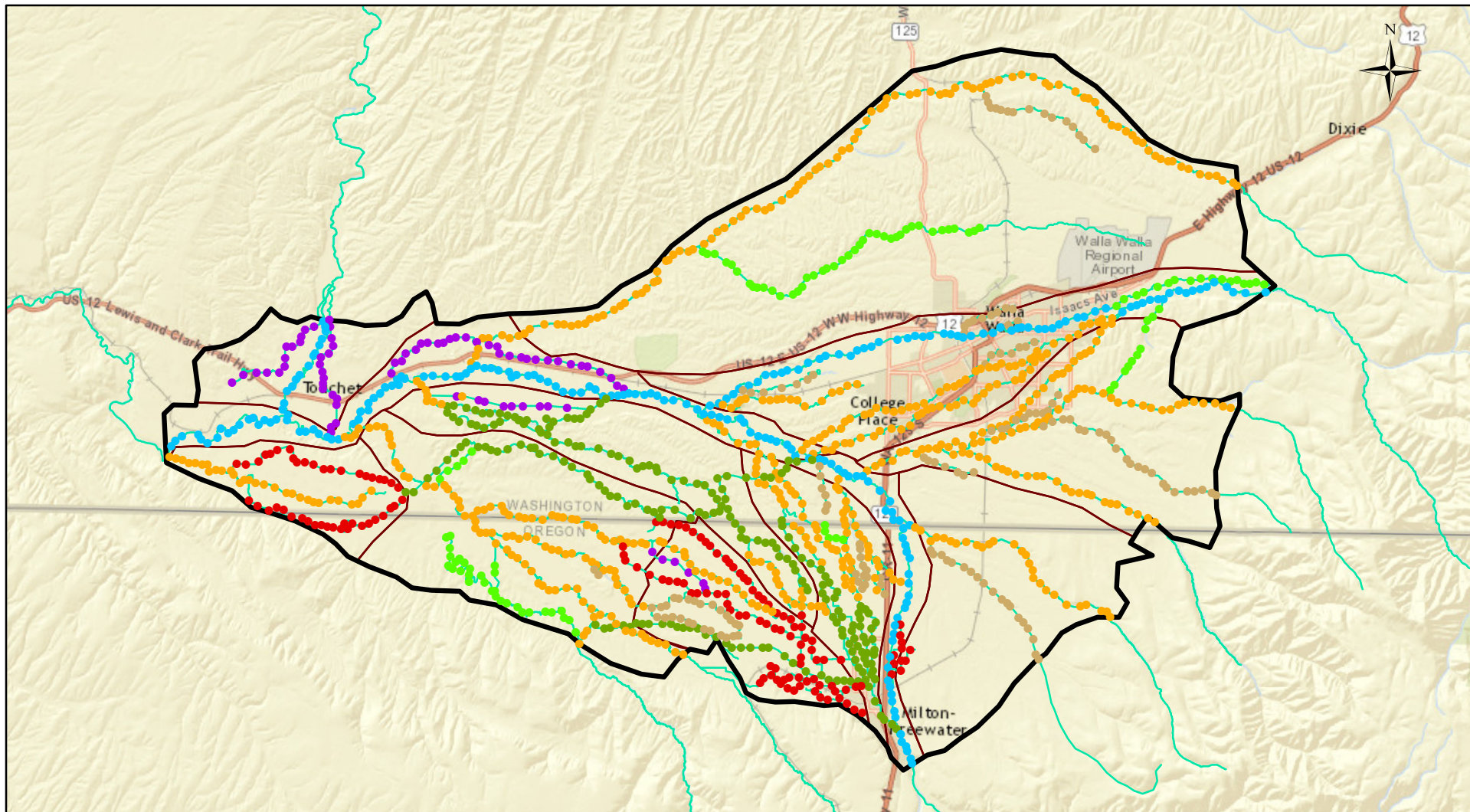
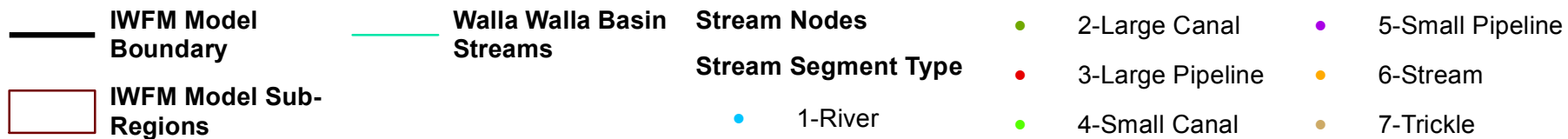


Figure 14. Walla Walla Basin surface water gauges grouped by gauge series and model inflowing streams



Legend



0 2.5 5 10 Miles

Figure 15. Walla Walla Basin model stream segment definitions and distribution

2.6.1 Surface Water Boundary Conditions

Surface water boundary conditions were defined by the flow rate of streams where they intersect the model boundary. There are 13 total inflowing rivers and streams, with the primary surface inflows being the Walla Walla River, the Touchet River, and Mill Creek (Figure 14).

Historic daily flow data was available for the Walla Walla River, the Touchet River, and Mill Creek; however, daily flow data was absent for the remaining ten streams that flow into the model. Partial flow data ranging from periodic measurements to limited periods of daily monitoring existed for Pine Creek, Dry Creek (OR), Dry Creek (WA), and Titus Creek. To develop the complete daily flow record necessary for model input a relationship between recorded creek flows and the daily data set for the Walla Walla River and the Touchet River was evaluated. Flow data for Dry Creek (OR), Dry Creek (WA), and Pine Creek were most strongly correlated to the Touchet River data set and the resulting regression equation was used to estimate flows in these creeks when direct measurements were unavailable (Figure 16). Data for Titus Creek was limited, though it receives flow from Mill Creek and estimated flows were determined based on the relationship between available flow data for Titus Creek and Mill Creek and consultation with the local water master.

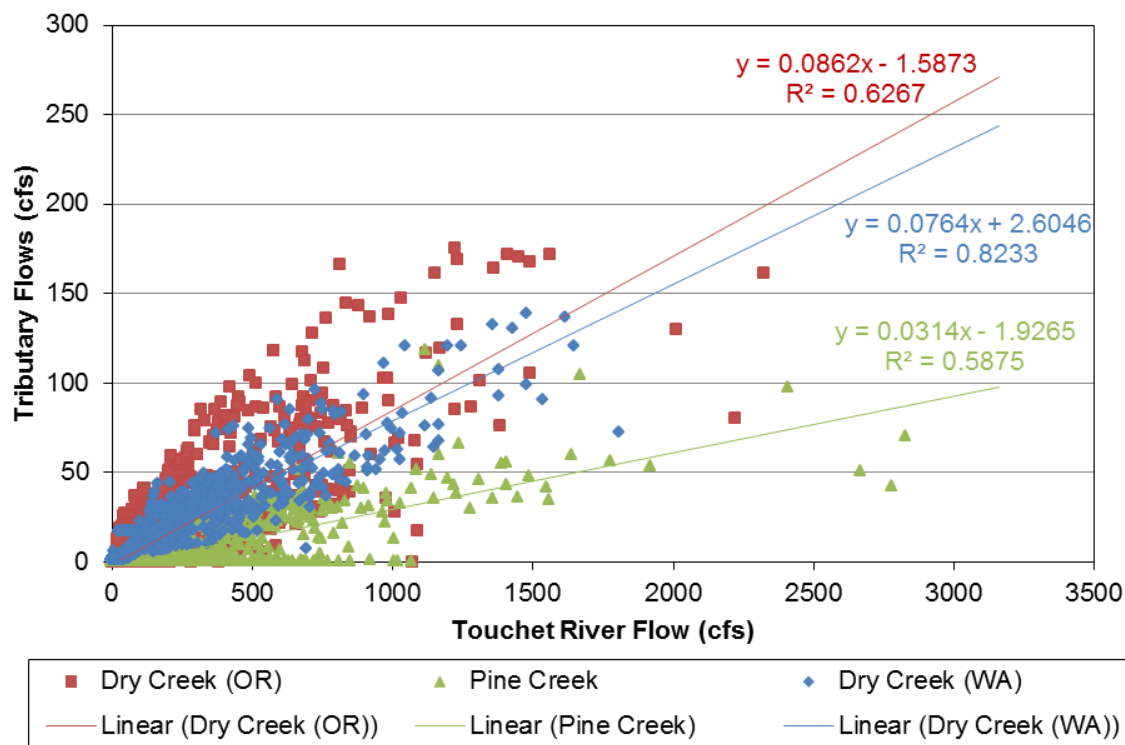


Figure 16 . Correlation between measured flow data for the Touchet River and Pine Creek, Dry Creek (OR), and Dry Creek (WA)

Stream flow data was not available for the remaining streams and was derived as follows. For Cottonwood Creek, Russell Creek, and Reser Creek, all tributaries of Yellowhawk Creek, flows were derived from gauge data collected from above (upper Yellowhawk Creek) and below (lower Yellowhawk Creek) their combined confluence with Yellowhawk Creek. The increase in flow between upper Yellowhawk Creek and lower Yellowhawk Creek was assumed to originate from Cottonwood Creek, Russell Creek, and Reser Creek. The relative contributory flow of each creek was determined from the measured width of the wetted channel, bank full width, and flow rate where flow conditions allowed. The increase in flow between upper Yellowhawk Creek and lower Yellowhawk creek was proportioned accordingly across all three creeks based on these measurements.

The Birch Creek and Pumpkin Hollow inflows were based on several flow measurements and channel characterization performed by GSA in October, 2014 and observations from local residents (i.e. months they are typically flowing). Flow for the East Touchet Canal was based on water rights, pipeline capacity, and typical diversion rates given by irrigation district managers and the Walla Walla Management Partnership.

Return flows of treated wastewater from the metropolitan areas are discharged into local streams over the winter and early spring months. These wastewater return flows are treated in the model as seasonal inflows, occurring at the appropriate locations and times. The rate of daily wastewater return flow and where these flows are discharged is discussed in Section 2.10.2.

There is only one location where surface water flows out of the model; the Walla Walla River downstream from Touchet, Washington. The surface outflow is calculated by the model and represents the combined net inputs and outputs from rivers, streams, canals and groundwater within the model area.

2.6.2 Surface Water Bypasses and Diversions

The canal network within the Walla Walla Basin is a complicated, yet effective means of moving water throughout the basin to supply irrigators. Within the model “Bypasses” refer to features that transfer water from one channel to another or to an aquifer recharge site. There are 134 bypasses in the model. The amount of water bypassed was based on gauge data whenever possible, whether directly, in relation to an upstream or downstream gauge, or based on a regression equation relating measured flow between canals.

“Diversions” refer to locations where water is withdrawn from the stream/canal network to supply an agricultural demand. Every stream node is a potential point of diversion that can be turned on

or off. The amount of water diverted was determined by stream segment. The quantity of water diverted at each point of diversion (i.e. stream node) was calculated by dividing the total amount of water allocated for diversions within the stream segment by the number of diversions switched on in the segment. All diversions that are turned on in a stream segment have the same amount of water allocated to them and thus diversion quantity can be adjusted by changing either the amount of water allocated for the stream segment or the number of diversion that are turned on.

Every stream segment within the model has a specific relationship for inputting daily diversion rates based on the difference between flow into and out of the segment. These relationships use gauge data as the basis for these calculations wherever possible. In instances when gauge data is not available, diversion rates are estimated from seasonal agricultural demand and area served by the diversion in addition to upstream gauge data. The calculations applied to estimate bypasses and diversions are included in Appendix B. Specified daily flows for all diversions and bypasses are provided in Appendix E.

2.7 Precipitation

Daily precipitation applied in the model was derived from five Ag-Weather Net weather stations managed by Washington State University (Figure 17). The weather stations span an elevation range that encompasses the model area surface elevations. Measured daily precipitation was linearly interpolated between stations at 20 meter elevation intervals. The interpolated precipitation was input into the model such that every model element received rainfall corresponding to its surface elevation. Complete weather station data and precipitation data processing are provided in Appendix F.

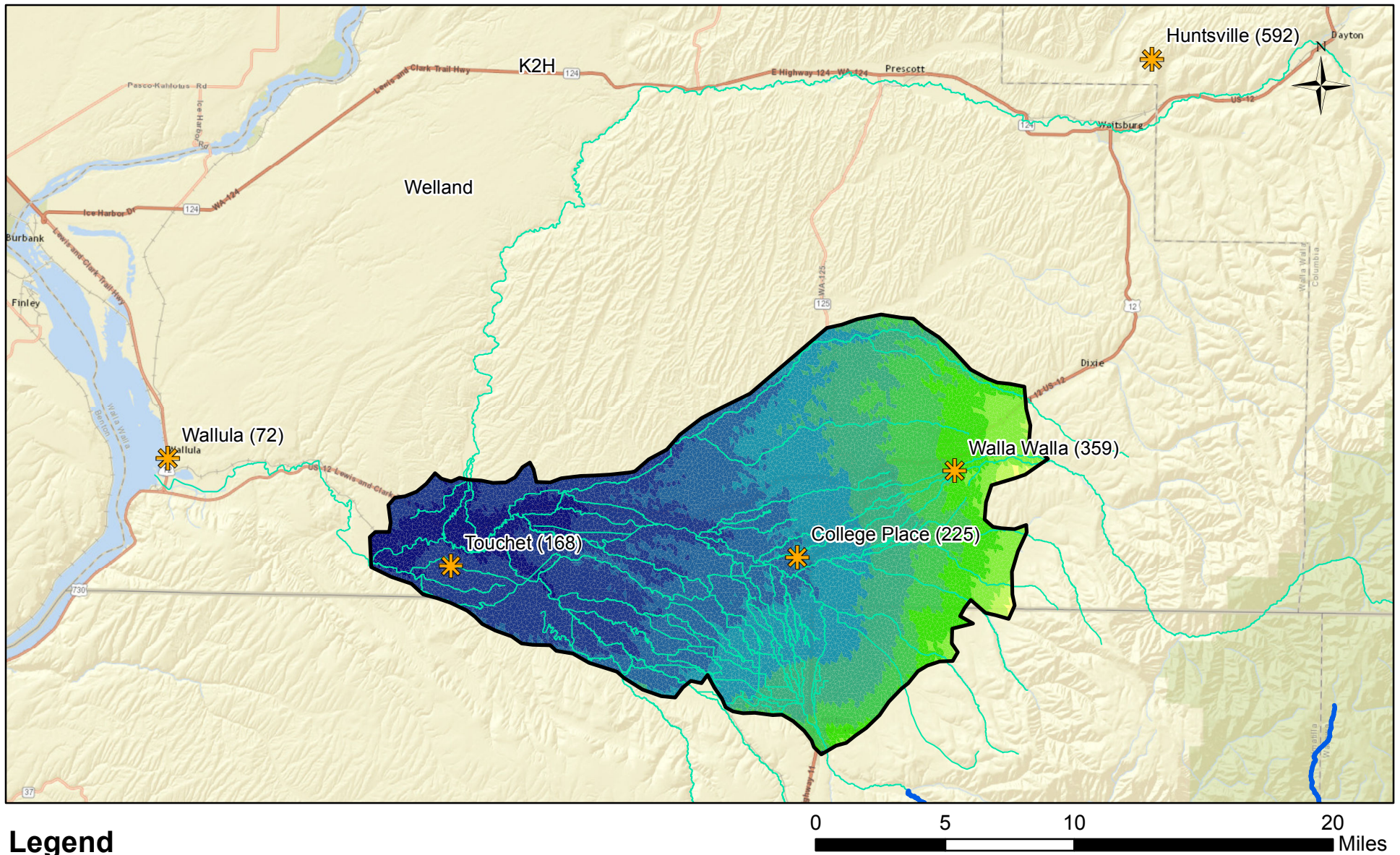


Figure 17. Ag-Weather Net stations and surface elevation within the model area used for precipitation data inputs.

2.8 Managed Aquifer Recharge

Within the Walla Walla Basin, Managed Aquifer Recharge (MAR) is accomplished by allowing surface water to percolate into the underlying alluvial aquifer. Two types of MAR facilities exist: recharge basins and infiltration galleries. Recharge basins are excavated pits on the land surface and infiltration galleries are buried perforated pipes surrounded by coarse gravel that allow water to drain into the surrounding alluvial material. Water used for MAR is diverted from the Walla Walla River and routed through the canal network to the MAR facility. MAR water diversions occur during the high Walla Walla River flow season, typically from mid-November to mid-May. MAR diversions typically do not occur in February when canals are shut down for maintenance.

At the end of the model calibration period (end of year 2013) there were seven active MAR facilities in the model area, all managed by the WWBWC (Figure 18). Table 2 provides the annual water application to each of the seven active MAR facilities based on WWBWC data records. The Johnson recharge site, managed by the Hudson Bay District Improvement Company (HBDIC), is the first and largest recharge facility receiving up to 16 cfs when supply is available; over the calibration period the Johnson site received annual inputs of between 2,508 and 3,787 acre-ft.

The canal network is used to convey water to the MAR facilities. Basin saturated hydraulic conductivity and maximum water holding capacity was set to ensure that water drained completely from the facility and did not overflow.

There are an additional nine MAR facilities that have been formally proposed and over 30 other locations that have been identified as having the potential for development into MAR facilities. Canal routing to the proposed and potential MAR sites is included in the model for use in future management scenario analysis, but these MAR sites do not receive water in the calibration model.

Table 2. Annual Manage Aquifer Recharge site water application during the model calibration period (2007 – 2013)

Year	Annual MAR applications (acre-feet per year)						
	Hall-Wentland	Johnson (HBDIC)	Anspach	Barret	Trumbull	Locher Road	Stiller Pond
2007	93	3416	0	0	0	15	0
2008	15	2700	0	0	0	48	0
2009	175	3342	0	0	0	176	0
2010	0	2508	0	0	0	0	0
2011	0	3194	67	0	0	93	96
2012	0	3787	186	323	202	334	374
2013	0	3439	186	891	557	105	189

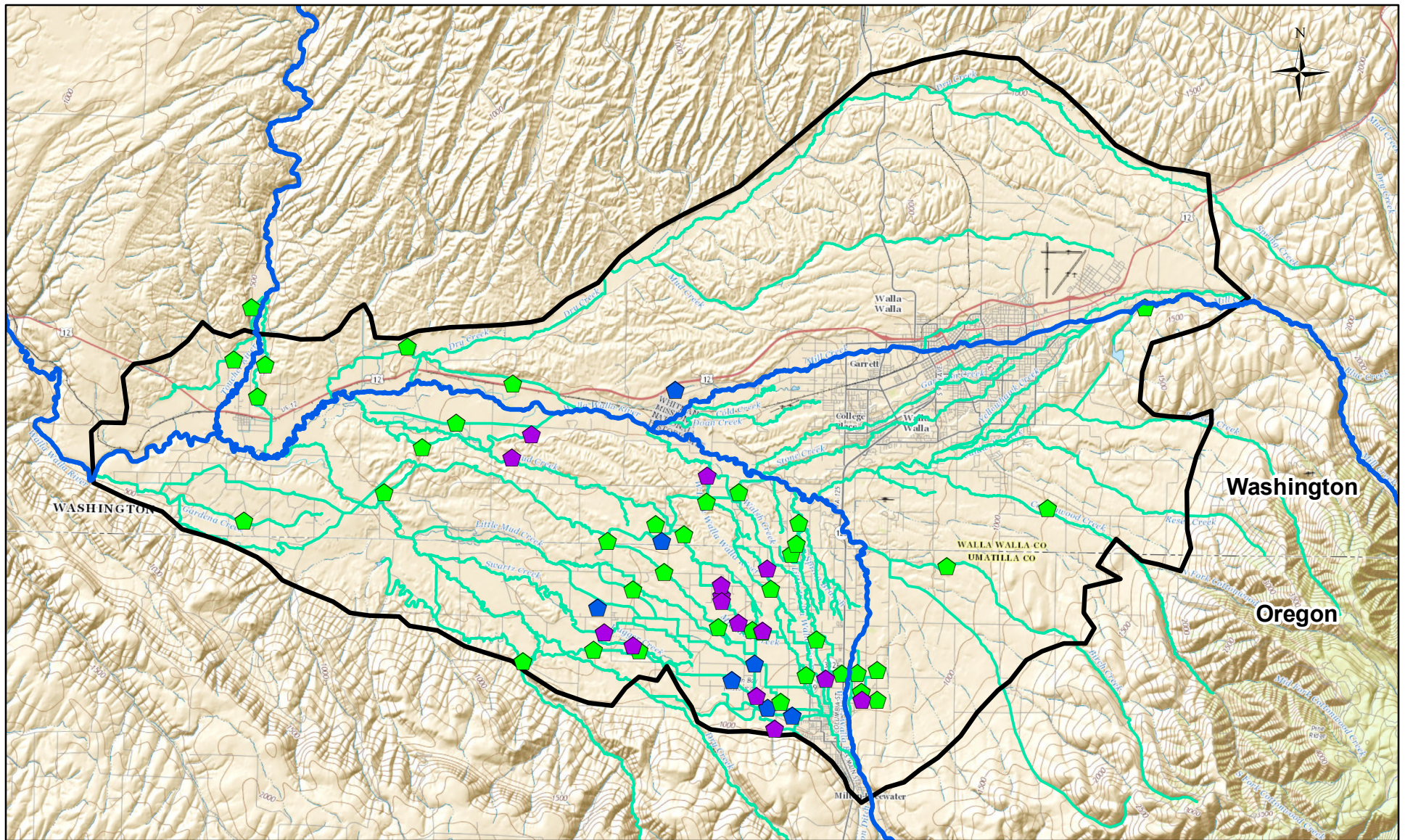


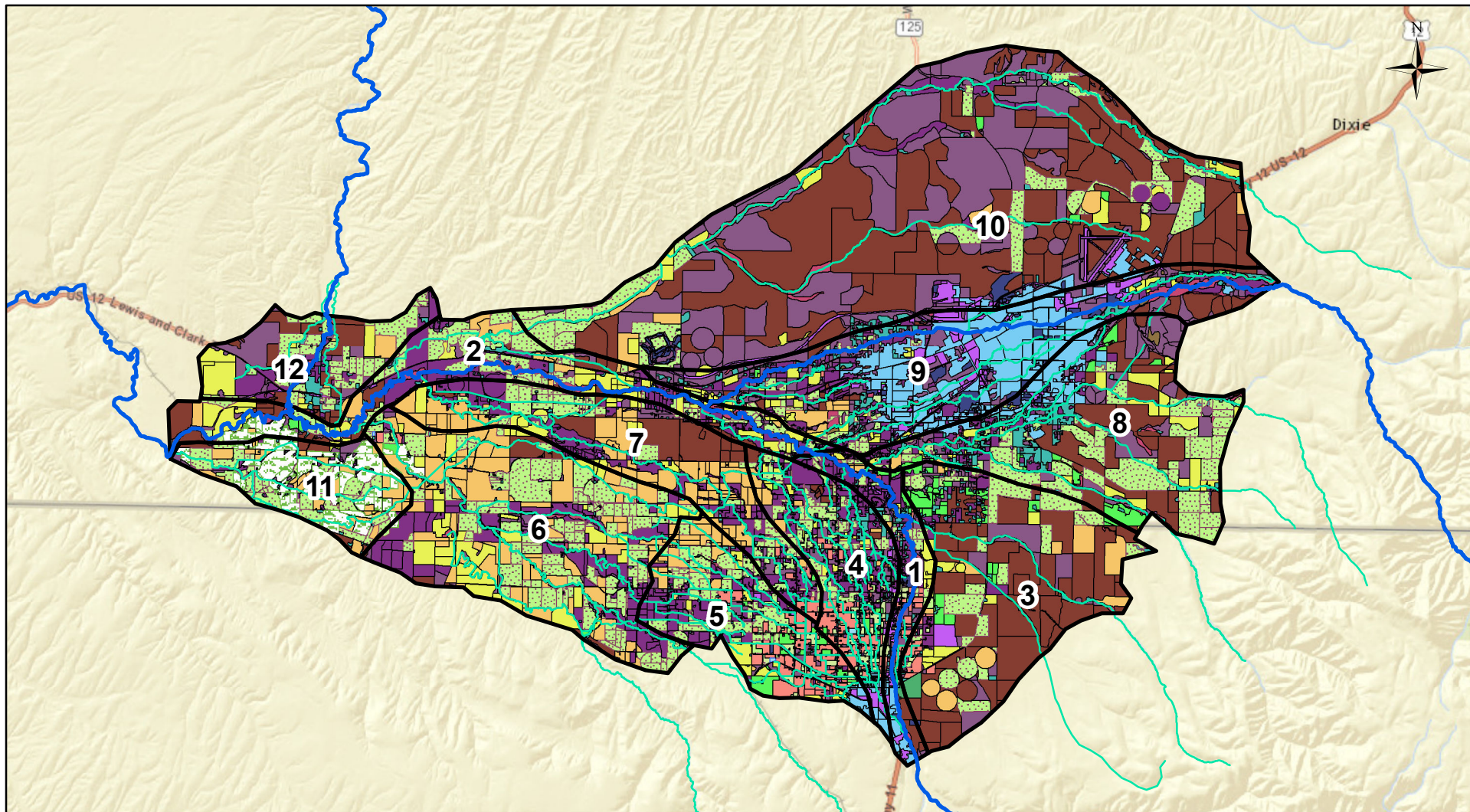
Figure 18. Location of active, proposed, and potential MAR facilities. Only active MAR facilities received water during the model calibration period (2007 to 2013).

2.9 Land Use Classification

The Walla Walla Basin model area was subdivided into 15 unique land use classifications, 12 of which are agricultural crops. The distribution of land use was determined by the WWBWC based on aerial photography and land based surveys (Figure 19). The land use information was input into the model in two ways: 1) the specific land uses were input in terms of areal coverage for each sub-region, and 2) every model element was assigned a percentage for each of the broad land use classifications (agricultural, urban, native vegetation, and water body/riparian areas). The first land use input is used to calculate sub-region based water demand and the latter is used in soil moisture routing calculations. Table 3 shows the percentage of land use within each sub-region. All land use data and associated data processing is provided in Appendix G.

Table 3. Percentage of land use classification within each model sub-region

Crop Type/Land Use	Model Sub-region											
	1	2	3	4	5	6	7	8	9	10	11	12
Alfalfa-seed	0.0%	3.9%	0.0%	0.0%	0.0%	1.1%	0.0%	0.0%	0.0%	0.0%	41.0%	0.0%
Alfalfa-hay	8.9%	25.7%	15.2%	18.1%	26.6%	31.0%	16.8%	27.5%	4.1%	9.2%	27.4%	28.2%
Apples	6.4%	0.0%	1.5%	11.5%	17.0%	0.2%	2.0%	0.0%	0.1%	0.0%	0.0%	0.0%
Cherries	1.7%	0.0%	0.1%	4.3%	2.6%	0.0%	0.0%	0.0%	0.1%	0.0%	0.2%	0.0%
Grapes	2.4%	0.5%	5.0%	1.4%	4.7%	0.3%	0.1%	3.5%	0.3%	0.2%	0.0%	0.0%
Grass Lawn (domestic)	3.1%	0.0%	0.1%	0.6%	0.2%	0.0%	0.1%	0.5%	3.1%	0.8%	0.0%	0.0%
Nursery	0.8%	0.0%	1.0%	0.1%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%
Orchards	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Pasture (Irrigated)	20.5%	17.0%	3.2%	27.2%	18.5%	18.7%	23.4%	5.8%	11.9%	2.2%	2.3%	12.9%
Row Crops	5.3%	13.9%	2.6%	2.8%	5.8%	12.2%	5.8%	6.7%	3.9%	1.7%	0.3%	12.5%
Dryland Wheat	5.5%	11.3%	49.9%	2.8%	0.0%	2.6%	15.9%	21.1%	6.3%	46.5%	4.3%	16.9%
Irrigated Wheat	1.8%	7.1%	7.3%	3.7%	10.1%	27.0%	27.7%	0.4%	1.9%	1.6%	16.5%	4.4%
Urban	21.5%	3.5%	3.8%	16.7%	7.8%	1.4%	3.4%	14.8%	44.9%	4.2%	3.3%	6.6%
Native Vegetation	11.7%	5.3%	8.9%	8.3%	5.3%	2.8%	3.8%	15.5%	17.0%	31.4%	4.2%	16.2%
Riparian	10.4%	11.8%	1.3%	2.6%	1.3%	2.6%	1.2%	4.0%	6.4%	2.2%	0.5%	2.4%



Legend



Figure 19. Walla Walla Basin model land use classification distribution

2.10 Water Use

2.10.1 Agricultural Water Use

Agricultural irrigation from surface water sources are specified in the model inputs and groundwater pumping from the alluvial and CRB aquifer is calculated to meet the discrepancy between agricultural water demand, stored soil moisture, and applied surface water. This approach to assigning groundwater pumping in the model was selected because basin groundwater pumping volumes are generally not known. Additionally, this method of calculated groundwater pumping permits the model to adjust groundwater pumping during future forward modeling scenarios that look at conditions such as increased water demand or decreased surface water availability.

Agricultural demand is calculated from model inputs of daily reference evapotranspiration (ET) for a well-watered grass, crop coefficients, and crop efficiency factor. Grass crop reference ET calculated from five Ag-Weather Net stations located inside or close to the model boundary (Figure 17) were interpolated by elevation to generate an estimated daily reference ET rate for each model sub-region. These values were then modified for each land use based on seasonal crop coefficients found in Allen (1998). The model then calculates the ET rate by sub-region based on land use distribution and the crop efficiency factor, defined as the amount of water consumed by irrigated plants divided by the amount of applied water. This value is a function of the irrigation methods used, assumed to primarily be Nelson Impact Sprinklers based on consultation with irrigation district managers. The product of this calculation is then subtracted from the available soil moisture at the specific model space and time to determine the actual agricultural water demand. The IWFM Theoretical Manual (Dogrul, 2013) refers to this algorithm as CUAW (Crop Use of Applied Water), which can be used to calculate the water demand for any sub-region, a subset of elements, or for the entire model area. Complete ET data and data processing is included in Appendix F.

Agricultural water demand is met by a combination of surface water diversions and groundwater pumping. Surface water diversions were determined using a mass balance approach based on upstream and downstream surface flow data, accounting for bypasses out of the canal and channel seepage as was described in Section 2.6.2. Groundwater pumping serves to meet the remaining agricultural water demand. The specific rate and distribution of pumping is calculated by the model based on distributed crop water requirements factored into the CUAW algorithm and pumping distributions applied in the model as described in Section 2.5.2.

2.10.2 Urban Water Use

Water supplies for the urban areas in the Walla Walla Basin model area, namely the cities of Walla Walla, College Place, and Milton-Freewater, are primarily sourced from outside of the

model area. All three of these cities use the CRB aquifer as a water source, and the city of Walla Walla also uses water from Mill Creek diverted upstream of the model area. The urban water demand is assumed to be equal to the water supply after accounting for inefficiencies in conveyance. Water supply data was provided by Public Works Department personnel for each of the municipalities.

In addition to water use, there are urban water return flows within the model occurring as the return of treated wastewater to both local streams and irrigation districts, conveyance inefficiencies (e.g. leakage), and the operation of the Bennington Lake reservoir.

The Walla Walla wastewater treatment plant supplies water to the Blalock and Gose Irrigation Districts from April through October, while the remainder of the year the treated wastewater is discharged into Mill Creek. Seasonal discharge rates were determined by consultation with the manager of the Walla Walla wastewater treatment plant and are included in Appendix H.

The College Place wastewater treatment plant supplies treated wastewater for irrigation to its surrounding area from April through October, and for the remainder of the year outflows are discharged into Garrison Creek. Seasonal discharge rates were determined by consultation with the Public Works director for the city of College Place and are included in Appendix H.

The Milton-Freewater wastewater treatment plant supplies treated wastewater for irrigation to a nearby golf course when needed, while for the remainder of the year outflows are discharged into a local canal for irrigation. Water use and treated wastewater discharge rates were supplied by the Public Works superintendent for the city of Milton-Freewater and are included in Appendix H.

It is estimated by the Walla Walla Public Works that approximately 30 percent of the water supplied to the city of Walla Walla is lost to leaks in the supply infrastructure. This water is assumed to percolate into the underlying alluvial aquifer and is input into the model as a recoverable loss from the diversions that account for urban water supply. Based on input from College Place and Milton-Freewater personnel, water loss due to leaks in their supply infrastructure was assumed to be negligible.

Bennington Lake is a reservoir in the northeastern portion of the model area, within the urban boundary of Walla Walla, and is managed by the US Army Corps of Engineers (USACE). In the spring the lake is filled with water from Mill Creek and from October through mid-December the lake is drained via an outlet channel into Russell creek. Lake filling rates, drainage rates, and seepage rates were provided by USACE personnel and are included in Appendix B. The lake is

estimated to seep at a rate of 0.1 ft/day, translating to an overall loss of three to four cfs to seepage.

2.11 Unsaturated Zone

The unsaturated zone is defined as the material between the water table and the land surface. The upper portion of this material is the soil, or root zone, where plants are capable of consuming water from the soil profile. Soil classifications and physical characterization data were obtained from Natural Resource Conservation Service (NRCS) soil surveys accessed from the NRCS Web Soil Survey tool (<http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm>). These data sets were used to determine model inputs for hydraulic conductivity, field capacity, effective porosity, and curve number.

Root zone thickness is calculated in IWFM by an area weighted average for each model sub-region based on crop types and their respective root depths, as reported in USDA (1997) and presented in Table 4. Unsaturated zone thickness, conductivity, and effective porosity values, presented in Table 5, were entered into the model as equal to those used for the QF unit because it is the uppermost of the sedimentary geologic units and does not behave as an aquifer (Lindsey, 2007). The thickness of the unsaturated zone is recalculated by IWFM to equal the distance between the land surface and the water table at a given time step. Model inputs for unsaturated zone effective porosity and hydraulic conductivity originated from area weighted averages of NRCS data for hydrologic group C type soils calculated for each model sub-region. This was done because the QF unit is fine grained with a slow infiltration rate, best fitting the description of NRCS hydrologic soil group C (USDA, 2009).. Values were input for each model element based on its sub-region.

Table 4. Rooting depths for each crop or other land use as applied in the model.

Crop Type/Land Use	Root Depth (ft)
Alfalfa-seed	4.5
Alfalfa-hay	4.5
Apples	4.5
Cherries	4.5
Grapes	4.5
Grass Lawn (domestic)	0.5
Nursery	3
Orchards	6
Pasture (Irrigated)	1.5
Row Crops	1.5
Dryland Wheat	3
Irrigated Wheat	3
Urban	1.5
Native Vegetation	4.5
Riparian	6

Table 5. Unsaturated zone parameters for each model sub-region

Sub-Region	Hydraulic Conductivity (ft/day)	Effective Porosity (cm ³ /cm ³)	Sub-Region	Hydraulic Conductivity (ft/day)	Effective Porosity (cm ³ /cm ³)
1	4.45	0.39	7	1.88	0.42
2	1.93	0.43	8	2.17	0.45
3	1.82	0.45	9	1.91	0.44
4	2.07	0.41	10	1.79	0.43
5	2.07	0.43	11	1.46	0.44
6	1.72	0.42	12	1.64	0.42

Field capacity and effective porosity, were assigned for each model sub-region and hydrologic group based on the area weighted average of each soil type within a given sub-region. The majority of the model area (~97%) was classified as soil group B and C. The assignment of curve numbers used within the model to estimate runoff potential were also based on NRCS reported curve numbers for agricultural, urban, native vegetation, and riparian areas on the basis of the hydrologic soil group and input into the model by sub-region. An additional parameter for soil

moisture routing is the percent of excess soil moisture that becomes percolation, also input into the model for each sub-region and soil type. This value was adjusted in the model calibration process based on the fit between measured and simulated data (Section 3.0). All soil moisture routing properties for hydrologic soil groups B and C are presented for each model sub-region in Table 6. Appendix I provides complete NRCS soil data and associated data processing for input into the model.

Table 6. Near surface soil moisture routing parameters

Sub-Region	Hydrologic Soil Group B							Hydrologic Soil Group C						
	Field Capacity (cm ³ /cm ³)	Effective Porosity (cm ³ /cm ³)	% of Excess Soil Moisture that Percolates	Curve Number -Ag	Curve Number -Urban	Curve Number -Native Veg	Curve Number -Riparian	Field Capacity (cm ³ /cm ³)	Effective Porosity (cm ³ /cm ³)	% of Excess Soil Moisture that Percolates	Curve Number -Ag	Curve Number -Urban	Curve Number -Native Veg	Curve Number -Riparian
1	0.16	0.39	0.70	74	83	51	60	0.20	0.39	0.50	82	88	63	73
2	0.19	0.44	0.70	74	83	51	60	0.21	0.43	0.50	82	88	63	73
3	0.25	0.45	0.70	74	83	51	60	0.24	0.45	0.50	82	88	63	73
4	0.12	0.34	0.90	74	83	51	60	0.24	0.41	0.60	82	88	63	73
5	0.11	0.33	0.70	74	83	51	60	0.25	0.43	0.50	82	88	63	73
6	0.22	0.44	0.70	74	83	51	60	0.24	0.42	0.50	82	88	63	73
7	0.19	0.42	0.70	74	83	51	60	0.24	0.42	0.50	82	88	63	73
8	0.25	0.46	0.70	74	83	51	60	0.22	0.45	0.50	82	88	63	73
9	0.19	0.39	0.70	74	88	51	60	0.23	0.44	0.50	82	92	63	73
10	0.25	0.46	0.70	74	83	51	60	0.24	0.43	0.50	82	88	63	73
11	0.16	0.44	0.40	74	83	51	60	0.21	0.44	0.30	82	88	63	73
12	0.18	0.46	0.40	74	83	51	60	0.22	0.42	0.30	82	88	63	73

3.0 MODEL CALIBRATION METHOD

Model calibration was based on data for years 2007 through 2009, 2011, and 2013 while data sets for years 2010 and 2012 were reserved for model validation. Model calibration was performed by adjusting the most sensitive model parameters for both surface water and groundwater in an iterative manner and evaluating the fit between observed and simulated groundwater elevation and surface water flow.

Model calibration of a smaller Walla Walla Basin IWFM model (Scherberg, 2012) and sensitivity analysis performed prior to model calibration indicated that simulated groundwater levels were most sensitive to the horizontal saturated hydraulic conductivity of the sedimentary units, stream bed conductivity, non-recoverable loss rate (evaporation), and recoverable loss rate (the percent of excess soil moisture that percolates to groundwater). As a result, these parameters were the primary parameters used for model calibration. The percentage of excess soil moisture that percolates to groundwater is an adjustable parameter of moderate sensitivity, though its effects are dwarfed by adjusting aquifer hydraulic conductivity (Scherberg, 2012). This parameter was adjusted to target specific areas where simulated groundwater elevations were persistently lower than observed.

Groundwater elevation monitoring data collected by the WWBWC was the primary source of data used for model calibration of groundwater conditions. Monitoring wells were assigned a rating of one through four as described in Section 2.5.1. Monitoring wells with a one rating were the most reliable and those with a four rating were considered anomalous and thereby excluded from the calibration data set. A total of 90 groundwater monitoring wells were used for model calibration (Figure 12).

Three different metrics were used for evaluating model predictive performance: correlation coefficient, root mean squared error (RMSE), and mean relative error.

Correlation coefficient shows the temporal relationship between the model simulated and measured groundwater elevation, calculated as:

$$\text{Cor} = \frac{\sum(\text{obs} - \overline{\text{obs}})(\text{sim} - \overline{\text{sim}})}{\sqrt{\sum(\text{obs} - \overline{\text{obs}})^2 \sum(\text{sim} - \overline{\text{sim}})^2}} \quad \text{Equation 1}$$

where,

Cor = Correlation coefficient

obs = observed value (groundwater elevation or surface water flow)

$\overline{\text{obs}}$ = mean observed value (groundwater elevation or surface water flow)

sim = simulated value for gauge (groundwater elevation or surface water flow)

$\overline{\text{sim}}$ = mean simulated value for gauge (groundwater elevation or surface water flow)

RMSE equates to the absolute mean error of all locations and is calculated as:

$$\text{RMSE} = \sum_{t=1}^n \sqrt{\frac{(GW_{obs} - GW_{sim})^2}{n}} \quad \text{Equation 2}$$

where,

RMSE = Root Mean Squared Error

GWobs = Monthly mean observed groundwater head

GWsim = Monthly mean simulated groundwater head

n = Number of observations

Mean relative error provides the average error of all locations, showing the overall direction of simulation error and is calculated as:

$$\text{MRE} = \frac{Q_{obs} - Q_{sim}}{Q_{obs}} \quad \text{Equation 3}$$

where,

MRE = Mean Relative Error

Q_{obs} = Mean monthly flow observed at gauge (cfs)

Q_{sim} = Mean monthly flow from model output data (cfs)

Surface water calibration was assessed by comparing model predicted surface water flow rates at stream node locations analogous to the locations of surface water gauges. A total of 53 stream gauges were used for model calibration. Surface water predictive performance was evaluated using correlation coefficient (Equation 1) and mean relative error (Equation 3). Diversion rates and stream bed conductivity were parameters used to calibrate surface water flows and, in the case of stream bed conductivity, to concur with measured seepage rates where available.

Initial conditions for the calibration model were determined using the process of model spin up. The objective of model spin up is to eliminate regions within the model where rapid changes in simulated groundwater levels occurred during the initial stages of the simulation. Model spin up was achieved by applying interpolated groundwater elevations (Section 2.5.1) and soil moisture for the first month of the simulation period and running the model repeatedly for three one year simulations, each using the final results as the initial conditions for the following model run.

4.0 MODEL CALIBRATION RESULTS

4.1 Groundwater

Calibration results for the four aquifer layers represented in the model domain are presented Table 7. The horizontal hydraulic conductivity of the MPC unit, calibrated to be 32.1 ft/day, was the single most sensitive parameter for groundwater elevation. Horizontal hydraulic conductivity for the QC, MPF, and MPBC units were estimated to be 65.6, 4.9, and 16.4 ft/day, respectively. Specific yield for each unit was initially estimated based on published data for similar material types (Morris and Johnson, 1967) and calibrated for best overall fit to measured groundwater data. Specific yield proved to be moderately sensitive. Vertical hydraulic conductivity and specific storage were initially estimated based on material descriptions (Batu, 1998) and were minimally adjusted due to both parameters being insensitive to model results.

Table 7. Calibrated hydraulic parameters for the model aquifer units

Geologic Unit	Horizontal Conductivity (ft/day)	Vertical Conductivity (ft/day)	Specific Storage (ft-1)	Specific Yield (%)
QC	65.6	19.7	9.5E-06	18
MPC	32.1	9.8	6.2E-05	14
MPF	4.9	0.4	1.0E-04	6
MPBC	16.4	2.0	4.6E-06	4

Table 8 presents a statistical summary of simulated versus observed groundwater elevation. Statistics for “best gauges” refer to monitoring wells assigned a “one” rating whereas statistics for “all gauges” include wells rated “one” through “three”. The mean correlation coefficient for “Best Gauges” was 0.71 and decreased to 0.48 when using “All Gauges”. This decrease in correlation reflects that the ‘All Gauges’ category includes monitoring wells that show poor consistency in seasonal data or minimal temporal variation, whereas model outputs are generally consistent in terms of seasonal trends from year to year. RMSE for “Best Gauges” was 10.85 ft and 12.31 ft for “All Gauges”.

Table 9 presents the mean correlation coefficient and mean error for each model sub-region. Positive mean error values indicate that the model predicted groundwater elevation are on average too low and negative values indicate that the model predicted groundwater elevations are on average too high.

The Upper Walla Walla River sub-region had predicted groundwater elevations that were on average 7.4ft higher than measured, whereas predicted groundwater elevations for the Lower Walla Walla River sub-region were on average 0.2 ft higher than measured. The heavily agricultural sub-regions of the HBDIC, Pine Creek drainage, and Mud Creek-Lowden had simulated groundwater elevations that were on average 8.1, 5.0, and 7.5 ft higher than measured. Sub-regions representing the Yellowhawk Creek drainage, the Walla Walla-College Place metropolitan area and Dry Creek (Washington), all in the northern portion of the model area, had predicted groundwater elevations that were lower than measured, being 4.6, 12.6, and 18.9 ft respectively. The western (down gradient) sub-regions of Gardena Farms and the Lower Touchet River had predicted groundwater elevations that were on average 0.1 ft and 4.6 ft higher than measured, respectively.

Correlation coefficients were strong (0.69 or higher) for the Upper and Lower Walla Walla Sub-regions, Yellowhawk drainage, Dry Creek (WA) drainage, and the Gardena Farms sub-region. Correlation coefficients for the Pine Creek and Mud Creek Lowden sub-regions were both 0.53, indicating reasonable agreement between simulated and measured groundwater elevation trends. Correlation coefficients in three of the remaining sub-regions were between 0.27 and 0.42, indicating potential hydrogeologic conceptual errors may exist in these model areas. The Lower Touchet River sub-region had a correlation coefficient of 0.08, indicating that the temporal trends in measured groundwater elevation in that region were not well represented by the model. It should be noted that the Lower Touchet River sub-region only included two monitoring wells. There were no monitoring wells located in the sub-region representing the Birch Creek drainage. Calibration results for all monitoring wells and complete summary statistics are provided in Appendix J.

Table 8. Statistical summary of model predicted versus measured groundwater elevation (2007 – 2009, 2011, 2013)

Statistical Metric	Average
Root Mean Squared Error - Best Gauges (ft)	10.85
Root Mean Squared Error - All Gauges (ft)	12.31
Correlation Coefficient - Best Gauges	0.71
Correlation Coefficient - All Gauges	0.48

Table 9. Statistical summary of model predicted versus measured groundwater elevation for each sub-region (2007 – 2009, 2011, 2013)

Model Sub-region	Number of monitoring wells	Correlation Coefficient	Mean Monitoring Well Error: Observed - Simulated (ft)
Upper Walla Walla River - 1	9	0.69	-7.38
Lower Walla Walla River - 2	6	0.79	-0.20
Birch Creek Drainage-Eastside Pipeline - 3	0	No Data	
Walla Walla River Irr. District - 4	16	0.31	5.71
HBDIC Irr. District - 5	23	0.42	-8.10
Pine Creek drainage-Gardena-HBDIC - 6	7	0.53	-4.95
Mud Creek-Lowden - 7	11	0.53	-7.48
Yellowhawk Creek drainage - 8	1	0.90	4.62
Walla Walla-College Place - 9	8	0.27	12.56
Dry Creek (WA) drainage - 10	2	0.69	18.93
Gardena Farms - 11	4	0.71	-0.13
Lower Touchet River - 12	2	0.08	-4.59

The groundwater statistical analysis results were interpolated over the model area to identify spatial trends. Figure 20 presents an interpolation of the average difference between observed and simulated groundwater head at monitoring well locations over the simulation period. Figure 21 presents the interpolated correlation coefficient between measured and predicted groundwater elevations. Model predicted and measured groundwater elevation time series for three representative monitoring wells identified in Figure 20 are provided in Figure 22 through Figure 24.

Monitoring Well 45 (Figure 22), located near the Johnson MAR site, had a correlation coefficient of 0.69, indicating that temporal trends in the simulated data generally follow observed trends. The simulated drop in groundwater elevation was less than observed, resulting in the simulated groundwater elevation being on average 5.1 ft higher than observed.

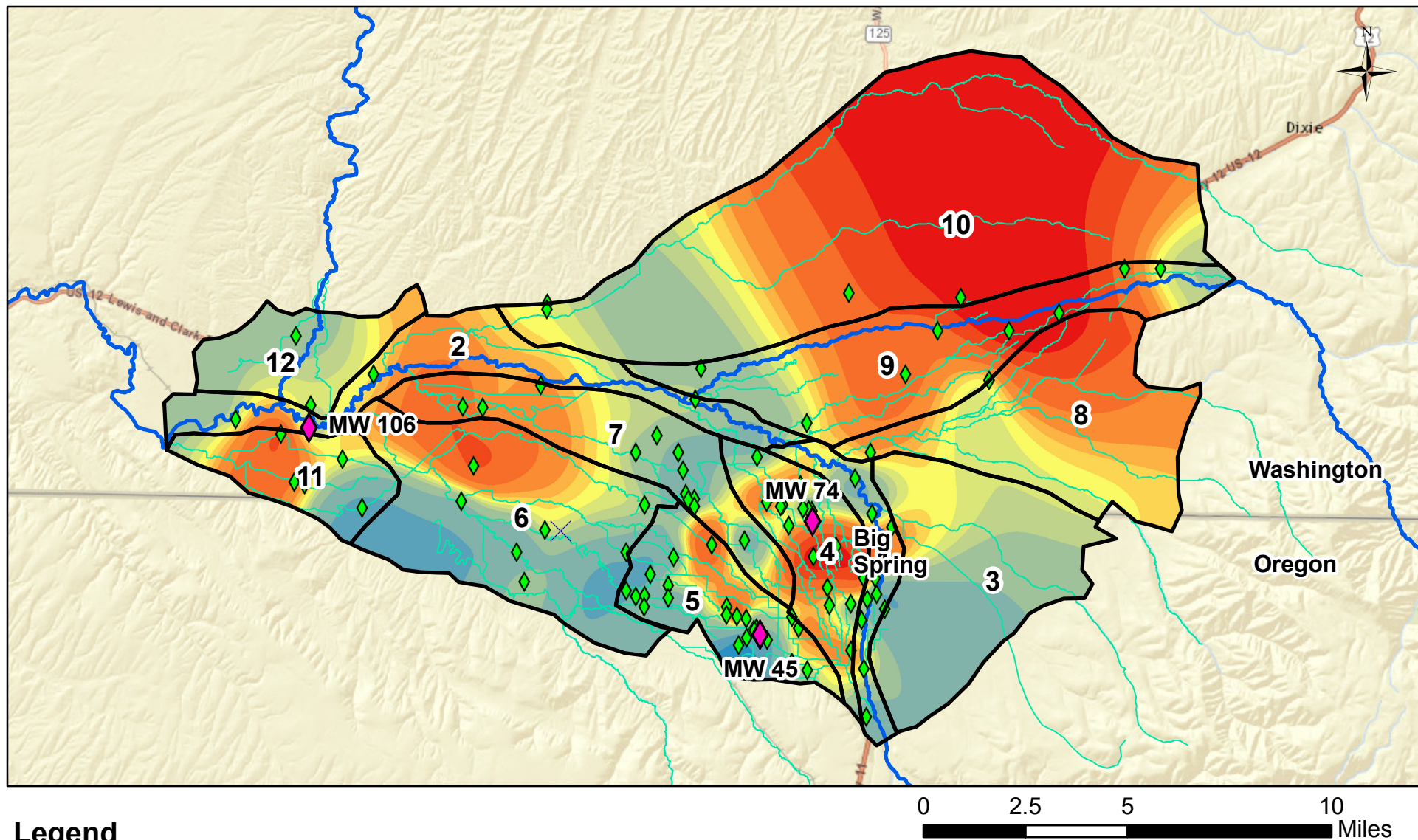
Monitoring Well 74 (Figure 23), located in the Walla Walla River Irrigation District, had a correlation coefficient of 0.05, indicating that temporal trends in the simulated data did not align with observed data, which included erratic peaks and low points that did not correspond to regional groundwater trends. The simulated groundwater elevation was on average 3.7 ft lower than observed.

Monitoring Well 106 (Figure 24), located near the Walla Walla River in the down gradient portion of the model area, had a correlation coefficient of 0.87. Temporal trends in groundwater elevation were consistent with observed data in both timing and magnitude of fluctuations. The simulated groundwater elevation was on average 4.9 ft higher than indicated by monitoring well data.

In general, model error is least through the central region of the model domain and greatest in the northern portion of the model area, primarily in sub-regions nine and ten, and around Big Spring (Figure 20). Error in model predicted groundwater elevation is likely to be related to uncertainty in the thickness of geologic units and the margin of error inherent in the ten meter DEM used as the basis for surface elevation, and thereby the elevation of the aquifers within the model domain. In some cases, the simulated groundwater elevation is lower than observed in one well while being higher than observed in a nearby well. In such cases the model cannot be adjusted to accurately simulate both wells; or conversely, correcting for one well will exacerbate the error at the other.

Correlation Coefficient is also strongest over the central portion of the model domain (Figure 21). There is poor correlation of simulated groundwater in sub-region 4, reflecting an apparent discrepancy between the conceptual model and physical conditions in this area as is also apparent in the groundwater error map (Figure 20). Poor correlations at several wells highlight where recorded groundwater levels do not correspond to regional trends, and may instead reflect irrigation practices in adjacent land parcels; as is the case for monitoring well 74 shown in

Figure 23. There are also poor correlation coefficients over part of sub-regions nine and ten, corresponding to areas where there groundwater hydrographs show minimal variability over time while simulated groundwater levels have some seasonal rise and fall.



Legend

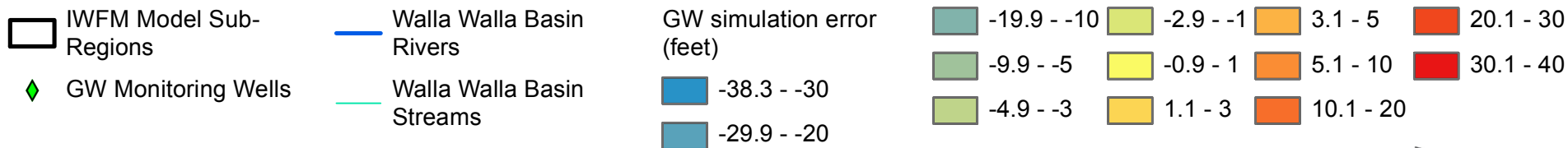
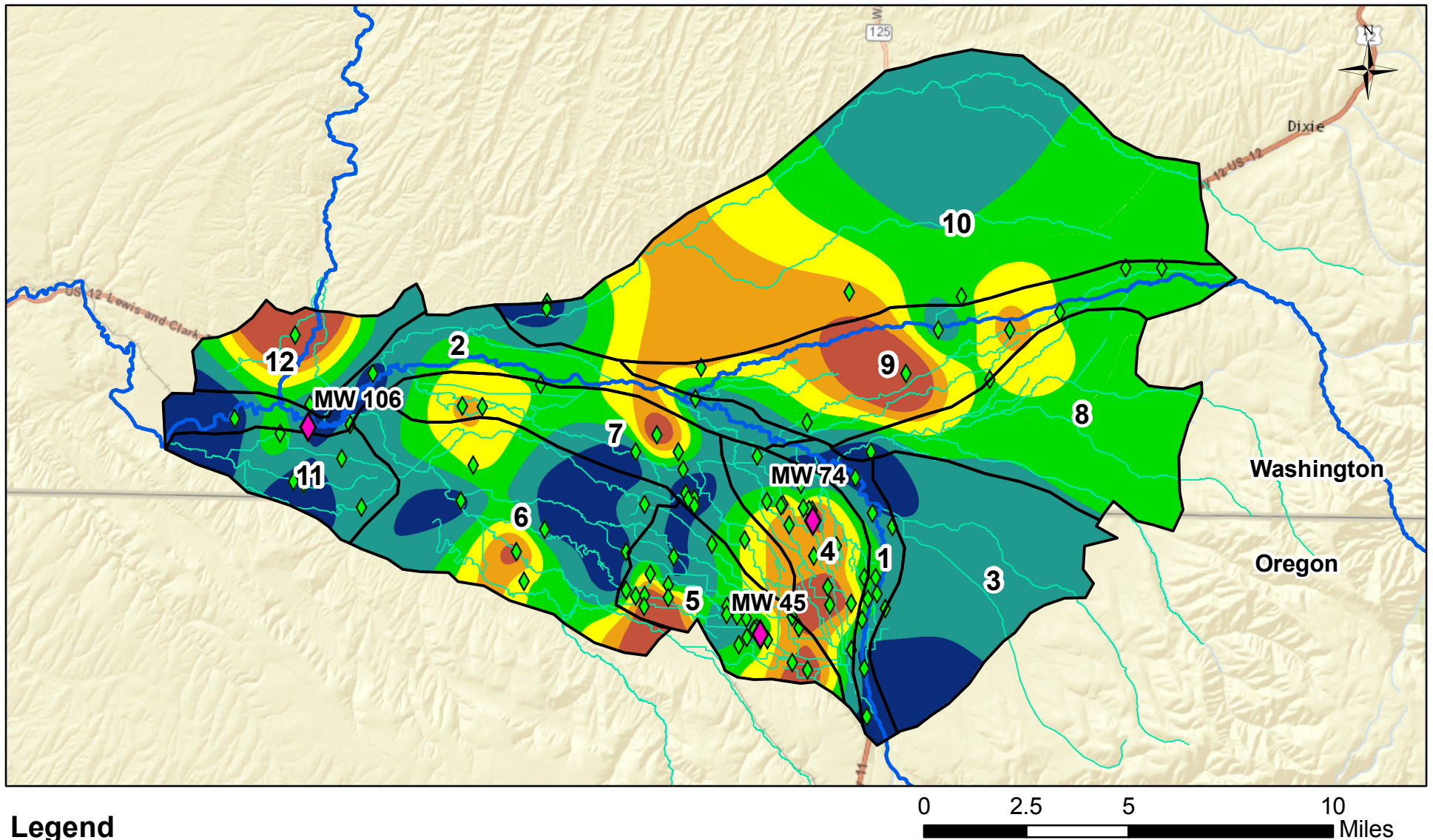


Figure 20. Interpolated error (observed - simulated) for simulated groundwater elevation at monitoring wells used for model calibration. Monitoring wells used for hydrograph examples are highlighted.



Legend

- | | | | | |
|------------------------|---------------------------|---------------------------------------|------------|------------|
| IWFM Model Sub-Regions | Walla Walla Basin Rivers | Simulation GW Correlation Coefficient | 0.01 - 0.2 | 0.61 - 0.8 |
| GW Monitoring Wells | Walla Walla Basin Streams | | 0.21 - 0.4 | 0.81 - 1 |
| | | < 0 | 0.41 - 0.6 | |

Figure 21. Interpolation of correlation coefficient for simulated groundwater elevation at monitoring wells used for model calibration. Monitoring wells used for hydrograph examples are highlighted.

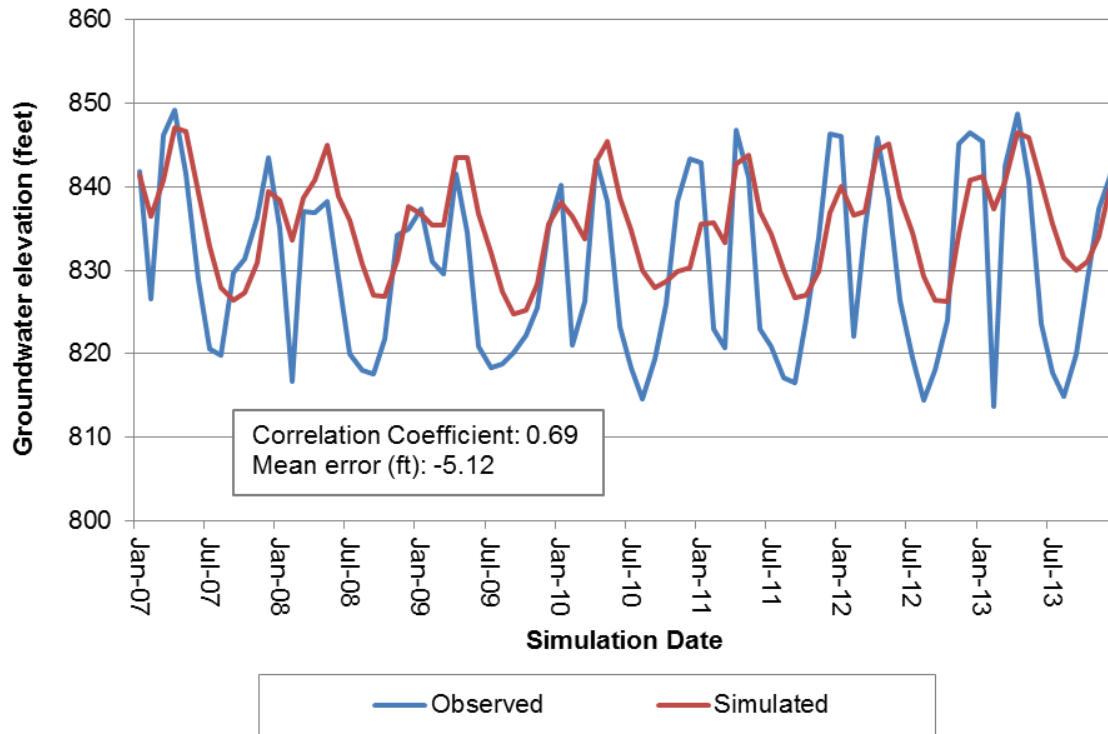


Figure 22. Monitoring Well 45 observed and simulated groundwater elevation

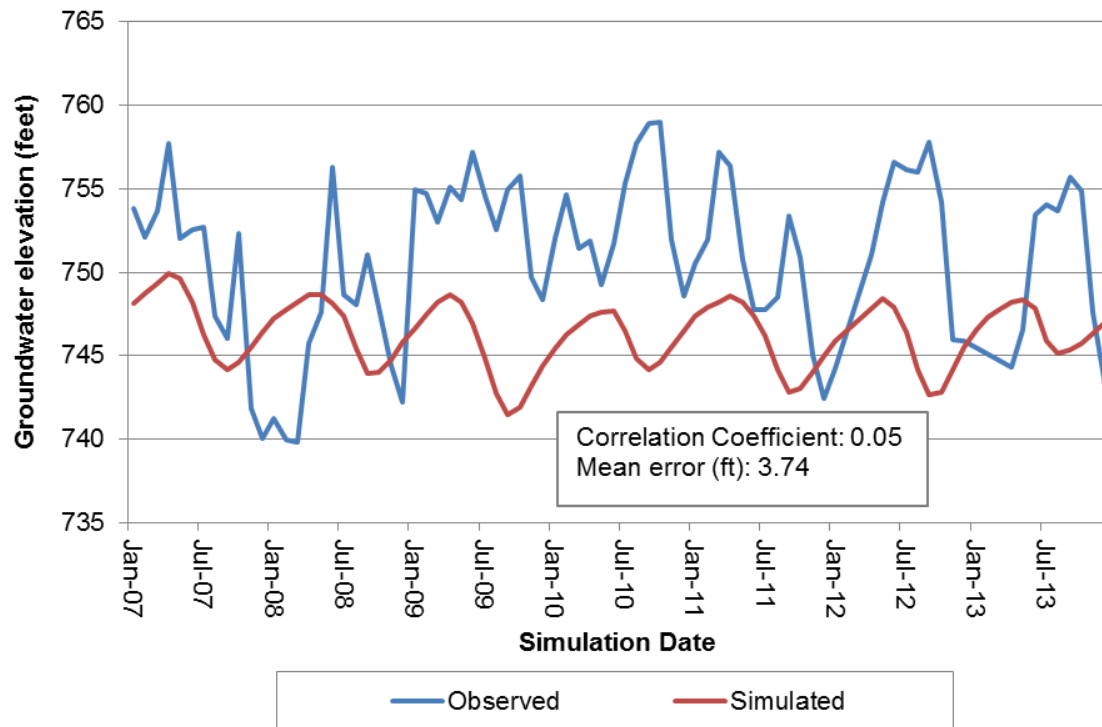


Figure 23. Monitoring Well 74 observed and simulated groundwater elevation

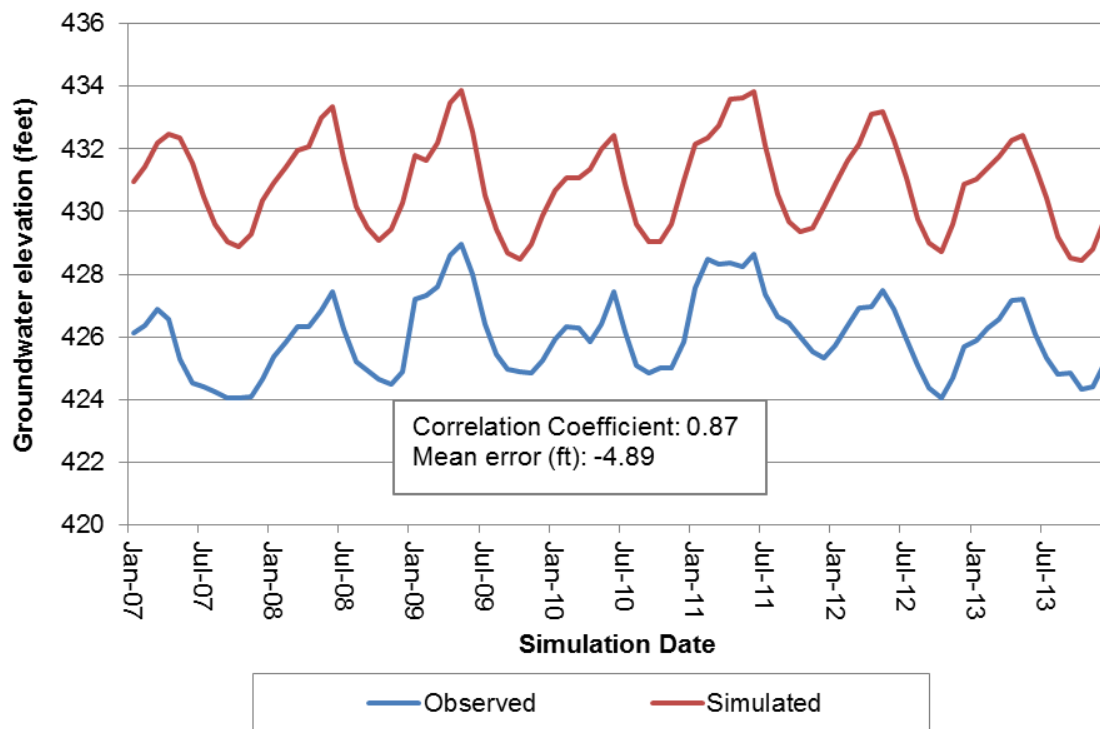


Figure 24. Monitoring Well 106 observed and simulated groundwater elevation

In general, for model areas where there is a relatively high density of available data the correlation between simulated and observed groundwater elevation tends to be the strongest. Monitoring wells are most concentrated in areas of relatively high agricultural production (Figure 19), thus the annual cycle of agricultural water use is reflected in the model.

The error in water storage can be calculated as a total volume by multiplying the mean error in simulated groundwater elevation, 0.55 ft, by the average specific yield (the volume of water per unit volume of aquifer material weighted by aquifer thickness), which is 9.8 percent. The result is an average of 0.05 ft of simulation error over the model area. Groundwater storage for the entire model area is on average 27.92 ft (Appendix C), thus the mean water storage error represents 0.19 percent of the mean total groundwater storage, supporting that the overall groundwater budget predictions are a reasonable indicator of available groundwater resources.

4.2 Surface Water

Calibration results for the six gauge series, defined by the WWBWC based on physical continuity or management entity (Figure 14), are presented in Table 10. Simulated surface water flows for the primary rivers, the Walla Walla and Touchet, closely fit gauge data with correlation coefficient of 0.98 and 0.99, respectively, and mean relative error of 20.8 percent and 10.2 percent. Other

gauge series incorporate canals and springs with low flow rates and measurement data sets that in some cases reflect inconsistencies between gauges that are on a single channel. The mean relative error between simulated and measured surface water flows for gauges in these series are large and in some instances have a poor correlation.

The trend between flow rate and mean relative error and correlation is provided in Figure 25 and Figure 26, respectively. Gauges with higher measured flow rates typically have a lower mean relative error (Figure 25) and higher correlation coefficient (Figure 26). This is related to several factors: contradictory data from gauges on a continuous canal, complex irrigation networks with no recorded data, and canals or springs where low flows magnify small errors in model predictions relative to the gauged flow.

Table 10. Statistical summary of model predicted versus measured surface water flow

Gauge Series	Walla Walla Basin Region	Correlation Coefficient	Mean Relative Error
100 Series	Walla Walla River	0.98	0.21
200 Series	Little Walla Walla River	0.45	0.76
300 Series	Mud Creek	0.35	1.03
400 Series	HBDIC-Pine Creek	0.53	1.30
500 Series	Mill Creek-Walla Walla Urban	0.64	0.58
600 Series	Touchet River	0.99	0.10

In terms of an overall model budget for surface water, prediction errors from low flow streams generally have little significance whereas a relatively small error on a major river, while appearing statistically minor, may have a significant impact on model predicted available resources. This is exemplified by model outputs for the gauges s-111 (Walla Walla River at Touchet WA), located on the Walla Walla River, and the gauge s-221 (Walsh Creek), located on a small canal in the Little Walla Walla irrigation network (Figure 27). The s-221 gauge has a correlation coefficient of -0.12 and a mean relative error of 106 percent, translating to a RMSE of only 0.41 cfs (Figure 28). Alternatively, model outputs for the s-111 gauge yield a correlation coefficient of 1.0, a relatively low mean relative error of 14.2 percent, with a RMSE of 99.9 cfs (Figure 29).

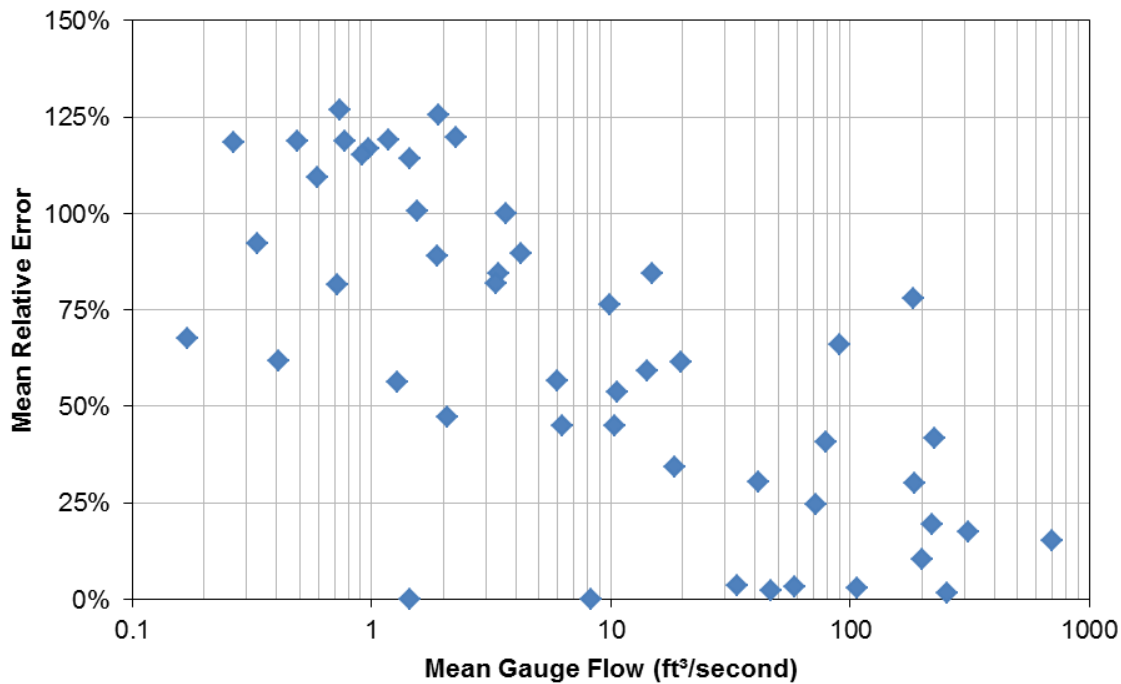


Figure 25. Mean gauge flow versus mean relative error (three gauges where mean flow was below 1.6 cfs and MRE above 280 percent are excluded from the above plot)

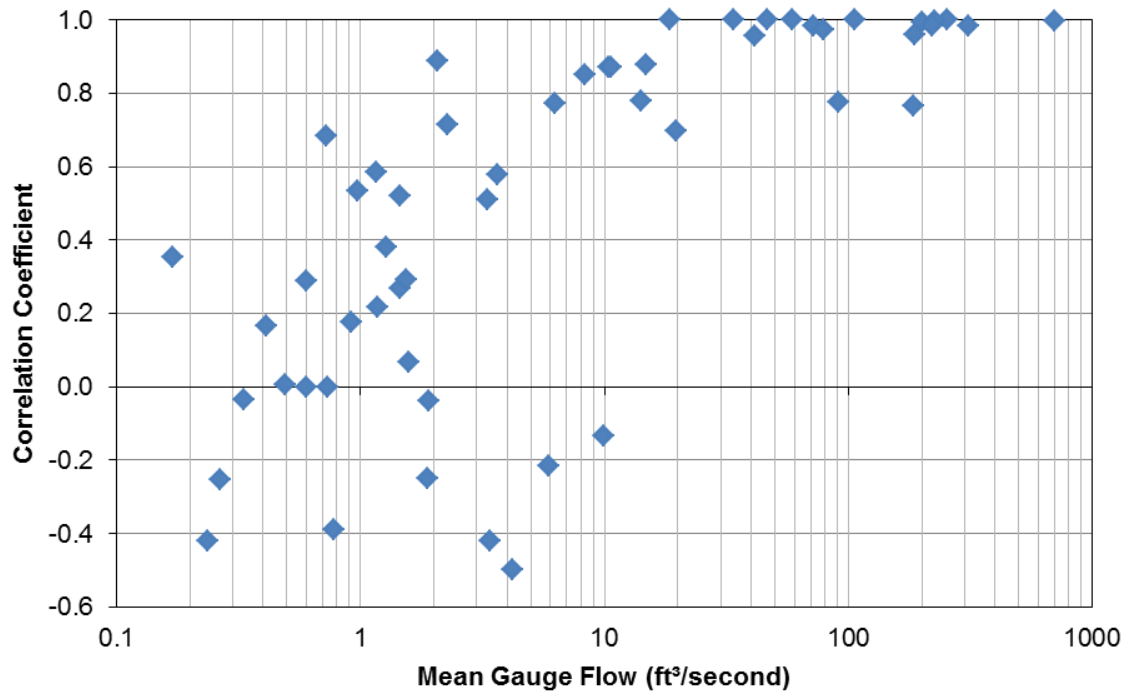
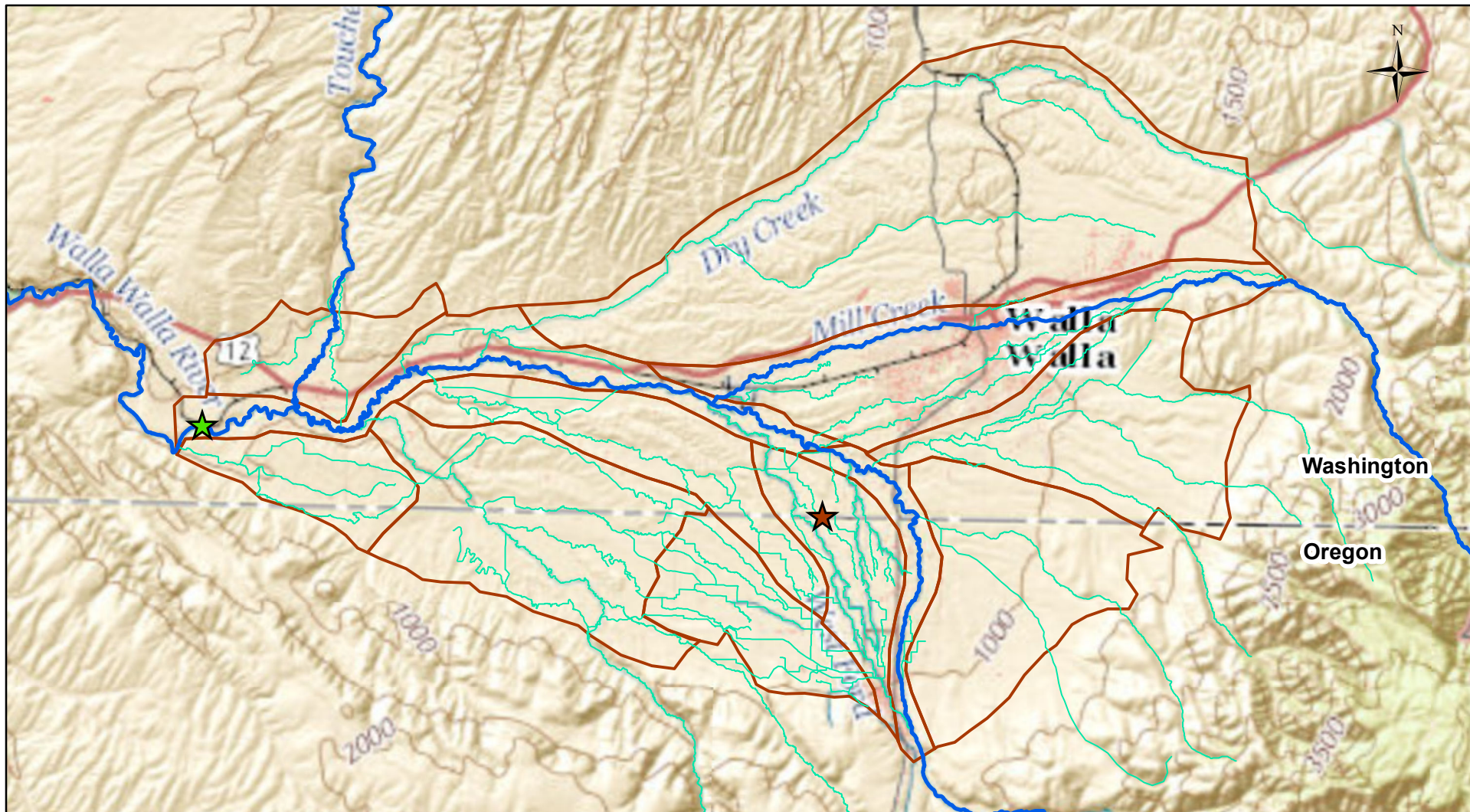


Figure 26. Mean gauge flow versus correlation coefficient

Many of the months where the mean relative error is greatest at gauge s-111 occur during low flow periods; however, there are several months during high flows where the simulated flow rate is over 300 cfs short of gauge data records. This discrepancy warrants scrutiny because the s-111 gauge is situated near the model outflow point and the accuracy of the simulation at this location can be taken to represent an overall hydrological balance for surface water within the model domain (Figure 27). Simulated surface water flows at gauge s-111 reflect a sum of inputs and withdrawals from surface water resources, including surface inflows, agricultural water use, water from external sources (i.e. the CRB aquifer, Bennington Lake, treated wastewater return flows), and groundwater-surface water interactions. Agreement between observed and simulated flows at gauge s-111 is an indicator of overall model accuracy.

During the calibration process, it was observed that simulated flows during some months were greater than 500 cfs less than gauged flows when river flow was at or near its annual peak. The primary cause of this discrepancy was thought to be due to inaccurately defining flows in Pine Creek, Dry Creek (WA) and Dry Creek (OR), all of which have a small flow measurement data record. Targeted adjustments were made to the inflows of Pine Creek, Dry Creek (WA) and Dry Creek (OR); however constraints were applied to maintain realistic values based on consultation with the WWBWC and analysis of available gauge data. The remaining surface flow error at s-111 may be related to compounding errors from underestimation of inflows from smaller streams, underestimation of groundwater inflow through the channel bed, or inaccuracy of the gauge data at peak flow conditions.

Nonetheless, the calibrated model results at the s-111 gauge near the model outflow indicate that model wide surface water is accurately represented, though flow rates in some small streams are not well simulated at times. Simulated surface water flows at all stream gauges are compared to observed data and summarized by sub-region in Appendix J.



Legend

- | | |
|---|-------------------------------|
| — Walla Walla Basin Rivers | Selected Surface Water Guages |
| — Walla Walla Basin Streams | ★ S-111 |
| IWFM Model Sub-Regions | ★ S-221 |

0 2.5 5 10
Miles

Figure 27. Location of stream gauges S-111 and S-221

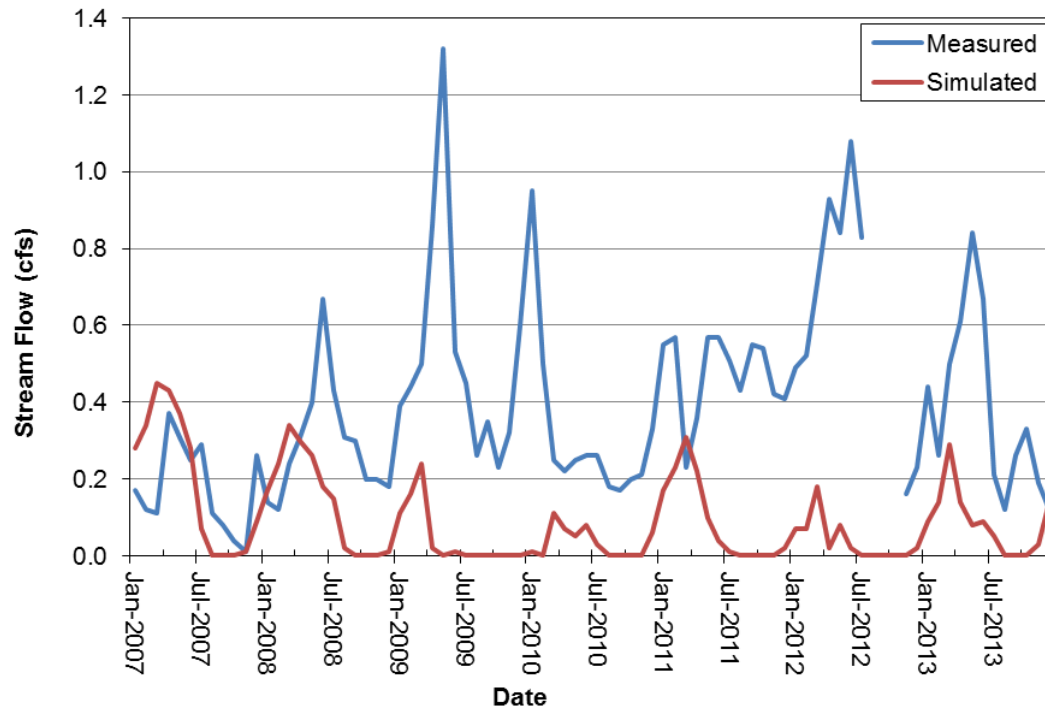


Figure 28. Monthly average measured stream flow for gauge s-221 (Walsh Creek) and model predicted stream flow

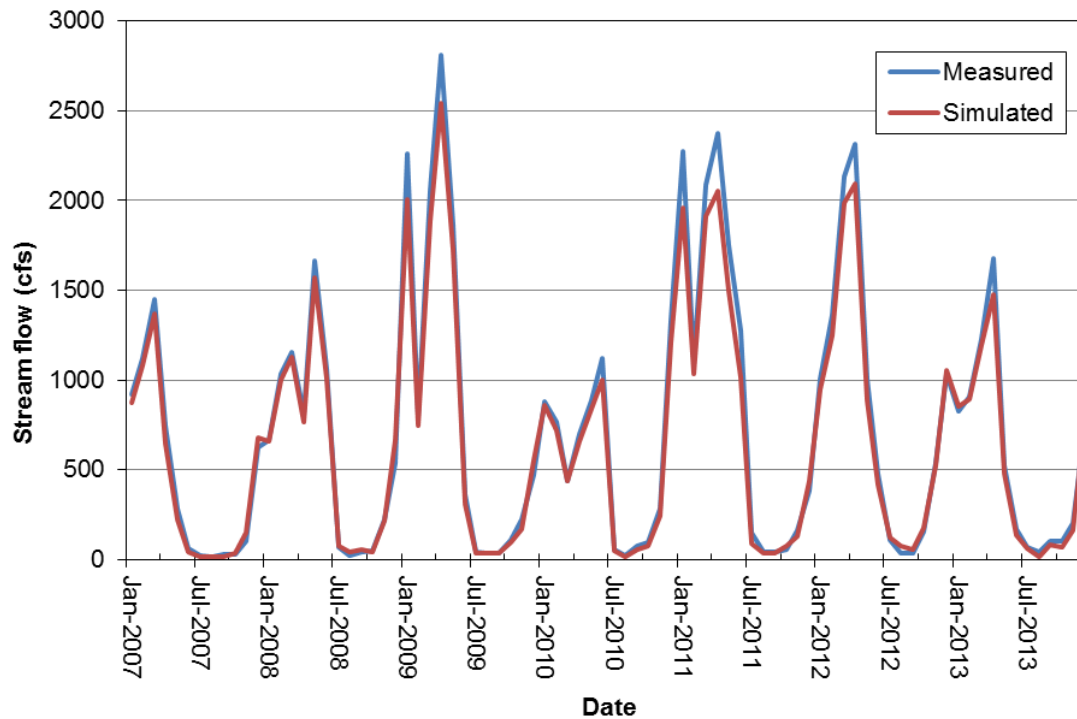


Figure 29. Monthly average measured stream flow for gauge s-111 (USGS Walla Walla River gauge at Touchet, WA) and model predicted stream flow

4.3 Model Validation

Model validation refers to applying model parameters obtained through the process of model calibration to a separate data set representing the same model domain. The purpose of model validation is to demonstrate that parameters obtained through model calibration are applicable to general conditions within the model domain and not merely fit to the calibration data set. Years 2010 and 2012 were reserved for model validation. These years were selected because a large number of monitoring wells were added in 2009 and several MAR sites were added or expanded in 2013. This allowed for data from the greatest number of monitoring wells to be used in both model calibration and validation, and avoided a model validation data set that included MAR sites that were not accounted for in model calibration.

The statistical metrics between predicted and measured groundwater elevations were similar for the calibration and validation data sets (Table 11 and Table 12). Overall correlation coefficient and RMSE for the 'Best Gauges' and 'All Gauges' data sets changed 0.0 to 2.8 percent, respectively, with the inclusion of the 2010 and 2012 data sets, in some cases improving the overall model fit (Table 11). The largest change in correlation coefficient was an improvement of 0.07 in the Dry Creek (WA) sub-region (Table 12). Mean error of simulated groundwater elevation changed by no more than 0.3 ft in any sub-region when including the validation data set; with model accuracy improving in six of the sub-regions when including all data. The small impact of the validation data on the statistical metrics indicates that the calibrated parameters are not overly fit to input data and the model predicts the physical processes that affect groundwater elevation.

Table 11. Statistical summary of model predicted versus measured groundwater elevation for combined calibration and validation data sets

Statistical Metric	Mean Result for Monitoring Wells	Change from Calibration Data Set	Percent Change from Calibration Data Set
Root Mean Squared Error-Best Gauges (ft)	10.83	0.02	0.15
Root Mean Squared Error-All Gauges (ft)	12.33	-0.02	-0.16
Correlation Coefficient-Best Gauges	0.69	0.02	2.82
Correlation Coefficient-All Gauges	0.48	0.00	0.00

Table 12. Statistical summary of model predicted versus measured groundwater elevation for combined calibration and validation data by sub-region

Model Sub-region	Number of Monitoring Wells	Correlation Coefficient	Mean Error (Observed - Simulated, ft)	Correlation Coefficient Change from Calibration Data Set	Change in Mean Error from Calibration Data Set (ft)
Upper Walla Walla River - 1	9	0.68	-7.65	0.01	0.27
Lower Walla Walla River - 2	6	0.78	-0.26	0.01	0.07
Birch Creek Drainage-Eastside Pipeline - 3	0	No Data			
Walla Walla River Irr. District - 4	16	0.28	5.97	0.03	-0.26
HBDIC Irr. District - 5	23	0.44	-7.90	-0.02	-0.20
Pine Creek drainage-Gardena-HBDIC - 6	7	0.52	-4.95	0.01	0.00
Mud Creek-Lowden - 7	11	0.52	-7.41	0.01	-0.07
Yellowhawk Creek drainage - 8	1	0.91	4.59	-0.01	0.03
Walla Walla-College Place - 9	8	0.3	12.76	-0.03	-0.20
Dry Creek (WA) drainage - 10	2	0.76	18.93	-0.07	0.00
Gardena Farms - 11	4	0.69	0.16	0.02	-0.30
Lower Touchet River - 12	2	0.14	-4.89	-0.06	0.30

Statistical metrics for predicted and measured surface water flow were generally similar or improved when including the validation data set (Table 13). The mean relative error for the 100, 400 and 600 gauge series all increased by approximately 6 percent while the mean relative error for the 200, 300, and 500 gauge series decreased slightly. With the inclusion of the validation data set, average correlation coefficients improved in four gauge series and were even and slightly lower in the other two (Table 13). The greatest change was a 0.04 (11 percent) improvement in the 300 Series (Mud Creek). Appendix J provides a summary of all model validation simulation results.

Table 13. Statistical summary of combined calibration and validation data sets for surface water gauge series

Gauge Series	Walla Walla Basin Region	Correlation Coefficient	Mean Relative Error	Change in Correlation Coefficient	Change in Mean Relative Error
100 Series	Walla Walla River	0.98	0.20	0.00	-0.01
200 Series	Little Walla Walla River	0.46	0.78	0.01	0.02
300 Series	Mud Creek	0.39	1.07	0.04	0.04
400 Series	HBDIC-Pine Creek	0.55	1.22	0.02	-0.08
500 Series	Mill Creek-Walla Walla Urban	0.63	0.60	-0.01	0.02
600 Series	Touchet River	1.00	0.09	0.01	-0.01

4.4 Hydrological Budgets

The model estimated hydrological budgets are an important aspect of any hydrological model because they quantify the distribution of water resources and water use within the basin. The comprehensive water budgets determine how simulated water demands are being met. The hydrological budgets also provide an estimate of total groundwater storage and the contribution of different groundwater influxes to groundwater storage. Groundwater pumping records are generally not available and the model estimated pumping provides a baseline estimate for the amount of pumping within the basin and the spatial distribution of that pumping. Model estimated water budgets quantify the distribution of surface water diversions used for agriculture and other purposes, highlight stream reaches with significant levels of groundwater-surface water interaction, and provide estimates of stream flows in under varying conditions.

This section presents major components of the simulated hydrological budgets. Complete hydrologic budgets for groundwater, surface water, and agricultural water use for each model sub-region, and the model as a whole, are available in Appendix I.

Figure 30 presents the simulated agricultural water demand and source of water to meet the demand. Total applied water in Figure 30 refers to the sum of all irrigation sources used, including water lost to systemic inefficiencies, which are represented as recoverable and non-recoverable losses in the model (i.e. irrigation water that is lost to percolation or evaporation). Agricultural water use is the amount of water that is transpired by plants, a value that is based on the model inputs for daily ET. Total ET in Figure 30 is the sum of transpiration by irrigated agricultural crops, non-irrigated crops (dryland wheat), and native vegetation.

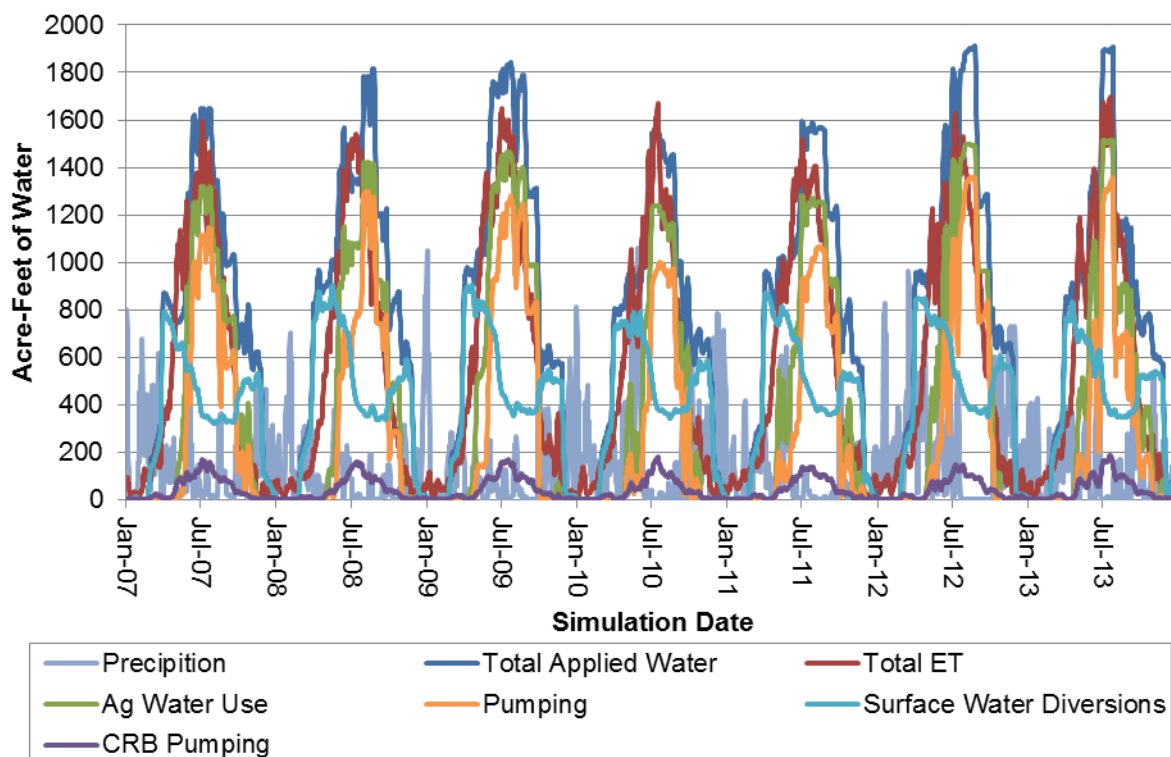


Figure 30. Simulated agricultural water demand and agricultural water sources

Water in the early spring and late fall months is applied in excess of agricultural demand (Figure 30). This is due to an effort on the part of farmers to apply water in excess of demand during these months when surface water is more readily available for the purpose of storing water in the unsaturated zone (Scherberg, 2012). This practice is further shown by the surface water diversions exceeding agricultural demand during these early spring and late fall months. Surface water typically becomes scarce in late June and is replaced by groundwater pumping as the primary agricultural water source during the summer months.

The primary groundwater budget components are presented in Figure 31. Negative values in Figure 31 indicate groundwater losses and positive values indicated groundwater gains. Total

groundwater storage over the simulation period is estimated to decline over the model area by approximately 34,000 acre-feet, or approximately 0.8 percent. Seasonal storage declines correspond to periods of groundwater pumping. Groundwater pumping is the dominant groundwater flux over the summer months, with little to no groundwater pumping occurring during the late fall through the early spring. The primary groundwater inputs are indirect recharge of the aquifer from water percolating through the unsaturated zone (e.g. irrigation water, precipitation) and groundwater inflow at the model boundary. Direct recharge from MAR and recoverable losses from agricultural diversions both contribute to groundwater storage, though are less significant groundwater sources than indirect recharge and groundwater inflow. The generally overall negative value for groundwater-surface water interaction (GW-SW Interaction in Figure 31) indicates that groundwater is predominately discharging to surface water and that on the whole model streams are gaining, though many individual reaches do lose water to seepage.

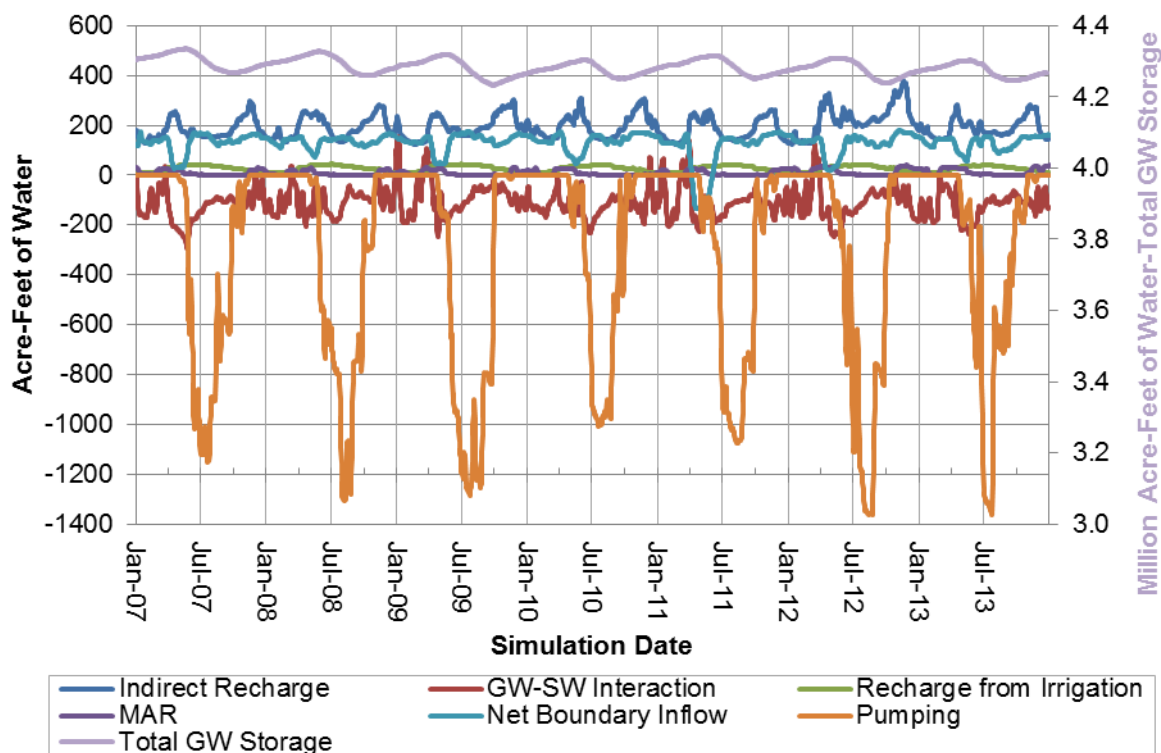


Figure 31. Calibrated model groundwater budget. Total GW Storage corresponds to right axis

The model period average groundwater hydrological inputs and outputs for each model sub-region are presented in Figure 32. The larger predicted surface water gain from groundwater in sub-region two (Lower Walla Walla River, Figure 4) is due to this sub-region primarily consisting of the Walla Walla River channel, its flood plain and its riparian areas. In the lower section of this sub-region, groundwater flows begin to coalesce due to the narrowing of the alluvial aquifer,

emerging in the Walla Walla River (Henry et al., 2013). Groundwater pumping is particularly prevalent in sub-region six (Pine Creek drainage-Gardena-HBDIC). Under current conditions, MAR contribution to groundwater is only notable in sub-region five (HBDIC Irrigation District) where the Johnson MAR site is located. In this sub-region, direct recharge to the aquifer from MAR helps to offset losses from groundwater pumping and promotes groundwater return flows into streams; though the groundwater return flows generally emerge in sub-region six. These results indicate that additional MAR facilities hold the potential to offset groundwater losses and increase groundwater return flows (Scherberg et al., 2014).

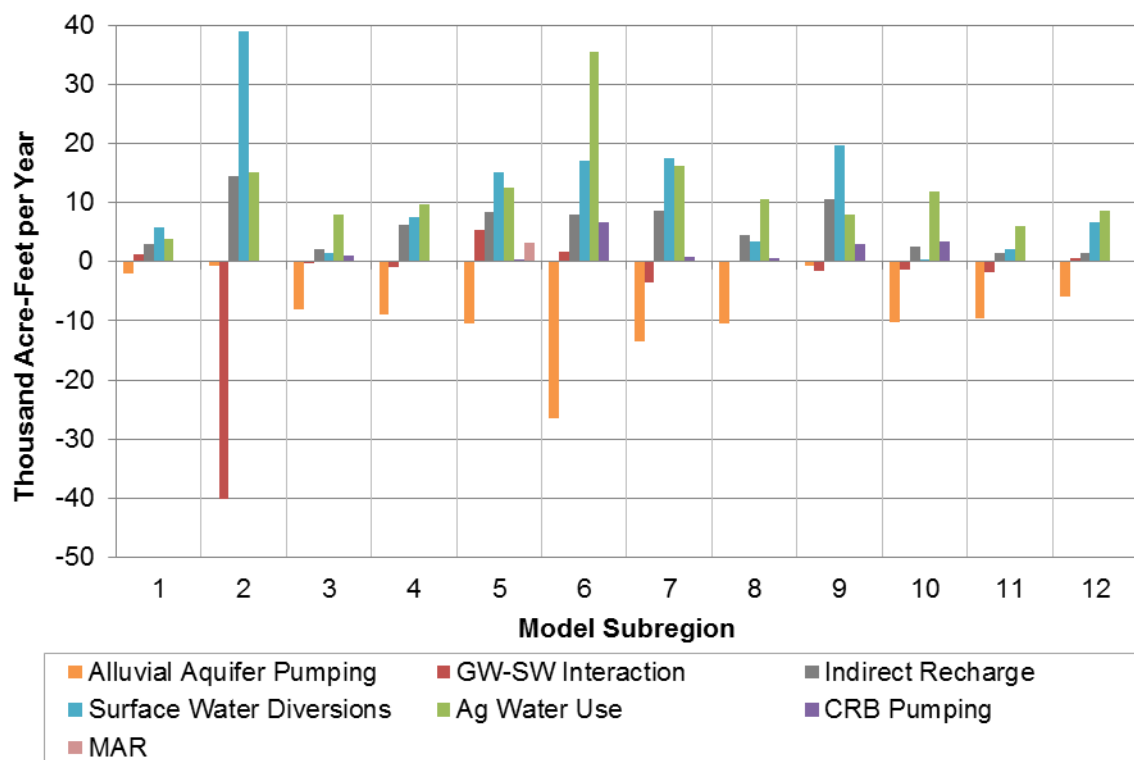


Figure 32. Calibrated model groundwater hydrological budget by sub-region

5.0 CONCLUSIONS

The Walla Walla Basin model was developed and successfully calibrated to represent current hydrological conditions in the Walla Walla Basin. The model was developed in collaboration with the WWBWC and utilizing data sources to define the basin geology, precipitation, groundwater and surface water conditions, land use classification, agricultural and urban demand, and soil properties.

Model calibration was performed by primarily adjusting horizontal saturated hydraulic conductivity of the sedimentary units, stream bed conductivity, non-recoverable loss rate (evaporation), and recoverable loss rate (percolation from soil to groundwater) in an iterative manner and evaluating the fit between observed and simulated groundwater elevation and surface water flow. Model calibration was based on data for years 2007 through 2009, 2011, and 2013 while data sets for years 2010 and 2012 were reserved for model validation. Calibration results were evaluated based on several metrics: RMSE, correlation coefficient and mean error for groundwater elevation and mean relative error and correlation coefficient for surface water flow.

The calibrated model RMSE for the most accurate groundwater data was 10.85 ft with a correlation coefficient of 0.71. Surface water gauges were divided into six gauge series, with calibrated model results for the larger rivers and streams considerably more accurate than the irrigation networks consisting of numerous small canals and springs. Correlations coefficients for the gauge series ranged from 0.99 for the Touchet River gauge to 0.35 for the Mud Creek gauge series. Mean relative error ranged from 10 percent for the Touchet River gauge to 130 percent for the HBDIC-Pine Creek gauge series.

Applying the calibrated model to the validation data set did not significantly change the statistical agreement between the measured and predicted groundwater elevations. Surface water fit was more affected by including the validation data set, though the model fit was improved for several of the gauge series. The statistical metrics between predicted and measured groundwater elevations were similar for the calibration and validation data sets, indicating that the calibrated model predicts the physical processes that affect groundwater elevation. Statistical metrics for predicted and measured surface water flow generally were similar or improved when including the validation data set.

Calibration model hydrological budget outputs indicate that agricultural water application is in excess of agricultural water demand due to inefficiencies in irrigation delivery and over application of surface water in the late fall and spring to store water in the unsaturated zone. Groundwater is the primary source of irrigation water over the summer months. During these months groundwater extraction exceeds the sum of all sources of groundwater inflow concurring with the simulated decline of groundwater storage. Streams are gaining from groundwater on the whole; however, some individual reaches, and entire sub-regions, lose water to channel seepage.

Groundwater recharge from MAR in the HBDIC sub-region helped to offset groundwater losses from groundwater pumping and increased return flows to streams, indicating that MAR can offset aquifer storage losses. The potential for MAR to contribute to basin wide goals for conjunctive use

of surface water and groundwater resources hinges on the optimization of MAR facility location and recharge volumes. The calibrated Walla Walla Basin model serves as a tool to further evaluate MAR in the basin in addition to analyzing water use, resource availability, and management alternatives that can form the development of a water management strategy that both meets requirements for instream flow and provides water for irrigators.

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Appendices (on CD)