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Using MODFLOW to Predict Impacts of Groundwater Pumpage to Instream Flow: Upper Kittitas County, Washington

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USING MODFLOW TO PREDICT IMPACTS OF GROUNDWATER PUMPAGE TO INSTREAM FLOW: UPPER KITTITAS COUNTY, WASHINGTON

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by

Zoe Oriel Futornick

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ABSTRACT

USING MODFLOW TO PREDICT IMPACTS OF GROUNDWATER

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Surface waters in the Yakima River Basin in central Washington are considered over allocated. Since 1960, new water demands have been met through groundwater withdrawals, with most groundwater users holding a later priority date than senior and junior surface water users. As a result of the discussions surrounding this issue, the Upper Kittitas Groundwater Rule has been in effect since 2010. Pumping from new domestic (i.e., permit-exempt or "exempt") groundwater wells in Upper Kittitas County is not allowed unless mitigation is used to offset the groundwater use.

The United States Geological Survey (USGS) has already created a basin-wide model for the Yakima River Basin for the period October 1959 through September 2001; however, the hydrogeology of Upper Kittitas County is coarsely represented in the USGS model because individual bedrock units are not delineated. Based on the USGS Yakima River Basin groundwater flow model (hereafter the YRB-GFM), an Upper Kittitas County groundwater flow model (hereafter the UKC-GFM) was extrapolated to refine the Upper Kittitas County modeled

region. This new model constitutes an M.S. thesis, done in collaboration with the USGS. The UKC-GFM contains 246 columns and 195 rows, with 1,000 foot grid cells, and five layers representing three basin fill units, basalt, and bedrock; it is populated with model information for the period October 1991 through September 2001. Refinements to the UKC-GFM include: (1) using a newer version of MODFLOW (MODFLOW-NWT) with the new Newton Solver and the Upstream Weighting (UPW) package. The YRB-GFM used MODFLOW-2005, the PCG2 Solver, and the Hydrogeologic-Unit Flow (HUF) Package; (2) incorporating zone arrays with multiple hydraulic properties into model bedrock layers; (3) extending streamflow-routing cells into smaller headland creeks; (4) changing simulated monthly reservoir stages from steady state to time variant; and (5) estimating new parameter values.

The UKC-GFM was calibrated using trial-and-error methods and automated parameter estimation with the software PEST. Groundwater model calibration involves comparing measured water levels and streamflow observations with simulated water levels and streamflow values. At 116 well observation points, the calibrated model produces a root-mean-square (RMS) error divided by the total difference in water levels of 1.5 percent, an acceptable error. Annual differences for measured and simulated streamflow ranged from 7 to 11 percent (percent difference) along the Yakima River, and ranged from 19 to 49 percent along tributaries.

Once calibrated, the UKC-GFM was run as three scenarios to assess responses of the flow system to potential changes in stresses. These scenarios are: (1) Existing Conditions without All Pumping, (2) Decrease Recharge by Fifteen Percent, and (3) Increase Pumpage by Fifteen Percent. The scenario with the greatest impacts to stream leakage is Scenario 2, where the annual difference in streamflow for the most downstream gage in 2001, the end of the model simulation period, is approximately 80 ft^3/sec. This is a 4.7 percent decrease in streamflow, versus Scenario 1 (all pumping removed), which produces a 0.17 percent increase in streamflow. A comparison of the applied scenarios suggests that potential climate changes that decrease recharge have more impacts on streamflow than groundwater pumping.

ACKNOWLEDGEMENTS

This thesis is the culmination of several years of research, and would not have been possible without the support of many individuals. Therefore, I would like to whole-heartedly offer my thanks to the following people who helped me with this project.

First, I would like to thank Dr. Carey Gazis, my advisor and a professor of hydrogeology in the Central Washington University (CWU) Department of Geological Sciences. Dr. Gazis provided me with constant support throughout the research and writing of this thesis. Her knowledge of hydrogeology, her keen eye for detail when it comes to scientific writing, and her commitment to, and encouragement for, her students were invaluable to me.

I would also like to offer my thanks to the other two members of my thesis committee, Matthew Bachmann and Dr. Breanyn MacInnes. Matthew Bachmann, a hydrologist and groundwater modeler with the Washington Water Science Center in Tacoma, Washington (U.S. Geological Survey, or USGS), readily made himself available to me while I researched and wrote my thesis. Matthew Bachmann was of vital support to me during the development of the Upper Kittitas County groundwater flow model, and provided me with tips and strategies to construct a reasonable and effective groundwater model. Dr. Breanyn MacInnes immediately stepped in to sit on my committee when my original third committee member became unavailable during the month of my master’s Defense. I truly appreciate her taking the time to review my thesis and to provide valuable feedback. My former committee member, Dr. Winston Norrish, a CWU professor, gave me a fresh and local perspective on the geology in the area and was happy to discuss this topic early on.

I would also like to acknowledge the help I received from Dr. David Matthew Ely, a former hydrologist and groundwater modeler with the Washington Water Science Center in Tacoma, Washington (USGS) who now works with the New Mexico Water Science Center (USGS). Dr. Ely has been tremendously and immeasurably helpful to me throughout this project. Dr. Ely showed me multiple methods for viewing and working with groundwater models, and I cannot thank Dr. Ely enough for his constant correspondence, hands-on guidance, and encouragement over my years of research.

I would like to thank yet more colleagues who I worked with at the Washington Water Science Center in Tacoma, Washington (USGS). These individuals include Mark Savoca, a hydrologist and my supervisor during my time as an employee and volunteer in the Tacoma office, who always offered a chair to sit in and advice for moving forward when I came to him with progress reports and questions. Sue Kahle, a hydrologist, provided me with insight into the Upper Kittitas County study area, and her encouragement and upbeat attitude when it came to research were greatly appreciated. Also from the Washington Water Science Center in Tacoma, Washington, I would like to thank Andy Gendaszek, John Vaccaro, Theresa Olsen, Lisl Fasser, and Wendy Welch for providing encouragement and help to me during my master's work.

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No amount of words can express the gratitude I have towards my family. Mom and Dad, you have supported me throughout my journey through college. I am very fortunate to have such intelligent and high-achieving parents who have always lovingly encouraged me to do my best. Sasha, I am forever lucky to have you as my twin sister, and as my friend. You have enthusiastically supported me through everything I do, including this thesis, and I love you very much. Rene, my fiancé, you have supported me in so many important ways while finishing my degree at CWU. I feel incredibly fortunate, thankful, and happy to have found such an encouraging and inspirational

partner, and I love you immensely. So much thanks and love go to my Nana, my aunt Karen, Lois Jewell, and all of my wonderful family, as well as my amazing friends in Oregon, especially Nicole Lesage and Megan Harinski.

With all my heart, thank you.

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CHAPTER I

INTRODUCTION

1.1 Background

Surface waters in the Yakima River Basin (Fig. 1-1) in south-central Washington are considered over allocated in dry years. Since about 1960, water demands for municipal, domestic, agricultural, industrial, and recreational uses have been met through groundwater withdrawals. Because of western water law, most groundwater users have junior water rights to most surface water users, generally farmers and irrigation districts. This means that if a grievance were taken to court, groundwater users could be required to turn off their water supplies during dry years so that users with senior water rights could secure their supplies. In 2007, to protect senior water rights, the Washington State Department of Ecology (WaDOE) was petitioned to unconditionally withdraw future groundwater appropriations in Upper Kittitas County (Fig. 1-2), upper Yakima River Basin, where the headwaters reside, until more is known about potential effects of groundwater withdrawals on instream flow. WaDOE instead signed a Memorandum of Agreement (MOA) with Kittitas County commissioners, which included stipulations for a groundwater study in the county, later contracted to the United States Geological Survey (USGS) (Ely, 2010; Gendaszek et al., 2014). As of October 2010, the Upper Kittitas Groundwater Rule is in effect, which does not allow pumping from new domestic (i.e., permit-exempt or "exempt") groundwater wells in Upper Kittitas County unless mitigation is used to offset the groundwater use (Washington Administrative Code 173-539A-WAC).

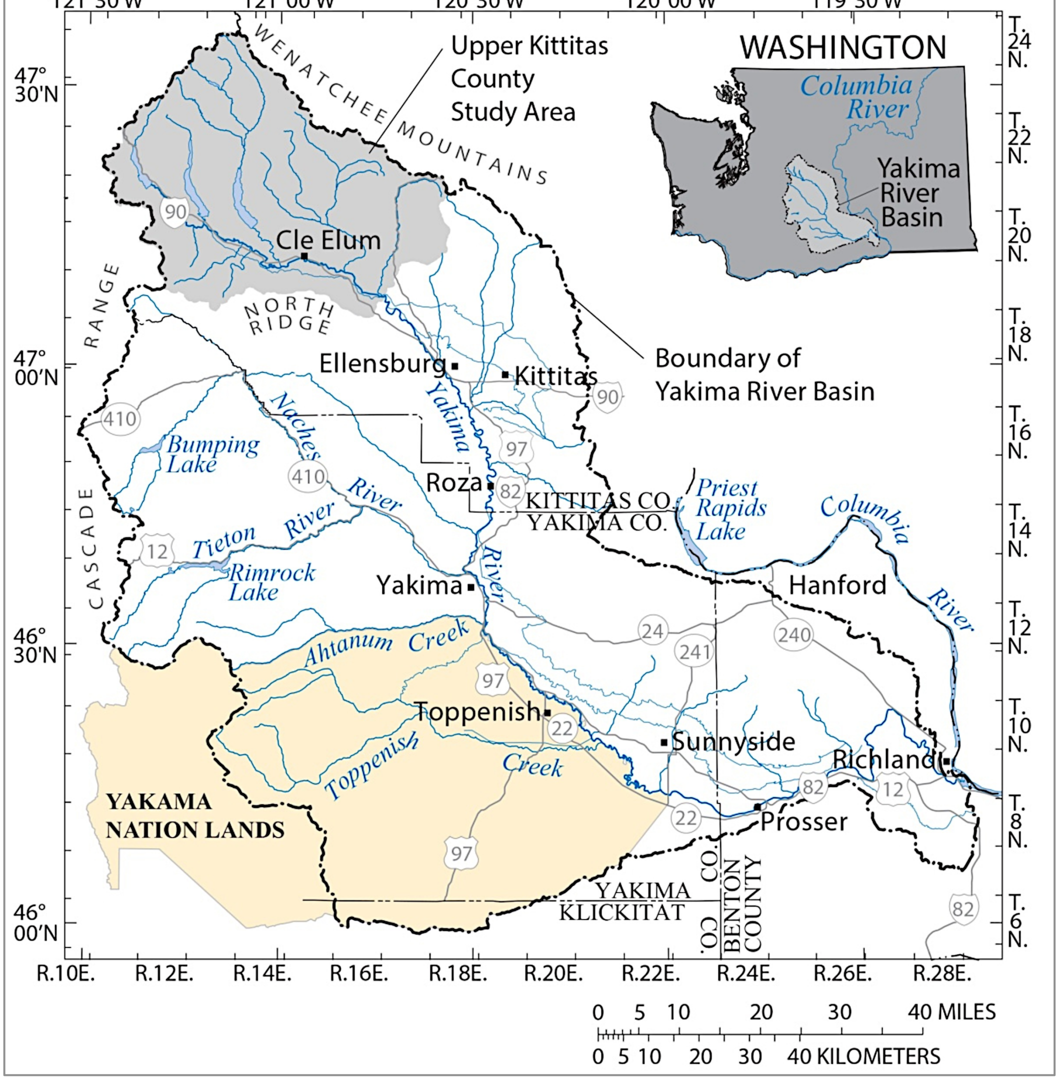


Figure 1-1. Yakima River Basin, Washington (modified from Vaccaro et al., 2009).

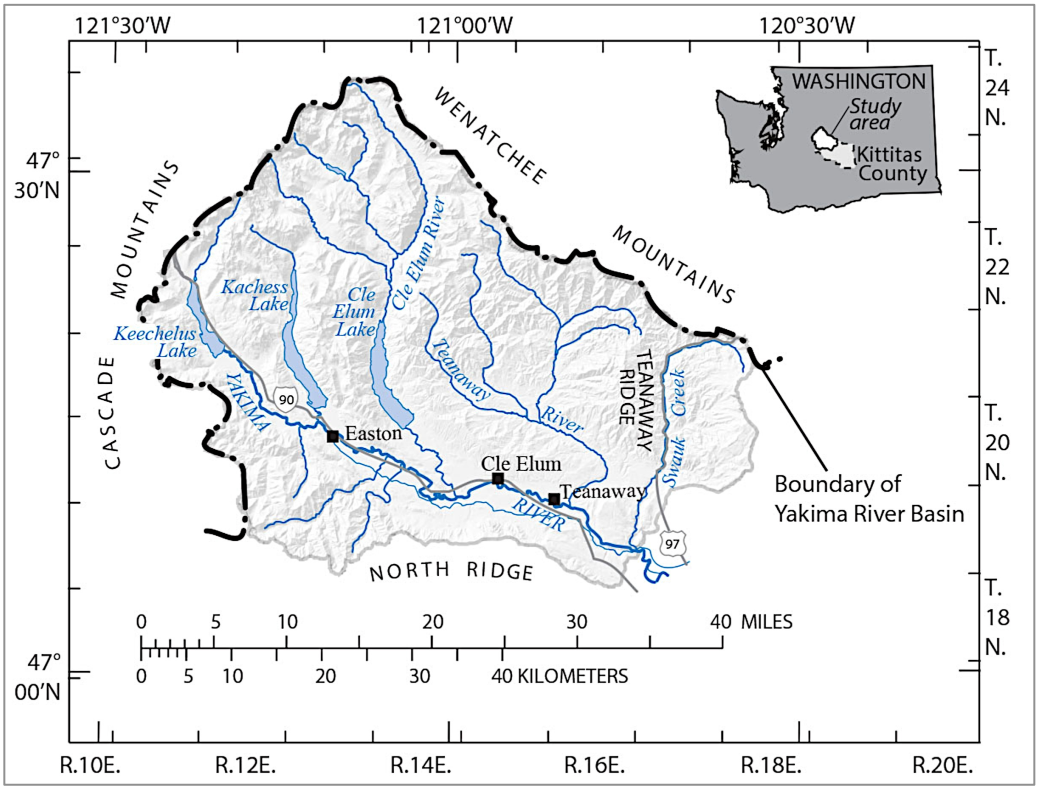


Figure 1-2. Upper Kittitas County, Washington.

In June 2000, following a 1999 groundwater moratorium issued by WaDOE, which halted the issuance of new well permits (excluding exempt wells), the USGS, in a cooperative effort with the Bureau of Reclamation (Reclamation), WaDOE, and the Yakama Nation, began a multi-phase study to characterize groundwater and surface-water demands and interaction in the Yakima River Basin. The USGS Yakima River Basin study (YRB-USGS) produced both a hydrogeologic framework (Vaccaro et al., 2009) and a numerical model (YRB-GFM; Ely et al., 2011) for water years 1960 through 2001. Table 1-1 provides a reference for acronyms to identify items like the YRB-USGS and the Upper Kittitas County groundwater flow model (UKC-GFM), as well as other useful acronyms as they will hereafter be referred to in this master's thesis.

TABLE 1-1. ACRONYMS FOR MODEL, PROJECT, AND AGENCY NAMES MENTIONED WITHIN THIS REPORT.	
ACRONYM	FULL NAME
UKC-GFM	Upper Kittitas County groundwater flow model
YRB-GFM	Yakima River Basin groundwater flow model
UKC-USGS	Upper Kittitas County United States Geological Survey project
YRB-USGS	Yakima River Basin United States Geological Survey project
USGS	United States Geological Survey
WaDOE	Washington State Department of Ecology
Reclamation	Bureau of Reclamation

The YRB-USGS and YRB-GFM emphasize groundwater flow between the Columbia River Basalt Group (CRBG) aquifers (Jones and Vaccaro, 2008) and the sediment-filled basins (Jones et al., 2006) within them, and therefore assign isotropic and homogenous properties (Vaccaro et al., 2009; Ely et al., 2011) to the various bedrock not associated with the CRBG. In Upper Kittitas County, the CRBG underlies only six percent of the land area (Ely, 2010), which means that the majority of simulated groundwater flow for this area of the YRB-GFM does not account for potential heterogeneities of the complex bedrock geology underlying Upper Kittitas County.

The research discussed in this master's thesis describes the development of the UKC-GFM, a three-dimensional, transient numerical model of groundwater flow and surface water within Upper Kittitas County during water years 1992 through 2001. The model extrapolates several components from the YRB-GFM, and adds significant model enhancements for the smaller scale county study area; most significant are the changes to bedrock hydraulic properties. Other enhancements include using a newer version of MODFLOW than the version used for the YRB-GFM, MODFLOW-NWT versus MODFLOW-2005, as well as increasing modeled streamflow extent compared to that of the YRB-GFM. This master's thesis is undertaken in collaboration with scientists in charge of the UKC-USGS study with the goal of providing a preliminary numerical groundwater model for Upper Kittitas County. As such, it will provide timely and useful information for policy makers in WaDOE and Kittitas County.

1.2 Purpose and Scope

This report describes the construction, calibration, and application of a computer model to simulate the groundwater flow system beneath Upper Kittitas County, Washington for the time period October 1991 to September 2001, water years 1992 through 2001. The primary purpose of the UKC-GFM is to enhance the modeled area of Upper Kittitas County from its previously modeled state in the YRB-GFM in order to better understand the relationship between groundwater and surface water in the study area, with emphasis on the impacts of groundwater withdrawals to instream flow; impacts of stresses to instream flow are mainly assessed through three scenarios, performed on the final calibrated model.

1.3 Description of the Study Area

1.3.1 Location and Setting

Upper Kittitas County (Fig. 1-2) encompasses approximately 860 mi^2 (within the greater 2,333 mi^2 Kittitas County area) in central Washington, and is bounded by: the eastern edge of the Cascade Range to the west, the Stuart Range / Wenatchee Mountains to the north, the edge of the Swauk Creek drainage basin where it contacts the Grande Ronde basalts to the east (near Lookout Mountain), and to the south an east-west trending anticlinal ridge known as North Ridge (Vaccaro et al., 2009). Land surface elevations range from 7,960 along the Cascade Crest to 1,730 ft at the eastern edge of the study area, with mean annual precipitation on the order of 80 inches (Vaccaro and Olsen, 2007), mostly as winter snow in the mountains. The Yakima River flows from west to east through southern Upper Kittitas County.

1.3.2 Overview of the Hydrology and Hydrogeology

1.3.2-1 Surface Water

The Yakima River is the main river body within Upper Kittitas County, and has its headwaters approximately 7,960 feet high on the eastern slope of the Cascade Mountains, or the Cascade Crest. From there, the Yakima River flows another 20 miles and decreases in elevation by 1,730 feet at the southeast boundary of Upper Kittitas County; it then flows 180 miles in a generally southeast direction across the remaining Yakima River Basin drainage area, until it discharges into the Columbia River near Richland, Washington. Tributaries to the Yakima River within Upper Kittitas County are the Cle Elum and Teanaway Rivers, Swauk Creek, and other smaller tributaries. Three reservoirs also regulate and feed the Yakima River in the study area: Keechelus, Kachess, and Cle Elum Lakes. Based on streamflow for the Yakima River at Cle Elum, Upper Kittitas County generates about 2,200 ft^3/s of unregulated runoff and 1,700 ft^3/s of runoff under regulated conditions. In upland areas, the surface water in Upper Kittitas County generally flows over volcanic, metamorphic, and sedimentary bedrock until it reaches basin fill deposits at lower elevations.

1.3.2-2 Groundwater Recharge

Upper Kittitas County is considered humid uplands within the greater Yakima River Basin. Most of the recharge for the Yakima River Basin occurs in these upland areas (Vaccaro and Olsen, 2007), with recharge driven by moisture from the Pacific Ocean, transported over the Cascade Mountains as rain in the spring and snow in winter, which becomes snowmelt in summer (Pearson, 1985). Based on a previous study of recharge in the Yakima River Basin (Vaccaro and Olsen, 2007), a dominant factor controlling groundwater recharge in Upper Kittitas County is the amount of precipitation, including snow melt. Recharge in Upper Kittitas County differs from much of the lower Yakima River Basin, which receives additional recharge from irrigation practices. Vaccaro and Olsen (2007) and Vaccaro et al. (2009) define recharge as potential recharge: "water leaving the active root zone or, for barren soils, the bottom of the mapped soil column" after accounting for surface runoff and evapotranspiration. Land cover in Upper Kittitas County is predominantly humid forested uplands, with some small towns within the river valleys. The recharge study of Vaccaro et al. (2007) numerically modeled recharge in the Yakima River Basin, discussed further in the *Specified Flux Boundaries* section of this master's thesis, and provided insight into the controls and variability of recharge in the humid Upper Kittitas County. In general, recharge in the study area enters basin fill material at shallow depths, and discharges and supports streamflow (Mastin and Vaccaro, 2002) instead of entering the deeper, low permeability bedrock (Vaccaro and Olsen, 2007).

1.3.2-3 Reservoirs

The three regulated reservoirs that feed the Yakima River in Upper Kittitas County are: Keechelus, Kachess, and Cle Elum Lakes. The reservoirs have a total reservoir storage capacity of approximately 833,900 acre-feet (Reclamation, usbr.gov). The reservoir storage capacity for Lake Keechelus, 158,000 acre-feet, is smaller than that of Kachess and Cle Elum Lakes, 239,000 acre-feet and 436,900 acre-feet, respectively. The reservoirs reside within U-shaped glacial valleys, formed by advancing alpine glaciers during the Pleistocene (Porter, 1976), and overlie volcanic and sedimentary bedrock. Levels in each reservoir fluctuate seasonally, rising in the spring and early summer due to snowmelt runoff, then declining during late summer and early fall due to releases of reservoir water to canals and down valley farms, as well as decreasing precipitation in the upper portion of the study area and increasing evaporation of lake water (Pearson, 1985). The cyclical pattern of these reservoirs is shown in Figure 1-3.

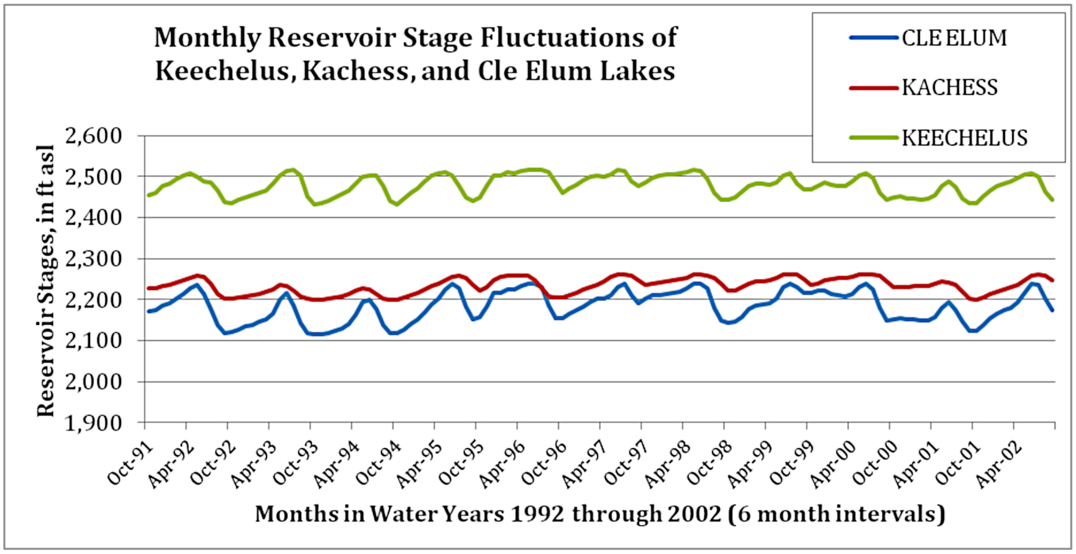


Figure 1-3. Reservoir stage fluctuations for Keechelus, Kachess, and Cle Elum Lakes in Upper Kittitas County, Washington.

1.3.2-4 Groundwater and Surface Water Interaction

Groundwater and surface water movement in Upper Kittitas County have been previously described by Kinnison and Sceva (1963) and Pearson (1985). These studies show that there are identifiable areas of groundwater and surface water interaction, and that most of the year, streamflow in the greater Yakima River Basin is largely baseflow, with perennial streams relying on groundwater. Based on well log and well yield data, Pearson (1985) reports that, although groundwater in the study area occurs largely in unconsolidated valley fill, it also occurs in older semiconsolidated units and in fracture zones in the consolidated igneous, sedimentary, and metamorphic rocks, specifically the basalt rubbly interflow zones. Due to the low permeability of the non-basalt bedrock beneath

Upper Kittitas County, there is less of a contribution to flow through this part of the subsurface (Kinnison and Sceva, 1963).

Kinnison and Sceva (1963) label Upper Kittitas County a groundwater basin, a structurally bounded area in which there is little subsurface flow across the basin boundary and where most groundwater within the basin discharges in a limited area, specifically the Yakima River at Horlick gage in the case of Upper Kittitas County. In general, groundwater moving down valley north of, and in reservoir areas, discharges into the respective lakes or their tributaries. Groundwater in the valley fill deposits, downstream from the respective lakes, is recharged from precipitation falling on the valley or the adjacent slopes, and by underground discharge from the lakes. Groundwater in the Yakima River valley, downstream from each of the dams, moves down valley and discharges into the Yakima River.

Based on these relationships between surface water and groundwater in Upper Kittitas County, it may be inferred that groundwater pumping alters surface water. In the case of the YRB-GFM, when all groundwater pumpage was removed from the modeled Yakima River Basin, average annual streamflow for the 42-year model period at the Yakima River at the Richland gage (near to where the Yakima River discharges into the Columbia River) decreased by 194 ft^3/s in 2001 (Ely et al., 2011).

1.3.3 Water Resources and Use

According to Parker and Storey, reporting in 1913, the Reclamation Enabling Act passed in Washington state in 1905. This legislation led to the Yakima Federal Reclamation Project for the Yakima River Basin, which called for the construction of "facilities to irrigate about 500,00 acres," and also called for the withdrawal of "all forms of further appropriation of unappropriated water in the basin" (Vaccaro and Olsen, 2007, p.6). This meant that, under this legislation, and in line with the Prior Appropriations Doctrine for western United States water law, the holders of pre-1905 water rights had seniority over newer water rights, including all of the irrigation networks that were planned for the Yakima Reclamation Project. In a dry year, when river levels decrease, a junior water right holder may be prohibited by the State from using their water unless compensation is made, while a senior water rights holder may be able to use the water allotted to them in their water right (Brady and Yoder, 2013). This priority system also applies to groundwater rights, which are considered junior water rights.

Since about 1945, population growth in Upper Kittitas County and the greater Yakima River Basin has driven the drilling of wells for domestic and public and/or irrigation uses. Currently, the study area boundary line is considered the boundary for an emergency rule within Upper Kittitas County (Chapter 173-539A WAC, the Upper Kittitas Groundwater Rule), a moratorium that has halted new groundwater pumping, including permit exempt wells, until the UKC-USGS study is completed. Permit exempt wells (domestic wells) are defined as wells that provide water for: (1) livestock, (2) a non-commercial lawn or garden, greater than or equal to one-half acre, (3) one or more homes (up to 5,000 gallons per day), (4) industrial purposes (up to 5,000 gallons per day) (Washington State Department of Ecology, 2006). Until 2009, new permit exempt wells were allowed, even though a previous groundwater pumping moratorium for non-exempt wells was already in place. Currently, only building permits granted and bestowed prior to July 16, 2009, as well as permits for potential water users which are determined to be water budget neutral are allowed; water banking through the Trust Water Right Agreement is an option for potential users seeking a water budget neutral water right.

1.3.4 Overview of the Geology

Upper Kittitas County rests to the east of the North Cascade Mountains, which are part of the Cordilleran mountains of western North America, a section of the Circum-Pacific orogenic belt, or the "Pacific Ring of Fire." Therefore, the geologic history of Upper Kittitas County is part of the geologic and tectonic progression and growth of the North American Cordillera, which has been detailed by Burchfiel et al. (1992) and Dickinson (2004). The geology of Upper Kittitas County has been mapped and described in various geologic maps of central-eastern Washington (Porter, 1976; Walker, 1980; Walsh et al., 1987; Cheney, 1999; Tabor et al., 2000; Dragovich et al., 2002; Brown and Dragovich, 2003; Haugerud and Tabor, 2009). Prior to the onset of this thesis, no current study focused solely on Upper Kittitas County geology; therefore this section of the report will combine and summarize current resources regarding the geologic history and setting of the study area. A more recent study by Gendaszek et al. (2014) provides a similar summarization of Upper Kittitas County geology. A recent map by Haugerud and

Tabor (2009) (Fig. 1-4) has been cropped to the Upper Kittitas County study area boundary.

1.3.4-1 Faults and Structural Features

Western Upper Kittitas County is dissected by two major north and northwest-trending strike-slip faults, the Straight Creek Fault (SCF) and the Darrington-Devils Mountain Fault Zone (DDMFZ). Additionally, the north and east sections of the study area are divided by a series of synclines and anticlines (Vaccaro et al., 2009) (Fig. 1-4). The SCF is an inactive, high-angle, right-lateral strike-slip fault that exists north of Upper Kittitas County, in Canada as the Fraser Fault, and runs south through the study area, where it joins with the DDMFZ (Haugerud and Tabor, 2009). Sedimentary evidence suggests that SCF movement began in the Paleogene (50 to 48 million years ago; Evans and Ristow, 1994), and Tabor et al. (1984) suggests an end to SCF movement in the Miocene, 35 Ma.

The DDMFZ is a high-angle north-side-up thrust fault with a dominant component of left-lateral slip (Tabor, 1994, Haugerud and Tabor, 2009). It is believed to be of similar age to the SCF, although some feel it is slightly younger (Tabor et. al., 1984; Evans and Ristow, 1994; Tabor, 1994; Haugerud and Tabor, 2009), with potential DDMFZ movement starting in the Eocene (post-42 million years ago) (Evans and

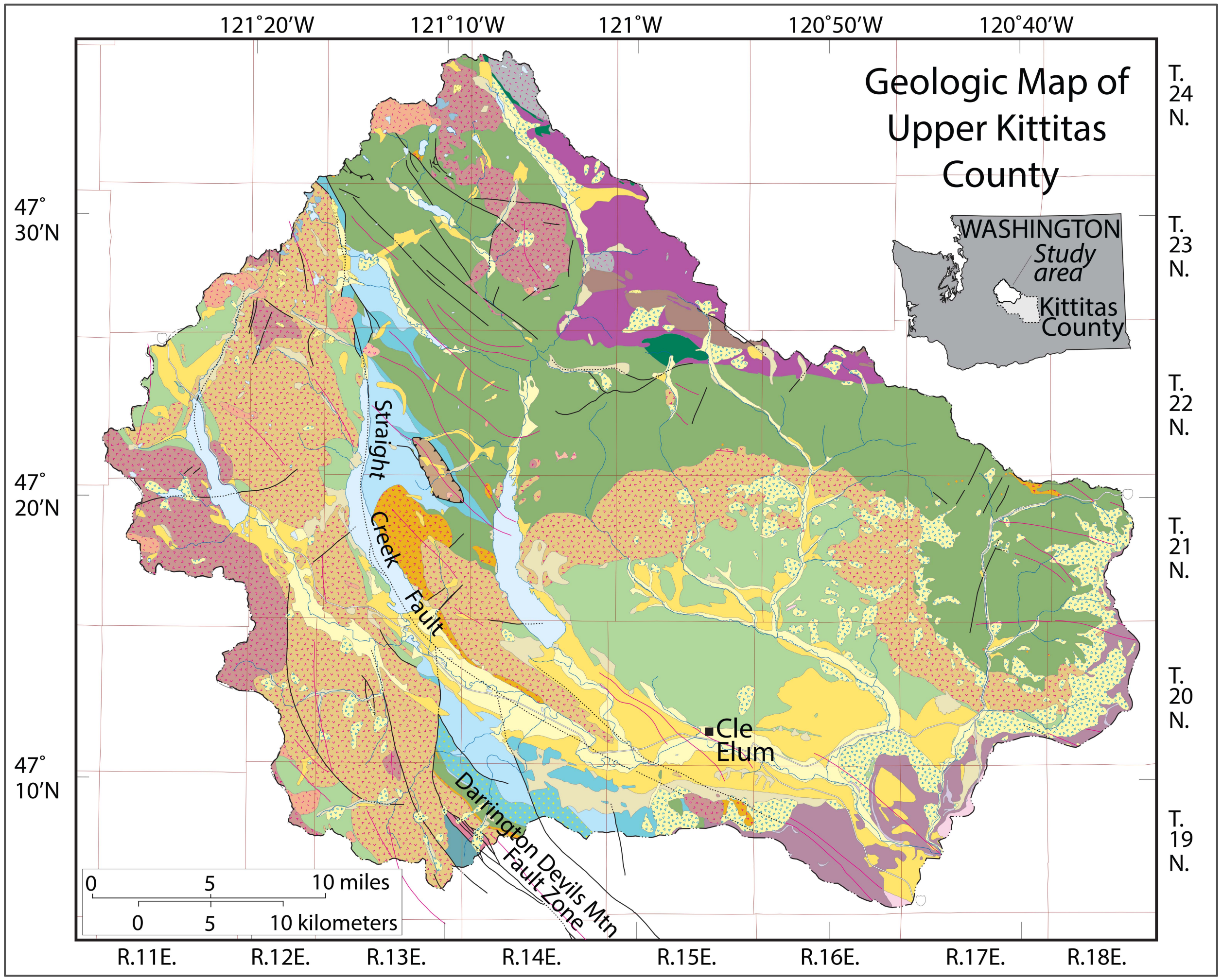


Figure 1-4. Map of surficial geology in Upper Kittitas County, Washington. Modified from Haugerud and Tabor, 2009 (edited by Theresa D. Olsen)

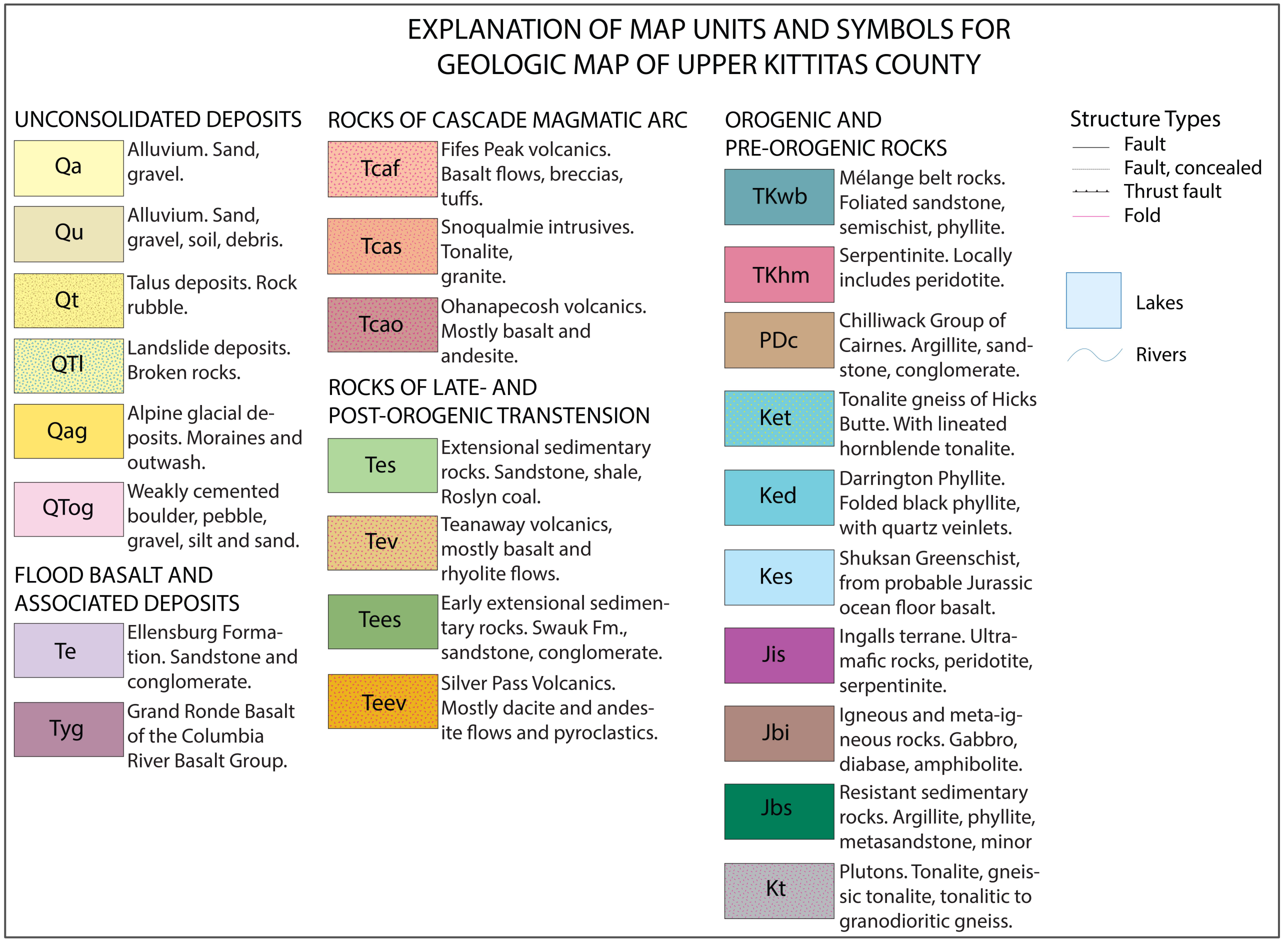


Figure 1-4, continued. Map of surficial geology in Upper Kittitas County, Washington. Modified from Haugerud and Tabor, 2009 (edited by Theresa D. Olsen)

Ristow, 1994). The DDMFZ exists west of the Cascade Range, and extends in a north-northwest alignment between the Northwest Cascade System and the Mélange Belts to a position north of Upper Kittitas County (Tabor, 1994; Haugerud and Tabor, 2009). It then runs south into west-central Upper Kittitas County, with an approximately north-south orientation until it splays into multiple faults in the southern portion of the study area.

Within Upper Kittitas County, the SCF and DDMFZ generally offset extensional non-marine sedimentary and volcanic rocks on either side. The Easton Terrane (units Ket, Ked, and Kes; Haugerud and Tabor, 2009) east of the SCF within Upper Kittitas County has also experienced offset, with much of the terrane west of the SCF being moved northward outside of the study area. The deformation history in Upper Kittitas County is also responsible for subsurface bedrock fracturing throughout the study area, the nature of which likely follows the patterns of faults seen on the surface (Tabor, 1994; Haugerud and Tabor, 2009).

1.3.4-2 Geologic History

The complex geology of Upper Kittitas County (Fig.1-4) is divided into six major groups (Fig. 1-5, Fig. 1-6), as previously identified in Gendaszek et al. (2014), Ely et al. (2009), and Vaccaro et al. (2009) as well as in the UKC-USGS proposal (Ely, 2010): (1) Metamorphic and intrusive rock, Pre-Tertiary; (2) Non-marine sedimentary rock,

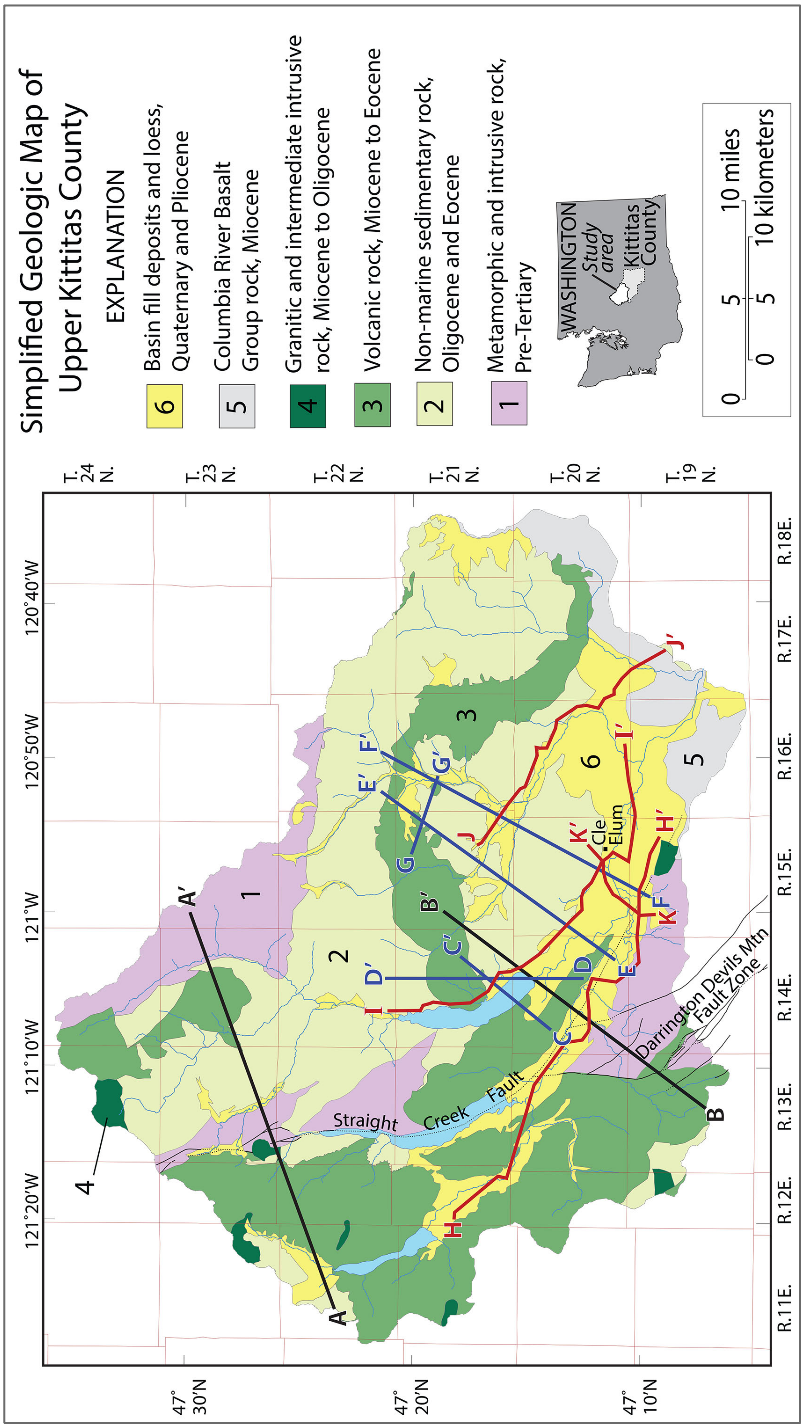


Figure 1-5. Simplified surficial geologic map of Upper Kittitas County.

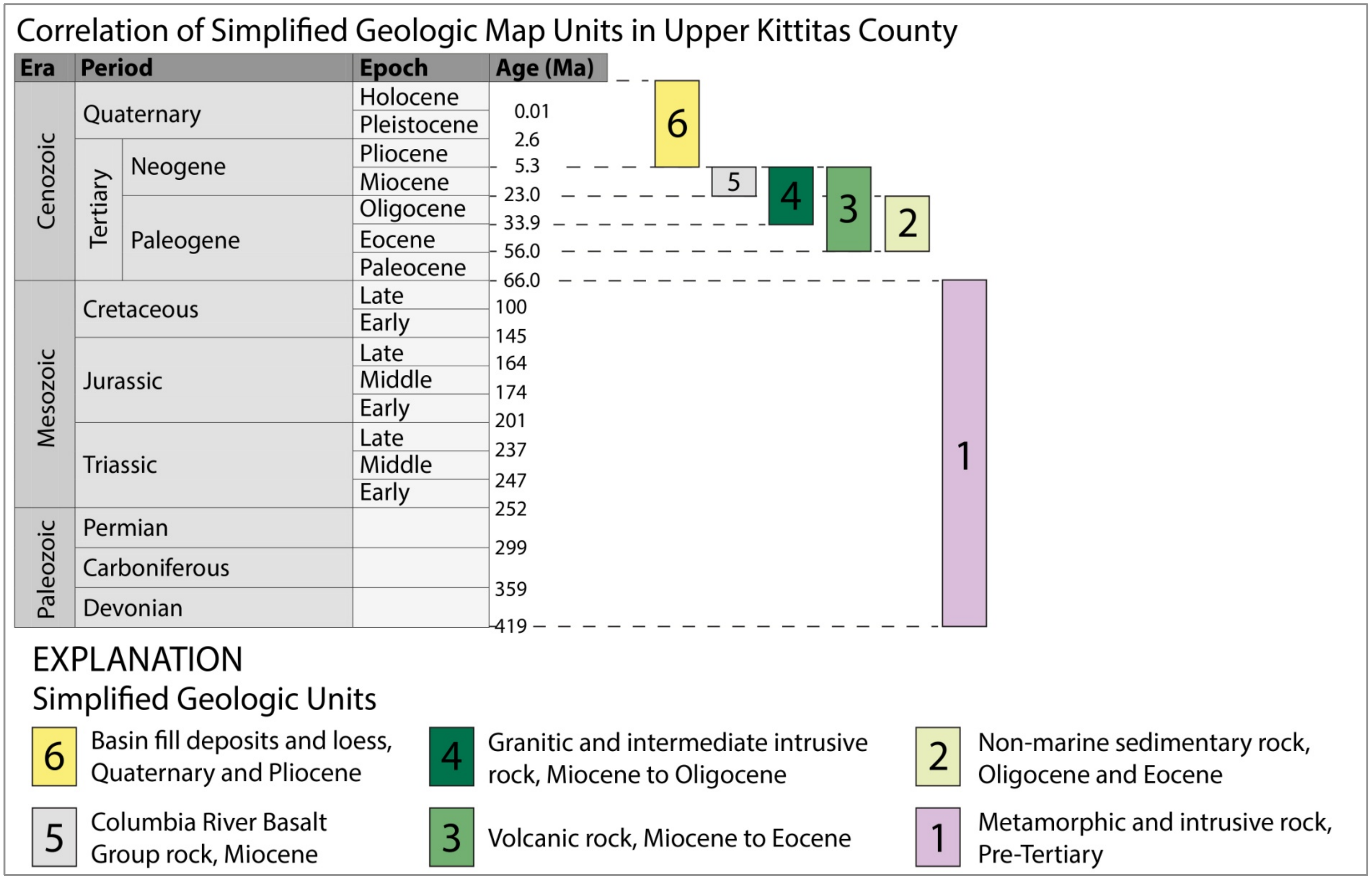


Figure 1-6. Correlation of simplified geologic map units in Upper Kittitas County, Washington.

Oligocene to Eocene; (3) Volcanic rock, Miocene to Eocene, (4) Granitic and intermediate intrusive rock, Miocene to Oligocene; (5) Columbia River Basalt Group rock (Grande Ronde Basalt unit), Miocene; and (6) Basin fill deposits and loess, Quaternary. Note that, although "Tertiary" is no longer a geologic period, the term is used in this report because the previous USGS proposal (Ely, 2010) used this terminology to label the six geologic groups. Additionally, the cross section lines in Figure 1-5 correspond to cross sections in Figure 2-3. The six geologic groups in Upper Kittitas County are described in detail in the following sections, and are incorporated into the UKC-GFM to serve as the basis for the model hydrogeologic units.

(1) Metamorphic and intrusive rock, Pre-Tertiary. The oldest group of rocks in Upper Kittitas County (Fig. 1-4; Fig. 1-5; Fig. 1-6) spans the Devonian to Cretaceous periods, approximately 375 million to 93 million years ago, and includes units PDc, Ket, Kes, Ked, Jis, Jbi, Jbs, TKwb, and TKhm (Fig. 1-4; Haugerud and Tabor, 2009). The rocks in this category are all grouped as orogenic and pre orogenic rocks of the North Cascades. Unit PDc (Fig. 1-4) is the Chilliwack Group of Cairnes (1944), also known as the Chilliwack River Terrane, part of the Excelsior Nappe (Haugerud and Tabor, 2009). Cairnes (1944) and Haugurud and Tabor (2009) define unit PDc as containing argillite and slate, sometimes metamorphosed to phyllite, as well as volcanic subquartzose sandstone, conglomerate, and minor limestone sometimes metamorphosed to marble. Also included are basalt and andesite, metamorphosed to greenstone in some instances, as well as intrusive gabbro and diabase. Unit PDc occurs in one small location within

Upper Kittitas County surrounded by other *group 1 metamorphic and intrusive pre-Tertiary* rocks (units Kes and Ked), and is a klippe. These rocks are categorized as Northwest Cascade System rocks, which formed as a result of offshore volcanic island arc activity, leading to deposition of unit PDc between 375 to 250 million years ago, during the Devonian, Carboniferous, and Permian periods (Haugerud and Tabor, 2009). Fossils found in limestone of unit PDc provide the dates for its deposition (Cairnes, 1944; Haugerud and Tabor, 2009). The rocks of unit PDc, the Excelsior Nappe, represent one of three **nappes**, large terranes or slabs of rock transported from their original positions and bounded by two thrust faults. The three nappes were transported and thrust over younger **autochthonous**, or native basement, sediments into what is now Upper Kittitas County (Brown, 1986; Dickinson, 2004; Haugerud and Tabor, 2009). The autochthon beneath the nappes, a 170 to 120 million year old (Jurassic period) submarine fan (Tabor and Haugerud, 1999; Haugerud and Tabor, 2009), is not present surficially in Upper Kittitas County, and is instead located northwest of the study area, where the majority of Northwest Cascade System rocks lie. Thrusting of the nappes of the Northwest Cascade System occurred approximately 90 million years ago in the Cretaceous period, after deposition of the autochthon. Chilliwack River Terrane rocks display overturned beds and penetrative fabrics not present within the autochthon, suggesting an event that must have occurred before or during thrusting over the autochthon (Tabor and Haugerud, 1999).

Unit PDC and the Excelsior Nappe are structurally the lowest of the three thrusted nappes. The middle nappe, as with the autochthon, exists outside of Upper Kittitas

County to the northwest. The highest nappe, the Shuksan Nappe, is found within Upper Kittitas County and is comprised of units Ket, Kes, and Ked (Fig. 1-4; Fig. 1-5). The Shuksan Nappe is also referred to as the Easton Terrane. Unit Ket is plutonic tonaliteand tonalite gneiss of Hicks Butte. Units Kes and Ked represent the Easton Metamorphic Suite of the Shuksan Nappe. Unit Kes is the Shuksan Greenschist, which includes blueschist, and is probable Jurassic ocean floor basalt (Haugerud and Tabor, 2009). Conformably above the Shuksan Greenschist is the Darrington Phyllite (unit Ked), mostly well crystallized, fine-grained, graphitic-albite-muscovite schist that cleaves along a secondary foliation with finer grained minerals and appears phyllitic. The Darrington Phyllite mud and sand protoliths were originally deposited on top of the Shuksan Greenschist basalt protolith, then both units were subducted beneath continental crust where they contacted the Hicks Butte tonalite protolith, and then all units were rapidly uplifted and exhumed (Haugerud and Tabor, 2009). Rocks of the Shuksan Nappe are located immediately east of the DDMFZ in Upper Kittitas County. Age-dating of zircons in metadiorites outside of the study area, enclosed in semischist associated with the Shuksan Nappe, provide a protolith age for the Shuksan Nappe of about 163 million years (Brown, 1986), during the Middle and Late Jurassic period; ages for metamorphism are about 130 million years, during the Early Cretaceous period (Haugerud and Tabor, 2009).

Some rocks categorized as *group 1 metamorphic and intrusive pre-Tertiary rocks* do not represent Northwest Cascade System rocks, and instead are rocks of the Jurassic Ingalls Terrane, located within the Wenatchee Block. The Wenatchee Block lies mostly north of Upper Kittitas County, although some of its rocks lie within the study area, south of the Mount Stuart Batholith. Wenatchee Block rocks within Upper Kittitas County include those of the Ingalls Terrane, units Jis, Jbi, and Jbs (Fig. 1-4; Fig. 1-5; Haugerud and Tabor, 2009). This terrane is also known as the Ingalls Tectonic Complex and the Ingalls Ophiolite Complex. Unit Jis, the most extensive unit of the complex, is comprised of ultramafic rocks such as peridotite, some of which are metamorphosed to foliated serpentinite. Unit Jbi contains igneous rocks such as gabbro and diabase, as well as metaigneous rocks such as greenstone and amphibolite. Unit Jbs includes sedimentary rocks such as argillite and chert, as well as metasedimentary rocks such as phyllite, metasandstone, metachert, and marble. The Ingalls Terraneis considered part of an **ophiolite sequence**, an assemblage of ocean floor and mantle rocks formed at an ocean spreading center, because it contains three layers of oceanic lithosphere: (1) ultramafic rocks of the upper mantle (unit Jis), which are structurally the lowest rocks in the sequence; (2) ocean floor crust basaltic rocks (unit Jbi); and deep ocean sedimentary rocks (unit Jbs). Mantle rocks of unit Jis are believed to be older than ocean floor crustal rocks (unit Jbi), which have a Uranium-Lead (U-Pb) zircon age of 161 million years, in the Late Jurassic period. Deep ocean sedimentary rocks (unit Jbs) contain fossil Radiolaria with "lower Oxfordian," or Late Jurassic, ages.

Additional *group 1 metamorphic and intrusive pre-Tertiary rocks* include units TKwb and TKhm (Fig. 1-4; Fig. 1-5; Haugerud and Tabor, 2009), both mélange units. **Mélanges** are accumulations of different types of rocks contained within a rock matrix of a different composition than the rocks it surrounds. Unit TKwb is the western mélange belt, mostly foliated sandstone and semischist, interbedded with argillite or phyllite, as well as chert, marble, and weakly metamorphosed subvolcanic diabase, gabbro, and tonalite. Fossil records indicate that the dominant sedimentary rocks of TKwb were deposited in a marine setting during the Late Jurassic to Early Cretaceous, and later disrupted and metamorphosed due to subduction zone processes during the middle Eocene to Late Cretaceous (Haugerud and Tabor, 2009). In the western mélange belt, most fossil ages are Early Cretaceous and Late Jurassic. Unit TKhm is the Helena-Haystack mélange, which Haugerud and Tabor (2009) split into two units. One of these units is unit TKhg, a combination of resistant blocks of mafic volcanic rocks and marine sedimentary rocks of the eastern mélange belt, plus the Northwest Cascade System. The second unit is unit TKhm, the incompetent peridotite turned serpentinite matrix that contains unit TKhg. Of the two, only unit TKhm is mapped within Upper Kittitas County. The Helena-Haystack mélange possibly formed during Late Cretaceous and (or) middle Eocene time via mixing of the resistant rocks into the matrix rock (unit TKhm) due to submarine landslides in a subduction zone setting (Tabor et al., 2002; Haugerud and Tabor, 2009), followed by subsequent obduction, or overthrusting, of the western and eastern mélange belts onto what is now known as the Northwest Cascades System (Tabor, 1994). The mélange belt rocks of units TKwb and TKhm are located within the DDMFZ in the southern portion of the study area.

The final *group 1 metamorphic and intrusive pre-Tertiary rocks* within Upper Kittitas County are from unit Kt (Fig. 1-4; Fig. 1-5; Haugerud and Tabor, 2009), tonalitic plutons that include mostly tonalite, gneissic tonalite, and tonalite to granodioritic gneiss.

Unit Kt plutons are known as stitching plutons because they intrude adjoining terranes after they were faulted together, thereby providing a record for when the terranes were assembled. Potassium-Argon ages of hornblende and biotite, as well as allanite fission-track ages from unit Kt provide an age of crystallization of about 93 million years (Engels and Crowder, 1971). At this time, in the Late Cretaceous, unit Kt plutons intruded terranes (Dickinson, 2004; Haugerud and Tabor, 2009) during continued arc magmatism, and are remnants of juvenile mantle components and recycled crustal material (Burchfiel at al., 1992). These tonalitic plutons are found mostly north of Upper Kittitas County in the Wenatchee and Chelan Block terranes, except for two locations within the study area where they intrude rocks of the Jurassic Ingalls Ophiolite Complex. Unit Kt includes the Mount Stuart Batholith, also just north of the study area.

In summary, *group 1 metamorphic and intrusive pre-Tertiary rocks* are predominantly metamorphic, with both metaigneous and metasedimentary rocks represented. However, in some instances igneous and metamorphic rocks remain unaltered, as in the Chilliwack Group of Cairnes (unit PDc) of the Excelsior Nappe and the Ingalls Ophiolite Sequence (units Jis, Jbi, and Jbs). The number of intrusive igneous rocks exceeds volcanic rocks, mainly basalt and andesite of unit PDc. Units belonging to the Shuksan Nappe and the Ingalls Ophiolite Sequence are the most extensive of *group 1 metamorphic and intrusive pre-Tertiary rocks* in Upper Kittitas County. A geologic summary of *Group 1* rocks in the study area begins with offshore island arc formation 375 to 250 million years ago, during the Devonian, Carboniferous, and Permian periods, evidenced by the Excelsior Nappe. Following this is the Shuksan Nappe, oceanic basalt and deep ocean sedimentary rocks formed during subduction 163 million years ago, in the Middle to Late Jurassic. The Ingalls Ophiolite Complex, rocks from an ocean spreading center, also formed during the Jurassic, and includes mantle rocks underlying oceanic crust of 161 million years (Late Jurassic), as well as Late Jurassic deep ocean sedimentary rocks. Deposition of marine sedimentary rocks of the western mélange belt in a subduction zone occurred during the Late Jurassic to Early Cretaceous, and from Late Cretaceous to middle Eocene during continued subduction, mantle serpentinite of the Helena-Haystack mélange formed and mixed with exotic resistant rocks, which were then overthrusted onto the Northwest Cascade System. Thrusting of the Northwest Cascade System (i.e., nappes) occurred during the Late Cretaceous, with the final stages of accretion and/or thrusting completed before the Eocene (Johnson, 1985). Finally, 93 million years ago during the Late Cretaceous, tonalitic plutons intruded older terranes through continued arc magmatism.

(2) Non-marine sedimentary rock, Oligocene and Eocene. Chronologically following *group 1* rocks are sedimentary rocks of late and post orogenic transtension (Haugerud and Tabor, 2009), which include units Tees and Tes (Fig. 1-4; Fig. 1-5; Fig. 1-6; Haugerud and Tabor, 2009). **Transtension** is defined as the deformation of Earth's crust due to stretching, or extension, as well as displacement by strike-slip faults (Haugerud and Tabor, 2009). Unit Tees rocks represent early extensional rocks of the middle and early Eocene, and include fluvial feldspathic sandstone, mudstone, and conglomerate of the Swauk Formation, deposited by streams in rapidly sinking, locally

fault-bounded basins (Johnson, 1985; Haugerud and Tabor, 2009). The Swauk formation, is regionally located within the Swauk Basin, which is a fault-bounded basin between the SCF in western Upper Kittitas County and the Leavenworth Fault (Johnson, 1985), which exists to the east of Upper Kittitas County. Locally the Swauk Formation spans the majority of northern Upper Kittitas County, and is wrapped around the Wenatchee Block (Haugerud and Tabor, 2009). Johnson (1985) observes that the Swauk Formation unconformably overlies pre-Tertiary basement of *group 1* rocks, including the Ingalls Tectonic Complex, stitching plutons, and the Shuksan Nappe (Tabor et al., 1984), and indeed there are no rocks from the Paleocene epoch within Upper Kittitas County. This unconformity is also noted in Haugerud and Tabor (2009) and Walker (1980). The Swauk Formation is 57 to 53 million years old, possibly 52 million years old (fission track ages of zircons, Tabor et al., 1984; Cheney and Hayman, 2007).

Another *group 2 Oligocene and Eocene non-marine sedimentary rock* is unit Tes, the Roslyn Formation, which consists of sandstone and conglomerate with subordinate shale, deposited by streams in fault-bounded basins, similar to the Swauk Formation. Coal seams are found within the extensional sedimentary rocks in the Roslyn Formation (Haugerud and Tabor, 2009), and the Roslyn coal field was first mined in 1882 (Walker, 1980). The three major sedimentary environments during formation of the Roslyn Formation include river channels with floodplains where coal beds formed, swamps where the more extensive coal seams formed, and lakes where clays and silts were deposited (Walker, 1980). Several sources (Walker, 1980; Tabor et al., 2000; Haugerud and Tabor, 2009) conclude that the source for the sediments is ancestral mountains to the east. According to Cheney and Hayman (2007), the Roslyn Formation is 46 to 43 million years old, although Haugerud and Tabor (2009) say that the age of this unit may extend to the early Oligocene.

Units Tees and Tes represent a time of Eocene dextral strike-slip faulting within Upper Kittitas County and the Pacific Northwest (Johnson, 1985; Burchfiel, 1992); during this time, crustal blocks tilted, forming low areas that filled with fluvial sediments (Haugerud and Tabor, 2009). Unit Tees, the Swauk Formation, is more extensive than unit Tes, with both units predominantly containing similar materials, such as sandstone and conglomerate. Eocene strike-slip faulting likely originated due to northward oblique convergence of the oceanic Kula plate beneath North America, approximately 52 million years ago. During this time, in the Eocene, Washington was north of a triple junction between the oceanic Kula and Farallon plates, and the North American plate (Johnson, 1985).

(3) Volcanic rock, Miocene to Eocene. Extensional volcanic rocks are also associated with Tertiary transtension in Upper Kittitas County, and are part of *group 3 volcanic rocks, Miocene to Eocene*. Extensional volcanism occurred as a result of extension and cracking of the crust which allowed molten rock to reach the surface and form interbasin volcanoes which became extensive volcanic rock deposits (Haugerud and Tavor, 2009). *Group 3* rocks include the middle and early Eocene Silver Pass Volcanic Member of the Swauk Formation Tes (Fig. 1-4; Fig. 1-5; Fig. 1-6) (unit Teev, Haugerud and Tabor, 2009), mostly dacite and andesite flows and pyroclastic rocks erupted from

early volcanoes during extension. Silver Pass volcanics are about 52 to 50 million years old based on fission track age dating for zircon (Tabor et al., 1984; Cheney, 1994). Silver Pass volcanics are located most prominently in the center of the study area, and are also locally interbedded in small outcroppings within the Swauk Formation.

Younger extensional volcanic rocks included in *group 3* rocks are those of the early Oligocene and Eocene unit Tev, which includes the Teanaway Formation, also known as the Teanaway Basalt (Haugerud and Tabor, 2009). Unit Tev rocks are mostly basalt and rhyolite flows, breccia, and tuff; basaltic feeder dikes intrude the Swauk Formation. Unit Tev is more extensive than unit Teev and crosses Upper Kittitas County in a band across central Upper Kittitas County, and is also found in the western part of the study area. The Teanaway Formation is 47 million years old (fission track dating, Gresens, 1982; Tabor et al., 1984; Johnson, 1985; Cheney and Hayman, 2007).

The sequence of the extensional deposits, both sedimentary and volcanic, is as follows: the Roslyn Formation (unit Tes; 46 to 43 Ma) comformably overlies the Teanaway Formation (unit Tev; 47 Ma), which unconformably overlies dipping beds of the Swauk Formation (unit Tees; 57 to 52 Ma), which is of similar age to the Silver Pass Member of the Swauk Formation (unit Teev; 52 to 50 Ma) (Tabor et al., 1994).

The sequence of the extensional deposits, both sedimentary and volcanic, is as follows: the dipping beds of the Swauk Formation (unit Tees; 57 to 52 Ma), which is of similar age to the Silver Pass Member of the Swauk Formation (unit Teev; 52 to 50 Ma), unconformably underlies the Teanaway Formation (unit Tev; 47 Ma). The Roslyn

Formation (unit Tes; 46 to 43 Ma) conformably overlies the Teanaway Formation (unit Tev; 47 Ma) (Tabor et al., 1994).

Additional volcanic rocks included in *group 3* rocks are not extensional volcanics and are instead rocks of the Cascade Magmatic Arc of the Cascade Subduction zone. Cascade Magmatic Arc volcanic rocks include those of the Oligocene Ohanapecosh Episode (unit Tcao; Haugerud and Tabor, 2009), mainly basalt and andesite with lesser rhyolite. These rocks formed from volcanoes that erupted between 34 to 30 million years ago. Younger volcanic rocks of the Miocene Fifes Peak Episode (unit Tcaf; Haugerud and Tabor, 2009) include basaltic andesite and basalt flows and breccias, with rhyolitic ash flow tuffs. These rocks formed from volcanoes that erupted 24 to 20 million years ago (Haugerud and Tabor, 2009). Peoh Point, a viewpoint south of the town of Cle Elum, is composed of volcanic rocks of the Oligocene Ohanapecosh Episode (unit Tcao), and unit Tcao is also located in the northern study area. The Fife's Peak Episode is located in relatively small locations just above Kachess Lake and in between Kachess Lake and Cle Elum Lake (Fig. 1-4). Its outcroppings are so small that they are not mapped with *group 3* in the simplified geologic map of Upper Kittitas County (Fig. 1-10). Volcanic rocks of the Cascade Magmatic Arc are more visible in Upper Kittitas County than north of the study area in the North Cascades because there has been more uplift in the north, causing erosion which ultimately exposed plutonic, rather than volcanic, rocks.

(4) Granitic and intermediate intrusive rock, Miocene to Oligocene. Additional Cascade Magmatic Arc rocks of the Cascade Subduction zone include intrusive rocks of the Miocene and Oligocene Snoqualmie Family, mostly tonalite, granodiorite granite, and rare gabbro that crystallized 28 to 22 million years ago (Fig. 1-4; Fig. 1-5; Fig. 1-6) (unit Tcas, Haugerud and Tabor, 2009; Tabor, 2000).

(5) Columbia River Basalt Group rock, Miocene. Cascade Magmatic Arc rocks are followed chronologically by *group 5* rocks in Upper Kittitas County, which are the Columbia River Basalt Group (CRBG) and its interbeds (units Tyg and Te, respectively; Haugerud and Tabor, 2009) (Fig. 1-4; Fig. 1-5, Fig. 1-6). The CRBG rocks are formed during the Miocene epoch, 17 to 6 million years ago (Jones and Vaccaro, 2008). The CRBGs erupted from fissures and vents southwest of Upper Kittitas County in northeastern Oregon, eastern Washington, and western Idaho (Waters, 1961; Swanson et al., 1979; Reidel et al., 1989; O'Connor et al., 2009). After erupting from fissures and vents, the CRBG lavas rapidly moved away from their points of origin as individual sheets of lava; over 300 flows have been identified, with each flow ranging from 10 feet to more than 300 feet thick (Tolan et al., 1989; Drost and Whitman, 1986; Gendaszek et al., 2014). Although there are four flood basalt groups, the only group that exists within Upper Kittitas County is the approximately 17 to 15.6 million year old Grande Ronde basalt unit (potassium-argon dating, Swanson et al., 1979; Reidel et al., 1989) (unit Tyg; Haugerud and Tabor, 2009). The Grande Ronde unit is located in southeastern Upper Kittitas County, making the study area a transitional area between the Yakima Fold Belt

sub-province, which is part of the greater Columbia Plateau, and the Cascade Mountain physiographic province. The Grande Ronde Basalt typically has microphenocrysts of plagioclase and clinopyroxene but no macroscopic phenocrysts (Drost and Whiteman, 1986). Reidel et al. (1989, p.22) describe the Grande Ronde unit as “typically composed of fine-grained, aphyric, tholeiitic basalt” (Gendaszek et al., 2014). Sedimentary interbeds within the Grande Ronde basalt were deposited and preserved between periods of lava flows, andgenerally range in texture from clay and silt to sand and gravel, with quartz and feldspar derived from eroded rocks of the North Cascades (Swanson et al., 1979; Drost and Whiteman, 1986; Gendaszek et al., 2014). The sediments overlying the Grande Ronde basalt within Upper Kittitas County is the Ellensburg Formation, dated Miocene to Pliocene, based on fossil evidence (unit Te, Haugerud and Tabor, 2009).

(6) Basin fill deposits and loess, Quaternary and Pliocene. The youngest units in Upper Kittitas County are unconsolidated basin fill deposits, both glacial and non-glacial (Fig. 1-4; Fig. 1-5; Fig. 1-6). Glacial deposits consist of those left by alpine glaciers that entered lower valleys about 22,000 to 18,000 years ago during the Fraser glaciation (Armstrong et al., 1965; Porter, 1976) (unit Qag, Haugerud and Tabor, 2009). These glacial deposits are not connected to glacial deposits from the Cordilleran Ice Sheet whose maximum extent lay farther north. Nonglacial deposits include landslide deposits (unit Qtl, Haugerud and Tabor, 2009) of the Holocene, Pleistocene, and Pliocene, the largest of which are seen along the edge of the CRBGs in Upper Kittitas County. Holocene and Pleistocene alluvium consists of moderately to well sorted river deposits

and lacustrine deposits found on major valley bottoms (unit Qa, Haugerud and Tabor, 2009), and an assortment of deposits (unit Qu, Haugerud and Tabor, 2009), including alluvium, colluvium, soil, alluvial fans, and some landslide debris. Other nonglacial deposits include unsorted talus (unit Qt, Haugerud and Tabor, 2009). All unconsolidated basin fill deposits are generalized as Quaternary deposits, although some are Tertiary in age.

CHAPTER II

METHODS

2.1 Governing Equations

When considering groundwater modeling and MODFLOW, it is important to remember the roots of groundwater as a quantitative science, and the scientific laws that make it so. Freeze and Cherry (1979) and the hydrology community trace this back to Henry Darcy. Darcy's significance to groundwater as a science and the UKC-GFM is his law for groundwater flow, defined as an equation for computing the amount of water flowing through an aquifer (Fetter, 2001). It adheres to the Continuity Equation for groundwater, which states that water is neither created nor destroyed in the hydrologic cycle and therefore the water budget must equal zero. Darcy's law and the Continuity Equation for groundwater are necessary for proper groundwater modeling.

Darcy's law is:

$$Q = -KA\frac{dh}{dl}, \qquad \textbf{Equation 2-1}$$

where: Q is equal to discharge (units of volume, L^3/T); K is equal to the permeability of the porous medium (L/T); A is equal to the cross-sectional area to flow (units of area, L^2); and dh/dl is the ratio of the hydraulic head [dh] divided by the length [dl] of the cylindrical column. The continuity equation for groundwater is written as:

$$(\sum \text{inputs}) = (\sum \text{outputs}) \pm \Delta\,\text{storage}. \qquad \textbf{Equation 2-2}$$

2.2 Comparison between the Yakima River Basin and Upper Kittitas County Groundwater Flow Models

The UKC-GFM is a portion of the greater YRB-GFM (Ely et al., 2011), and represents the northern portion of the Yakima River Basin. Therefore, some aspects of the UKC-GFM are the same as the YRB-GFM, while others have been refined to reflect the detail of the smaller county-scale model. These updates include: (1) using a newer version of MODFLOW (MODFLOW-NWT; Niswonger et al., 2011), with the new Newton Solver and the Upstream Weighting (UPW) package. The YRB-GFM used MODFLOW-2005, the PCG2 Solver, and the Hydrogeologic-Unit Flow (HUF) Package; (2) incorporating zone arrays with multiple hydraulic properties into model bedrock layers; (3) extending streamflow-routing cells into smaller headland creeks; (4) changing simulated monthly reservoir stages from steady-state to time-variant; and (5) estimating new parameter values. Detailed explanations of these updates are provided in the following sections about the development and calibration of the UKC-GFM.

2.3 MODFLOW Modeling Program

The UKC-GFM uses the Newton formulation of MODFLOW-2005, called MODFLOW-NWT (Niswonger et al., 2011). MODFLOW-2005 (Harbaugh, 2005) is a finite difference groundwater flow modeling program that uses a modular structure and consists of individual packages written in FORTRAN code, with text formatted input files. Each package controls a particular feature of the simulated hydrologic system, and each package consists of optional individual subroutines. Model files and data tables for the UKC-GFM are available upon request; please contact the author.

Aquifer systems modeled with MODFLOW are represented by layers, rows, and columns, which create a system of blocks called cells. Each cell must satisfy Darcy's Law, written differently here to accommodate MODFLOW's simplification and notation of the equation:

$$q_x = -K\frac{\partial h}{\partial x}, \qquad \textbf{Equation 2-3}$$

where: q_x is the volumetric flow rate (L^3/T), -K is again the hydraulic conductivity of the material (L/T), and ∂h is the change in hydraulic head across a given length, ∂x. The application of Darcy's Law to the continuity equation for the three-dimensional movement of groundwater produces the partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t}, \qquad \textbf{Equation 2-4}$$

where: K_{xx}, K_{yy}, and K_{zz} are values of hydraulic conductivity (L/T); h is the potentiometric head (L); W is a volumetric flux per unit volume, with $W<0.0$ for outflow and $W>0.0$ for inflow (T^{-1}); S_s is the specific storage of the porous material (L^{-1}), and t is time (T) (Harbaugh, 2005).

For most groundwater models, including the UKC-GFM, continuous partial differential equations for groundwater movement, as in Equation 2-4, are replaced with finite difference equations to approximate the solutions in complex aquifers. These equations use a finite set of discrete points, called nodes; terms are calculated from the differences in head values between these nodes (Harbaugh, 2005). The following equations are the governing finite difference equations for groundwater movement within the MODFLOW program.

The finite difference equation, used in MODFLOW programming, for the balance of flow into cell i,j,k in the row direction from cell i,j-1,k (Fig. 2-1) is given in Darcy's Law as:

$$q_{i,j+1/2,k} = KR_{i,j-1/2,k} \Delta C_i \Delta V_k \left(\frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_{j-1/2}} \right) \qquad \textbf{Equation 2-5}$$

"where: $h_{i,j,k}$ is the head at node i,j,k, and $h_{i,j-1,k}$ is the head at node i,j-1,k; $q_{i,j-1/2,k}$ is the volumetric flow rate through the face between cells i,j,k and i,j-1,k (L^3T^{-1}); $KR_{i,j-1/2,k}$ is the hydraulic conductivity (harmonic mean) along the row between nodes i,j,k and i,j-1,k (L^{T-1}); $\Delta C_i \Delta V_k$ is the area of the cell faces normal to the row direction; and $\Delta r_{j-1/2}$ is the distance between nodes i,j,k and i,j-1,k (L)" (Harbaugh, 2005, p.23). The term "1/2" is used to indicate the region between two nodes, and not the halfway point between them (Harbaugh, 2005).

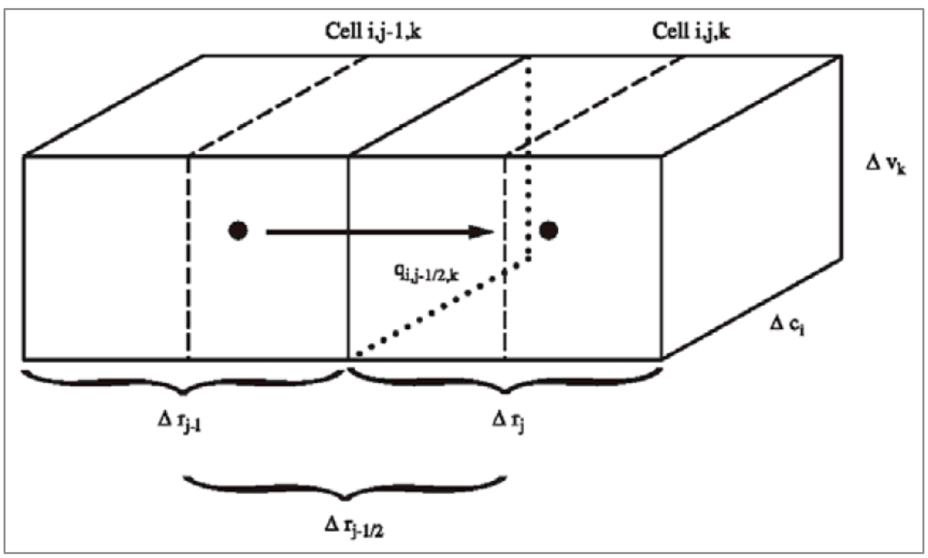


Figure 2-1. Flow into cell i,j,k from cell i,j-1,k (from Harbaugh, 2005).

2.3.1 MODFLOW-NWT

The UKC-GFM uses a Newton formulation of MODFLOW-2005, called MODFLOW-NWT (Niswonger et al., 2011). MODFLOW-NWT is a standalone program that solves problems involving drying and rewetting nonlinearities of the unconfined groundwater flow equation; MODFLOW-NWT uses the new Newton Solver, which uses the Newton linearization method, discussed in Section 2.3.2 of this report, to solve non-linear differential equations as well as problems representing unconfined aquifers. The Newton Solver is applied to provide model stability. Additionally, packages in MODFLOW-NWT, such as the Upstream Weighting Package (UPW) are used instead of some packages used previously in MODFLOW-2005; Table 2-1 is a list of packages that are compatible with MODFLOW-NWT, and includes the packages used in the UKC-GFM.

2.3.2 The Newton Solver

The Newton method in MODFLOW-NWT solves a system of equations that can be written in symbolic form as:

$$\mathrm{J}(\mathrm{h}^{\mathrm{n-1}})\Delta \mathrm{h}^{\mathrm{n}} = \mathrm{R}^{\mathrm{n-1}} \qquad \textbf{Equation 2-6}$$

where *n* and *n*–1 are the nonlinear iteration counters for the present and previous iterations, respectively; J is the Jacobian matrix $\mathrm{J}_{\mathrm{r,l}} = \frac{\partial \mathrm{R}_{\mathrm{r}}}{\partial \mathrm{h}_{1}}$, and *l* is an index ranging from 1 to the total number of active cells starting at the upper left cell and counting along columns, then rows, and then layers; *r* is the index for each row in the Jacobian matrix; $\Delta h^n = h^n - h^{n-1}$; h^n *and* h^{n-1} are the groundwater head at iteration *n* and *n* – 1; *R* is the residual vector representing cell-by-cell errors in water balance. *R* is calculated by summing all cell inflows and outflows to each cell, *i,j,k* (Niswonger et al., 2011). The use of the UPW package in MODFLOW-NWT further enables application of the Newton solution method for unconfined groundwater flow problems because conductance derivatives required by the Newton method are smooth over the full range of head for a model cell (Ely and Kahle, 2012).

2.3.3 Upstream Weighting Package

An important development in the MODFLOW-NWT programming is the Upstream Weighting Package (UPW), a new internal flow package for calculating intercell conductance. The UPW Package uses the design of the MODFLOW-2005 Layer Property Flow Package (LPF) with some small modifications, but differs in the use of the upstream weighting function, which uses a continuous function and not the discrete function for drying and rewetting of cells that is used in the Block-Centered Flow (BCF), LPF, and Hydrogeologic-Unit Flow (HUF) Packages (Anderman and Hill, 2000; Harbaugh, 2005; Ely and Kahle, 2012). The upstream-weighting approach avoids groundwater flow out of dry cells, which is not physically realistic and can cause model convergence failure. This means that the LPF Package will set a dewatered cell to a no flow condition, with a rewetting option, if the cell has time variant transmissivity, while MODFLOW-NWT and the UPW Package will not and therefore need no rewetting data (Niswonger, 2011). For these reasons, MODFLOW-NWT may improve model stability and convergence time.

TABLE 2-1. LIST OF PACKAGES USED IN THE UPPER KITTITAS COUNTY GROUNDWATER FLOW MODEL; MODIFIED FROM NISWONGER ET AL. (2011).			
Package abbreviation	Package name	Modified for MODFLOW-NWT*	Package Description
NWT	Newton Solver	Yes (new)	Solver; solves finite difference equations in each step of a stress period.
BAS	Basic	No	Program control; specifies the locations of active/inactive cells, and heads in all cells.
OBS	Observation Process	No	Observation inputs, in this case heads (HOB).
GAG	Gage	No	Hydrologic/stress; designates the stream segments and reaches in the model, and allows for streamflow output files after the model is run.
UPW	Upstream Weighting	Yes (new)	Hydrologic/internal; specifies properties controlling flow between cells.
DRN	Drain	No	Hydrologic/stress; simulates head-dependent flux boundaries (head-water streams) by allowing simulated groundwater to exit into drain cells.
GHB	General-Head Boundary	No	Hydrologic/stress; simulates head-dependent flux boundaries, lakes/reservoirs.
RCH	Recharge	No	Hydrologic/stress; simulates specified flux distributed atop the model, multiplied by the horizontal area of the cells to calculate the volumetric flux rates. From DPM/PRMS models.
SFR	Streamflow Routing	Yes	Hydrologic/stress; simulates and routes streamflow through the model.
WEL	Well	Yes	Hydrologic/stress; simulates specified flux to individual cells; well recharge.

*Packages are compatible with MODFLOW-2005, and were used in the YRB-GFM, except for those labeled “Yes (new)”.

The upstream weighting approach is shown in this equation for the intercell conductance term (Niswonger et al., 2011),

$$\frac{b_{up}\, K_{ave} w}{L}, \qquad \textbf{Equation 2-7}$$

where: b_{up} is the upstream saturated thickness, K_{ave} is the average hydraulic conductivity between cells during model initialization, w is the width of the cell interface, and L is the length of the flow path.

The horizontal row conductance between cells i,j–1,k and i,j,k when upstream weighting is applied is calculated as:

$$CR_{i,j-\frac{1}{,k}} = \Delta C \frac{K_{ave}}{\Delta R_{j-1}} \left[h_{up} - BOT_{up}\right] \qquad \textbf{Equation 2-8}$$

where: b_{up} has been replaced by $[h_{up} – BOT_{up}]$; h_{up} is the maximum head of either $h_{i,j,k}$ and $h_{i,j-1,k}$; ΔR_{j-1} is the distance between the center of cells *i,j*–1,*k* and *i,j,k*; ΔC_i is the column width for cell *i,j,k*; and BOT_{up} is the cell bottom altitude corresponding to h_{up}. Additionally, if h_{up} is greater than TOP_{up} (the cell top altitude corresponding to h_{up}), then the horizontal row conductance is calculated for confined conditions as:

$$CR_{i,j-1/,k} = \Delta C \frac{K_{ave}}{\Delta R_{j-1}} \left[TOP_{up} - BOT_{up}\right] \qquad \textbf{Equation 2-9}$$

If h_{up} is less than BOT_{up} then the horizontal row conductance is calculated as:

$$CR_{i,j-1/,k} = 0. \qquad \textbf{Equation 2-10}$$

As previously stated, dry cells are not set to a no flow condition in the UPW Package, as they are in the BCF, LPF, and HUF Packages. Following the groundwater flow equation, if a cell is dry (head is below cell bottom) and overlies a saturated cell, horizontal conductance will equal zero, and the head in the dry cell can be calculated from the flow into the dry cell in the following manner:

$$Q_{i,j,K+1/2} = Q^{in}_{i.j.k}, \qquad \textbf{Equation 2-11}$$

$$Q_{i,j,K+1/2} = CV_{i,j,k+1/2}\left(h_{i,j,k+1} - h_{i,j,k}\right), \qquad \textbf{Equation 2-12}$$

$$h_{i,j,k} = \frac{Q_{i,j,k}^{in}}{CV_{i,j,k+1/2}} + h_{i,j,k+1},$$ **Equation 2-13**

where: $Q_{i,j,k}^{in}$ is the sum of inflow to cell i,j,k from adjacent cells or from an external source, and $CV_{i,j,k+1/2}$ is the conductance between nodes i,j,k and i,j,k+1 (Nisonger et al., 2011).

2.4 Description of the Upper Kittitas County Groundwater Flow Model

2.4.1 Spatial and Temporal Discretization

MODFLOW requires a groundwater system be divided (discretized) into rows, columns, and layers which subdivide the system into a three dimensional grid of blocks, called cells. The UKC-GFM is a refinement of the previous USGS YRB-GFM (Ely et al., 2011). The UKC-GFM consists of 600 columns, 600 rows, 1,000 feet cell sides (widths), and 24 model layers. The UKC-GFM has 246 columns and 195 rows, 1,000 feet cell sides, and five model layers (Fig. 2-2). The UKC-GFM is coincident with the northwest corner of the USGS YRB-GFM.

There are 239,850 cells in the UKC-GFM, with 53,782 active cells. The active cells include an area of 862 mi^2 and constitute 365 mi^3 of aquifer-system material. Total model domain thickness ranged from 1,740 to 7,910 feet, with a mean of 3,620 feet. Mean layer thickness, minimum thicknesses, and maximum thicknesses for each of the layers are displayed in Table 2-2. The model extends to a constant depth (elevation) of 500 feet above sea level, a depth that makes it possible to assess the impacts of pumping from deep bedrock aquifers.

The model was subdivided into five layers (Table 2-3, Fig. 2-4). The three upper layers, layers 1 through 3, represent three hydrogeologic units comprised of basin-fill sediments. Layer 4 represents the upper 100 feet of basalt and bedrock and is zoned, with one zone representing exposed bedrock and the other zone representing bedrock beneath the sediments. Layer 5 represents the remaining basalt and bedrock, zoned to reflect hydraulic properties for five hydrogeologic units (Fig. 2-4) based on the simplified surficial geologic map of Upper Kittitas County (Fig. 1-10), with uniform boundaries to depth. For discontinuous units within the model domain (in this case, the first three units of basin-fill), model Layers 2 or 3 have a one foot thickness and are assigned the hydraulic property of hydrogeologic Unit 1. All model layers were simulated as convertible (variable transmissivity based on head in the cell) except for Layer 5, which is confined.

While the UKC-GFM has vertical uniform boundaries to depth, a recent hydrogeologic framework for Upper Kittitas County (Gendaszek et al., 2014) used well log information to develop cross sections which display lithologic boundaries for hydrogeologic units in the subsurface (Fig. 2-3); cross sections in Figure 2-3 correspond to cross section lines in Figure 1-5. Although beyond the scope of this report, future work could combine the UKC-GFM with the newly delineated aquifer boundaries to better constrain and model subsurface materials. Additional model properties that were beyond the scope of this report and therefore were not incorporated into the UKC-GFM include the simulation of hydrologic (or horizontal) flow barriers such as faults, fractures, and folds, which all exist in the study area. Caine et al. (1996) states that structures like

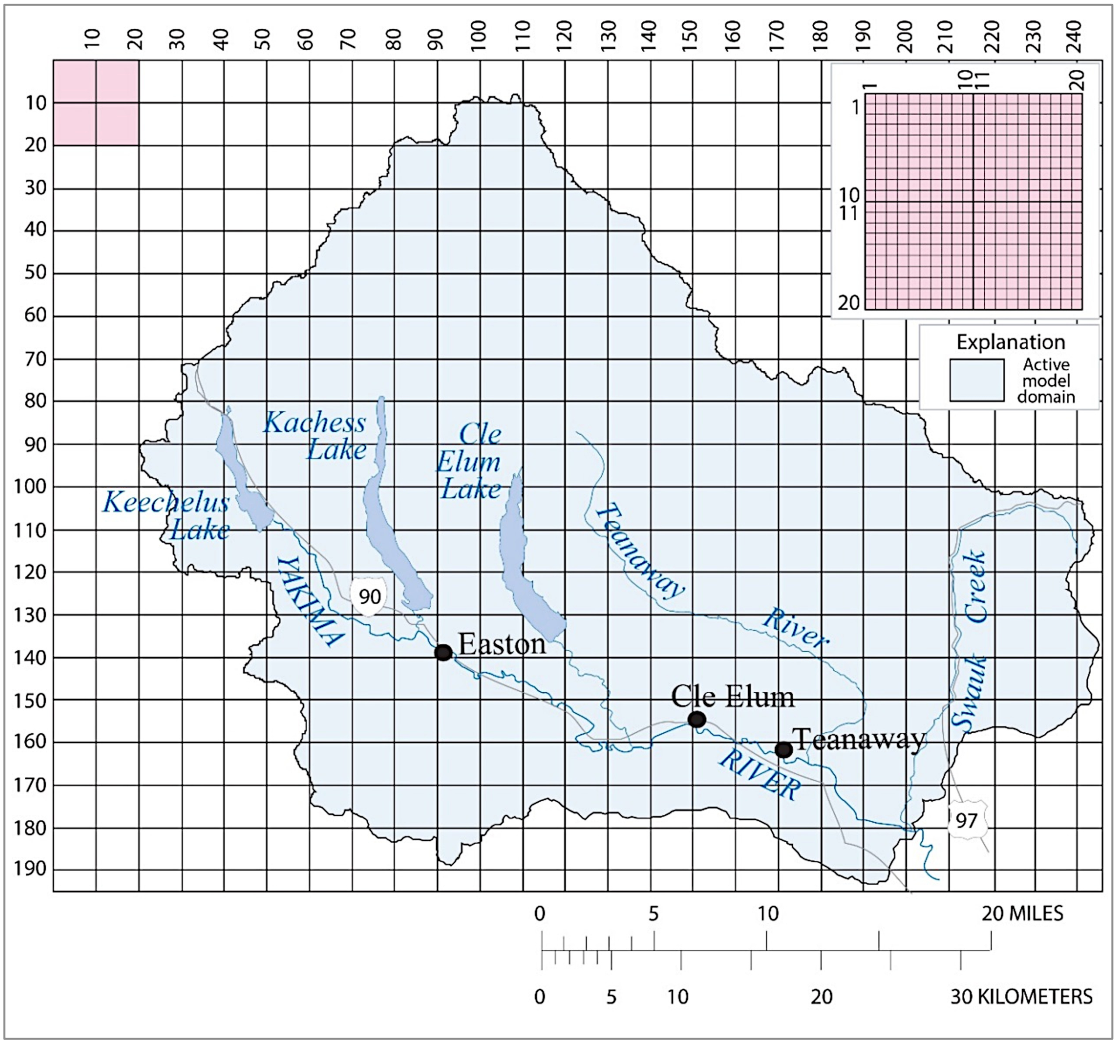


Figure 2-2. Location and extent of the UKC-GFM grid. The red insert depicts the detailed horizontal discretization for the first 20 rows and columns of the grid.

TABLE 2-2. DESCRIPTIVE STATISTICS FOR THE THICKNESS OF GROUNDWATER-MODEL LAYERS, UPPER KITTITAS COUNTY, WASHINGTON.

Model layer	Mean layer thickness (ft)	Percent of total model thickness, using mean layer and model thicknesses	Minimum layer thickness (ft)	Maximum layer thickness (ft)
1	81	2.58	15	325
2	155	4.97	5	487
3	50	1.60	5	224
4	20	0.64	20	20
5	3,090	99.0	685	7,392

TABLE 2-3. MODEL LAYERS IDENTIFIED AND USED IN THE UPPER KITTITAS COUNTY GROUNDWATER FLOW MODEL.	
Hydrogeologic unit	Model layer
1. Basin-fill – Unit 1, coarse grained	1
2. Basin-fill – Unit 2, clay	2
3. Basin-fill – Unit 3, productive gravel	3
4. Bedrock – CRBG and interbeds	4, 5
5. Bedrock – Volcanic unit	4, 5
6. Bedrock – Intrusive unit	
7. Bedrock – Sedimentary unit	
8. Bedrock – Metamorphic unit	

faults and fractures can act as either barriers or conduits to fluid flow. Gendaszek et al. (2014) found that, in Upper Kittitas County, groundwater flows through unconsolidated basin fill sediments via pore space, while groundwater flows through bedrock units via fractures and secondary porosity. A method of determining properties such as fault locations is to observe continuous simulated differences in groundwater elevations on two sides of a linear path, to use this information to estimate the hydraulic conductance along the faults, and then to simulate these faults by inserting horizontal flow barriers (HFB) into the model through use of the MODFLOW HFB package (Hsieh and Freckleton, 1993).

The UKC-GFM simulation period extends from October 1, 1992 to September 30, 2001, for a total of 10 water years (water years 1992 through 2001). This means that the model has 120 monthly stress periods for the 10 year model, with transient data for specified stresses. These transient stresses include previously calculated monthly recharge data from Precipitation-Runoff Modeling System (PRMS) and Deep Percolation Model (DPM) (Vaccaro and Olsen, 2007), as well as monthly data for pumpage (DOE and USGS), reservoirs (Reclamation), and diversions and returns (Reclamation). The

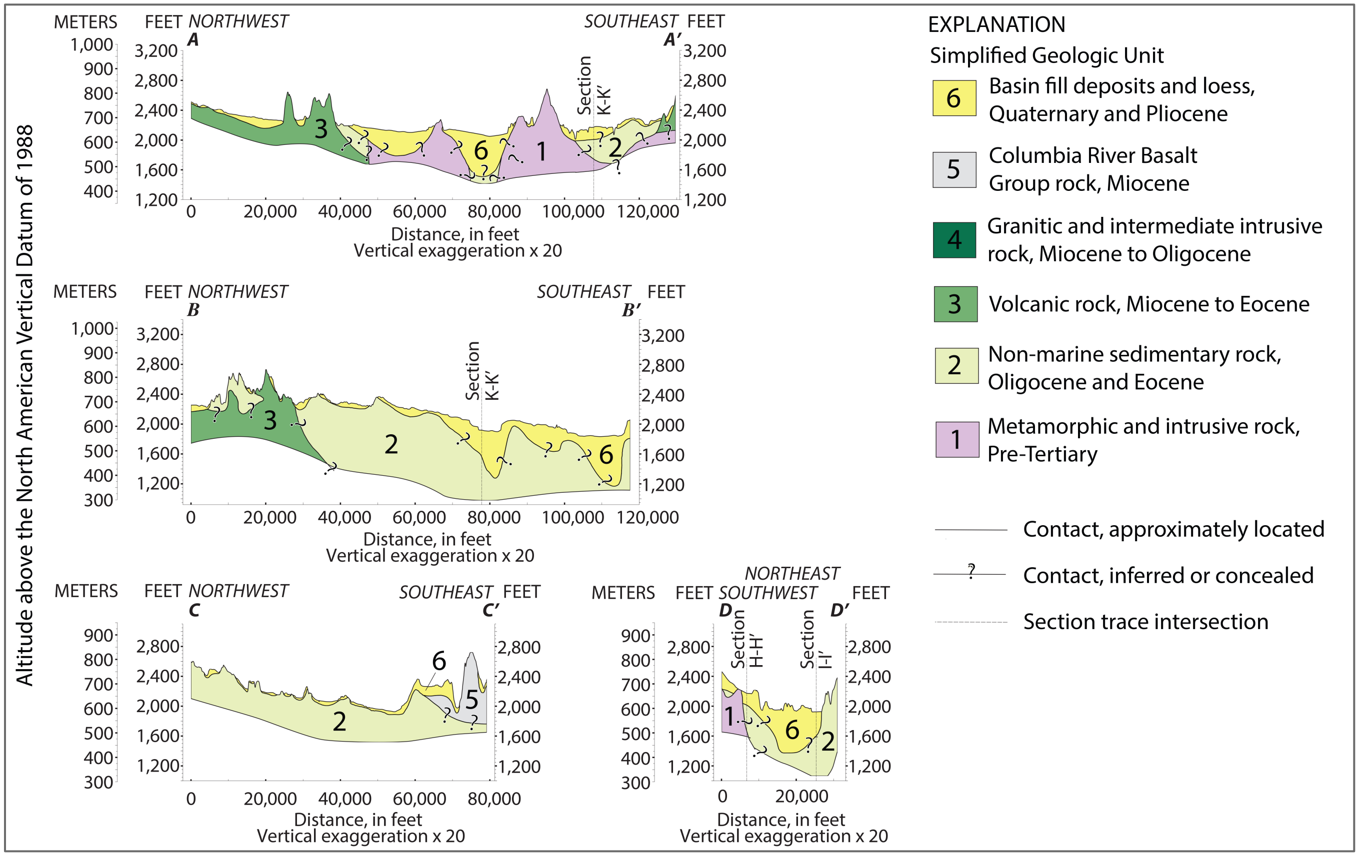


Figure 2-3. Cross sections for simplified geologic units in Upper Kittitas County, Washington. Modified from Gendaszek et al. (2014).

model runs on daily time steps. The 10 year simulation period allows for changes in pumping and climatic conditions and, thus, the potential for large ranges in simulated streamflow and groundwater recharge.

2.4.2 Model Hydrogeologic Framework

The original YRB-GFM (Ely et al., 2011) identified five hydrogeologic units within Upper Kittitas County: hydrogeologic Units 1 through 3 were part of a greater basin-fill unit, with the remaining hydrogeologic units being Unit 4, the CRBG and its interbeds, and Unit 5, "older bedrock" (Ely et al., 2011). The UKC-GFM includes these units (Table 2-3), and expands upon them to add more detail to the bedrock via model zoning methods. The UKC-GFM bedrock zones allow for variable hydraulic parameters, assigned to model cells using the UPW package, and refined during model calibration. Initial and final parameter values are discussed in more detail in Sections 2.4.5 and 2.5.3 of this report.

All hydrogeologic units identified and incorporated into the UKC-GFM include 11 distinct units, again based upon the simplified surficial geologic map of Upper Kittitas County (Fig. 1-10, Fig. 2-4, Table 2-3; Table 2-4), with some additional units.

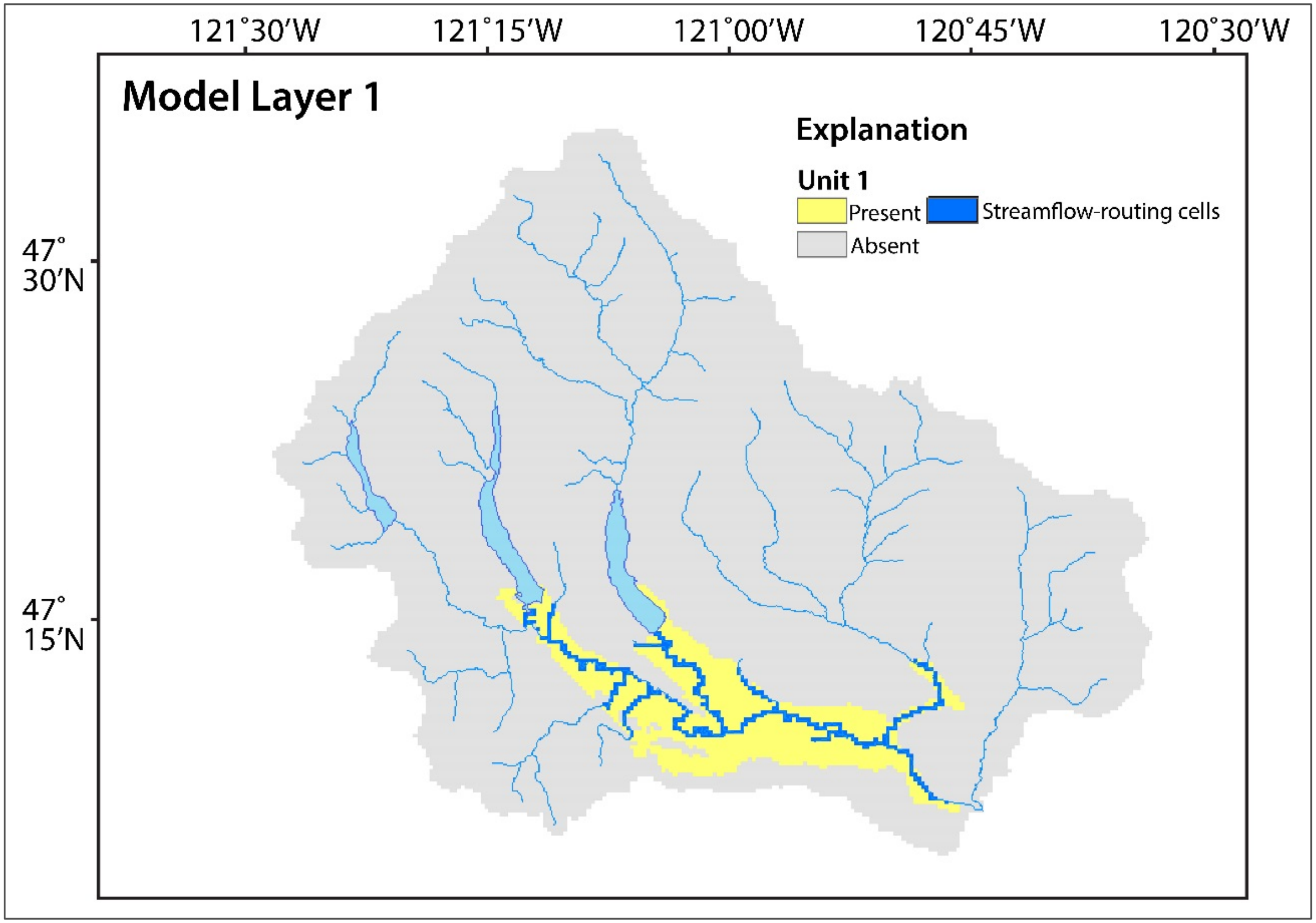


Figure 2-4. Areal extents of model layers and locations of streamflow routing, general head cells, and drain cells in Upper Kittitas County groundwater flow model.

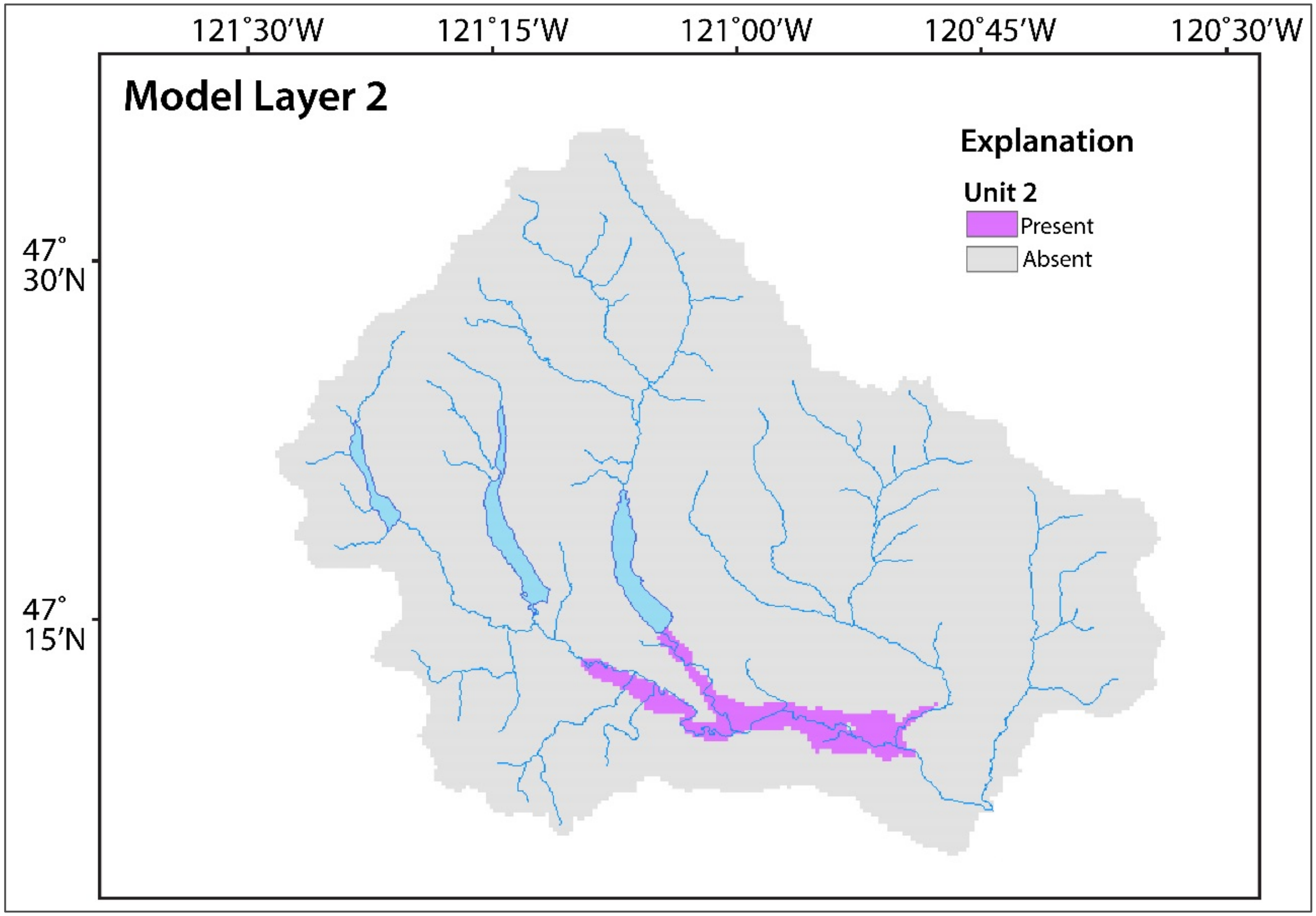


Figure 2-4, continued. Areal extents of model layers and locations of streamflow routing, general head cells, and drain cells in Upper Kittitas County groundwater flow model.

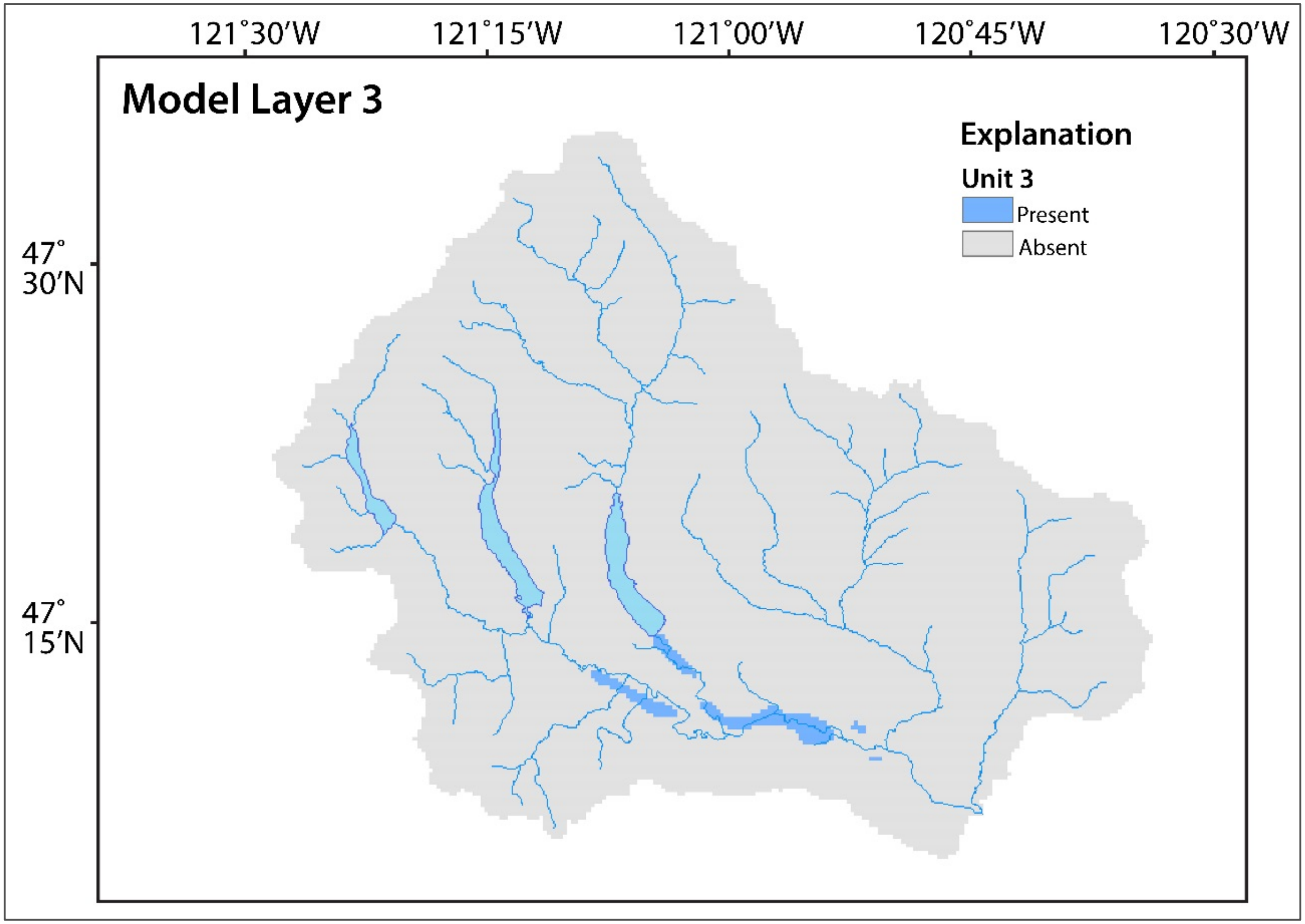


Figure 2-4, continued. Areal extents of model layers and locations of streamflow routing, general head cells, and drain cells in Upper Kittitas County groundwater flow model.

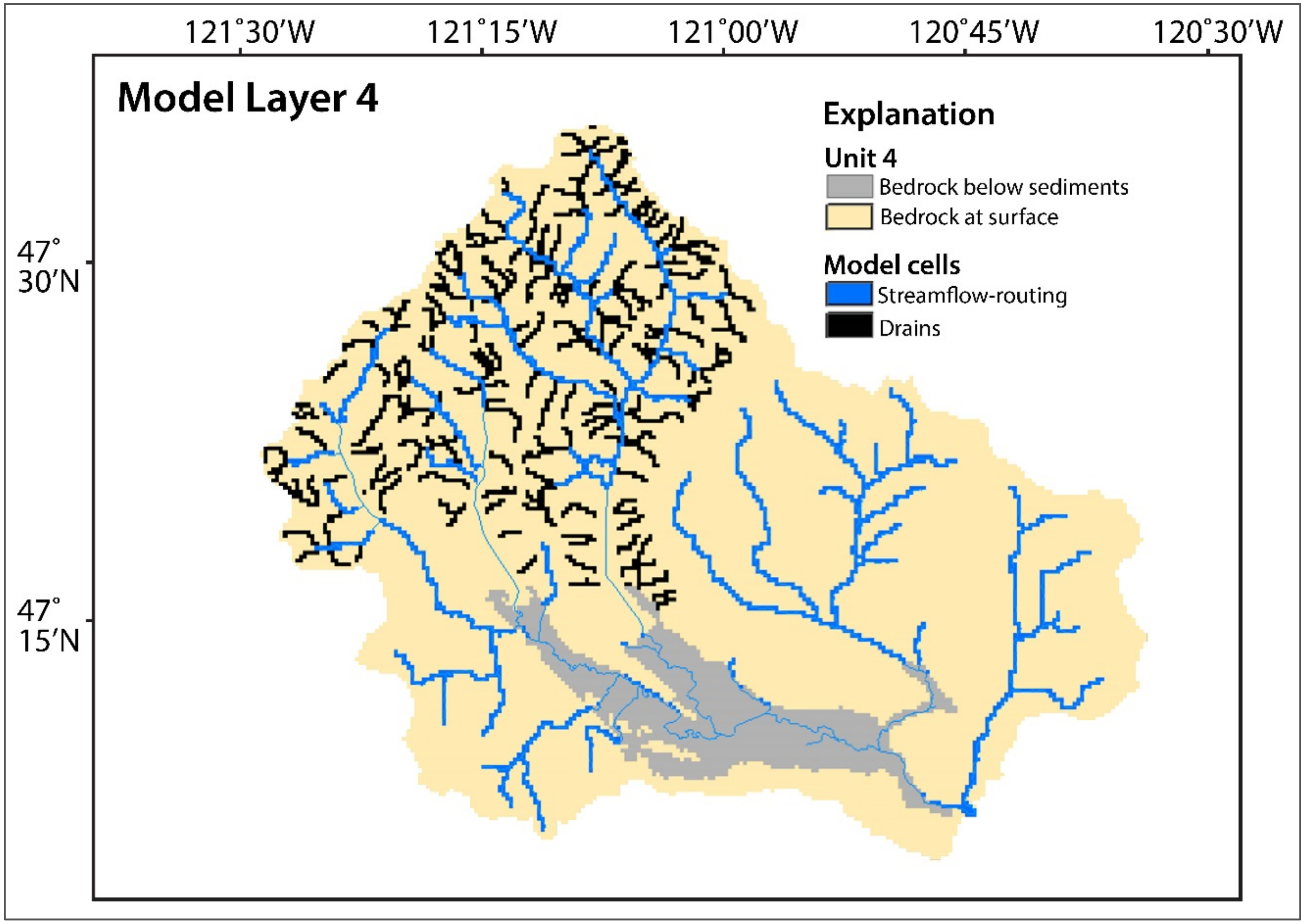


Figure 2-4, continued. Areal extents of model layers and locations of streamflow routing, general head cells, and drain cells in Upper Kittitas County groundwater flow model.

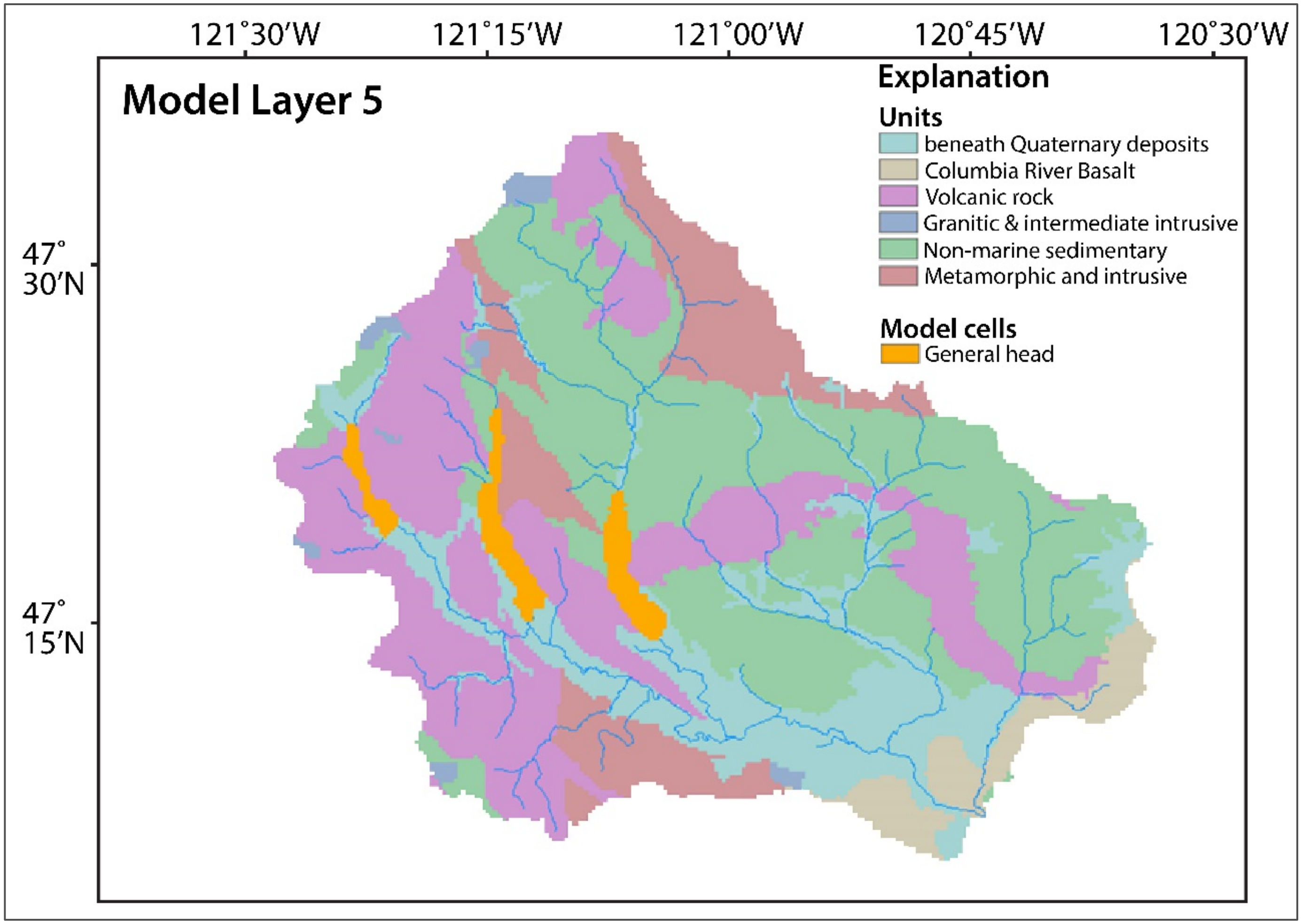


Figure 2-4, continued. Areal extents of model layers and locations of streamflow routing, general head cells, and drain cells in Upper Kittitas County groundwater flow model.

TABLE 2-4. CORRELATION OF SIMPLIFIED GEOLOGY IN UPPER KITTITAS COUNTY TO MODELED HYDROGEOLOGIC UNITS IN THE UKC-GFM.	
Hydrogeologic Unit	Simplified Geologic Unit Groups
Unit 1 Basin-fill: Upper coarse-grained (gravel and sand) Unit 2 Basin-fill: Middle fine-grained (silt and clay) Unit 3 Basin-fill: Lower coarse-grained (gravel)	Group 6 Basin-fill deposits and loess, Quaternary
Unit 4 Bedrock: At the surface (≤ 100 ft deep)	Groups 5 through 1
Unit 5 Bedrock: Under basin-fill (≤ 100 ft deep)	Groups 5 through 1
Unit 6 Bedrock: Beneath Quaternary deposits	no group
Unit 7 Bedrock: Grande Ronde Basalt and interbeds	Group 5 Columbia River Basalt Group Rock, Miocene
Unit 8 Bedrock: Intrusive unit	Group 4 Granitic and intermediate intrusive rock, Miocene to Oligocene
Unit 9 Bedrock: Volcanic unit	Group 3 Volcanic rock, Miocene to Eocene
Unit 10 Bedrock: Sedimentary unit	Group 2 Non-marine sedimentary rock, Oligocene to Eocene
Unit 11 Bedrock: Metamorphic unit	Group 1 Metamorphic and intrusive rock, Pre-Tertiary

One unit is the Quaternary unconsolidated unit, or basin-fill, covering about 27 percent (229.4 mi^2) of the study area (Gendaszek et al., 2014) and reaching depths of 700 ft (Jones et al., 2006). Quaternary hydrogeologic units of the UKC-GFM correspond to *group 6 basin-fill deposits and loess from the Quaternary period*. Most basin-fill units are concentrated in the Roslyn Basin, which is one of six structural basins in the Yakima River Basin (Jones et al., 2006), and is located in southern Upper Kittitas County. There are three subunits that make up the Quaternary unconsolidated sediment. Each unit is separated in the UKC-GFM and the YRB-GFM as three distinct hydrogeologic units in the first three model layers: Unit 1) an upper coarse-grained (gravel and sand) aquifer with a median thickness of 80 ft; Unit 2) a middle fine-grained (silt and clay) and low productivity unit with a median thickness of 170 ft, and Unit 3) a lower coarse-grained productive (gravel) aquifer with a median thickness of 50 ft (Fig. 2-4; Table 2-3; Table 2-4) (Gendaszek et al., 2014). Units containing combinations of sand and gravel are associated with horizontal hydraulic conductivities ranging from 1 to 1,000 ft/day, units containing silt and clay may range between 0.001 to 1 ft/day, and units containing predominantly gravel may yield hydraulic conductivities again ranging from 1 to 1,000 ft/day, or greater (Bear, 1972; Heath, 1983). These values were considered when assigning initial hydraulic properties (Sections 2.4.5 and 2.5.3) to model hydrogeologic units, and many hydraulic properties for basin-fill were taken from the YRB-GFM, although some were slightly adjusted.

The remaining units encompass the bedrock hydrogeologic units in Upper Kittitas County (Fig. 1-10, Fig. 2-4, Table 2-3; Table 2-4). The basalt unit, unit 4, includes basalt and sedimentary interbeds, and occurs at land surface over about three percent (24.6 mi^2) of the study area in the southeast portion only. Heath (1983) provides a range of hydraulic conductivities for basalt as low as about 10^{-7} when unfractured, about 10^{-2} ft/day when fractured, and up to 10^{3} ft/day for a "lava flow." Final calibrated model hydraulic values in the YRB-GFM for horizontal hydraulic conductivities in the Grande Ronde basalt ranged from 4.28 to 90.97 ft/day, mean of 22.99 ft/day, in the interflow zones, and from 7.61E-05 to 1.54E-03 ft/day, mean of 3.59E-04 ft/day in the flow interiors (Ely et al., 2011).

In the YRB-GFM, the remaining bedrock hydrogeologic units were assigned a constant horizontal hydraulic conductivity of 24.88 ft/day for the upper 10 feet of bedrock (YRB-GFM HGU 47), and all remaining bedrock hydrogeologic units were undifferentiated (YRB-GFM HGU 48) and assigned horizontal hydraulic conductivity values ranging from a minimum of 0.01 ft/day, a maximum of 1.09 ft/day, and a mean of 0.03 ft/day (Ely et al., 2011). Heath (1983) provides a range of hydraulic conductivities of about 10^{-8} ft/d for unfractured shale, to 10^{-3} ft/d for fractured shale; ranges of 10^{-4} ft/d for fractured sandstone, to 1 ft/d for semiconsolidated sandstone; and ranges of 10^{-8} ft/d for unfractured igneous and metamorphic rocks, to 10 ft/d for fractured igneous and metamorphic rocks. The volcanic unit, unit 5, occurs at land surface over about 27 percent (231.3 mi^2) of the study area including most of the highlands west of Cle Elum Lake and in a band in the central part of the study area including Teanaway Ridge (Fig. 1-10, Fig. 2-4, Table 2-3; Table 2-4). The intrusive unit, unit 6, occurs at land surface over about only five percent (45.4 mi^2) of the study area mostly in the Wenatchee Mountains and in very limited occurrences along the westernmost margin of the study area. The sedimentary unit, unit 7, occurs at land surface over about 34 percent (290.9 mi^2) of the study area including most of the northeast part of the basin. The metamorphic unit, Unit 8, occurs at land surface over only about four percent (38.4 mi^2) of the study area in a northwest trending band in the west central part of the basin (Gendaszek et al., 2014).

2.4.3 Model Boundary Conditions

Three types of model boundaries are used in the UKC-GFM to simulate water entering and exiting the aquifer system. These model boundaries are: (1) no flow boundaries (groundwater divides), (2) head dependent flux boundaries (streams, drains, general head (reservoirs)), and (3) specified flux boundaries (pumpage and recharge, streamflow [diversions and returns], and general head). The following section describes the simulation of boundaries in the UKC-GFM.

2.4.3-1 No Flow Boundaries

Topographic highs define the UKC-GFM perimeter, and are simulated as no flow boundaries because they coincide with groundwater divides. The base of the groundwater system, beneath the bedrock, is also simulated as a no flow boundary. In MODFLOW no flow boundaries occur at cells where no water is permitted to flow into or out of the cells.

2.4.3-2 Head-Dependent Flux Boundaries

2.4.3-2a Streamflow Cells.

The Yakima River and its major tributaries within Upper Kittitas County were simulated using the MODFLOW Streamflow-Routing (SFR2) package (Niswonger and Prudic, 2005) to route streamflow (Fig. 2-5). The UKC-GFM has 105 SFR2 segments and 2,248 reaches (cells), compared to the YRB-GFM which has 250 SFR2 segments and 8,533 reaches, of which 25 SFR2 segments and 670 reaches route streamflow in Upper

Kittitas County alone. In the UKC-GFM, each SFR2 segment is composed of multiple reaches, with each reach length equal to the length of an individual SFR2 cell. Most UKC-GFM SFR2 coverage was extended further into the smaller headland creeks than in the previous YRB-GFM because these reaches had been less detailed as per the scope of the YRB-USGS (Fig. 2-5).

Groundwater-surface water interaction is controlled by the differences between groundwater levels and stream stages, which is what makes streamflow-routing cells head-dependent flux boundaries. In the UKC-GFM, stream stages for the Yakima River, its major tributaries, and some smaller headwater tributaries were determined using the USGS 1-m DEM at various locations along the streams, and stages were linearly interpolated between these locations. The altitude of the top of the streambed was calculated as the DEM elevation minus the stream depth.

The SFR2 package for MODFLOW allows streamflow to route through an SFR2 cell with channel dimensions. As in the YRB-GFM (Ely et al. 2011), the relation between stage and discharge for the UKC-GFM was calculated using Manning's equation,

$$V = \frac{1.49\, R^{2/3} S^{1/2}}{n}, \qquad \textbf{Equation 2-14}$$

where: V is the average velocity (ft/s); 1.49 is a conversion factor of $\text{Length}^{1/3}$/Time; R is the hydraulic radius, or the ratio of the cross-sectional area of flow in square feet to the wetted perimeter (ft); S is the energy gradient, which is the slope of the water surface; and n is the Manning roughness coefficient. (Fetter, 2001). For routing

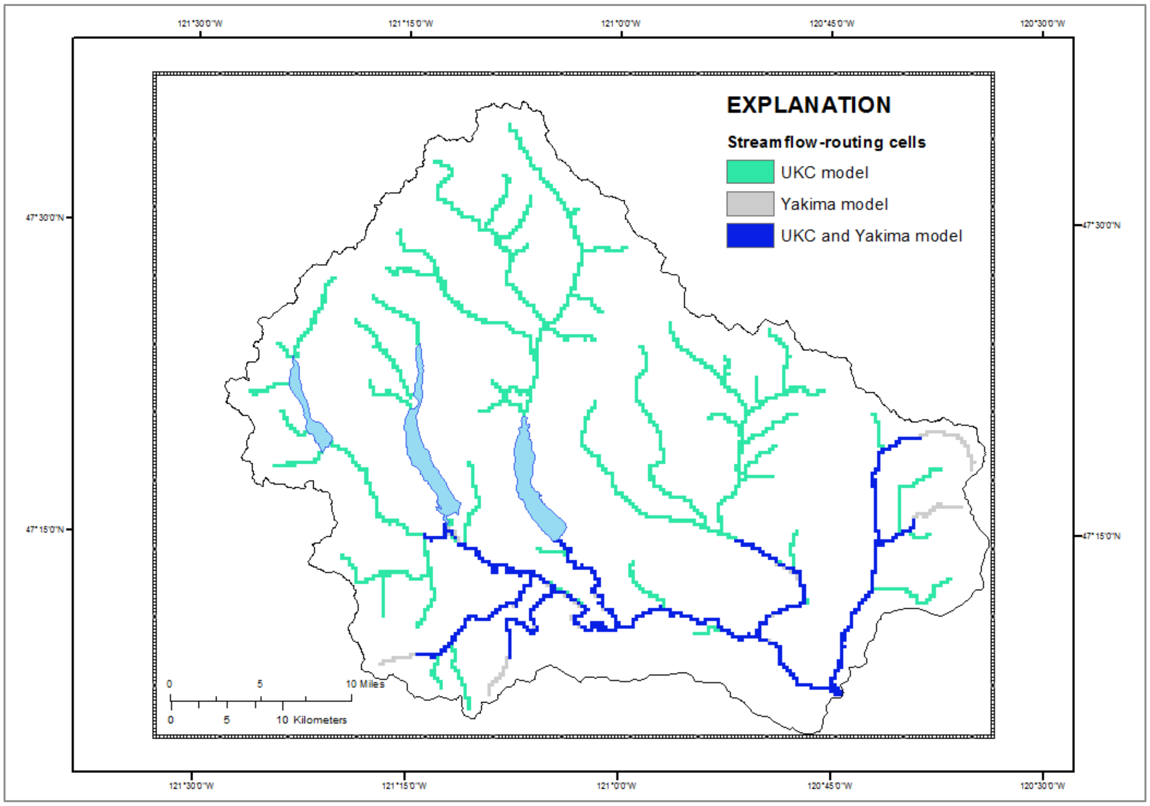


Figure 2-5. Comparison of SFR2 coverage between YRB-USGS (Yakima model) and UKC-GFM.

streamflow, a constant value of 0.04 was used for Manning's coefficient in streams where depth and stage are calculated by the model; 0.04 is the Manning's roughness coefficient value for mountain streams with rocky beds (Fetter, 2001). Stream depths for the Yakima River, its major tributaries, and some smaller headwater tributaries were computed assuming eight-point cross sections (with the second and seventh points along the cross-section equal to total depth (feet) multiplied by .25, and the third through sixth points equal to total depth, giving the stream a flat bottom (Fig. 2-6)). Average depth and width for the cross sections were based on mean annual streamflow from the USGS National Hydrography Dataset (http://nhd.usgs.gov/index.html) and regression equations determined by Magirl and Olsen (2009). The following equation represents the method used to approximate stream geometry:

$$D_h = \frac{A}{W_t}, \qquad \textbf{Equation 2-15}$$

where Dh is equal to the hydraulic depth (mean depth) of the channel in feet; A is equal to the cross-sectional wetted area in feet-squared; and Wt is equal to top width, from discharge measurements. Another variable approximated by Magirl and Olsen (2009) is Wb, the bottom width of the channel; this variable is more complicated to estimate due to irregularities in the surface of the streambed, so it was set at channel width at the hydraulic depth of the cross-section.

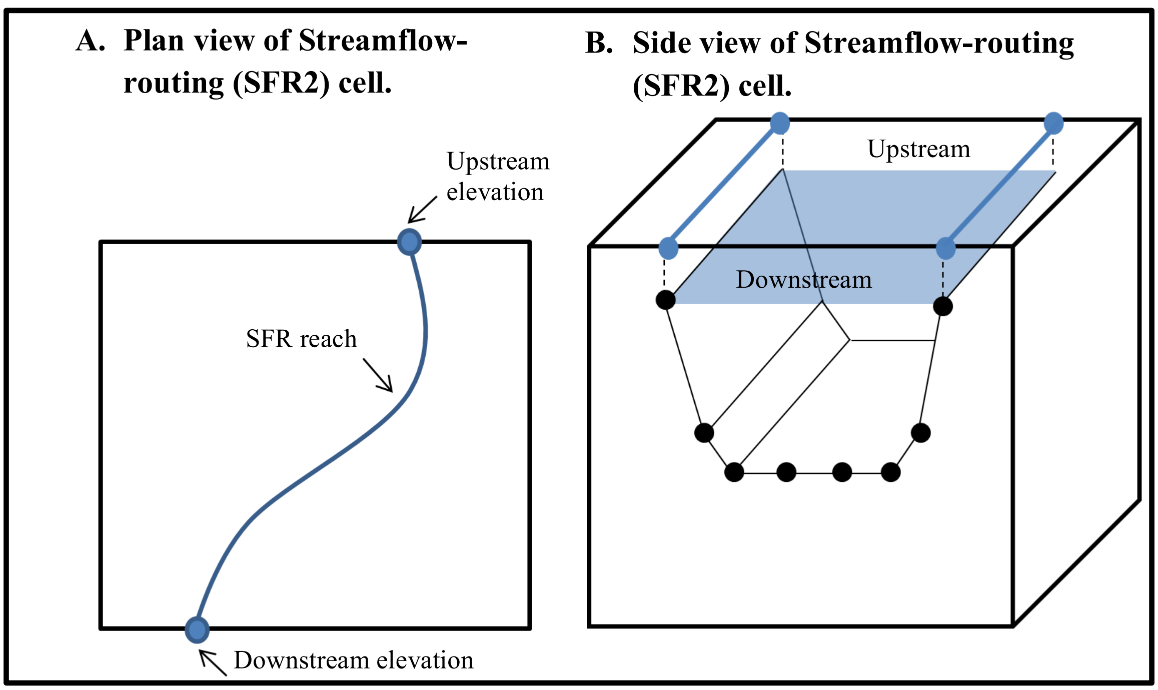


Figure 2-6. Schematic of a Streamflow-routing (SFR2) cell. Figure shows A) the upstream and downstream points used to average the elevation across the reach (each cell), and shows B) a simplified 8-point cross-section for the channel geometry of each reach.

Initial streambed conductance values were based on stream length (determined using GIS) and width (Magirl and Olsen, 2009), estimated streambed hydraulic conductivity, and streambed thickness; streambed thickness was set at 1 ft for all stream reaches. Initial estimates of streambed hydraulic conductivity were based on Hansen et al. (1994) and adjusted during model calibration; for final values, see the Final Parameter Values and Sensitivities section.

The UKC-GFM internally multiplies the hydraulic conductivity value (ft/d) by the stream reach length (ft) and width (ft), divided by the streambed thickness (ft), resulting in the streambed conductance (ft^2/d):

$$\text{Streambed conductance} = (K)(t)(lw). \qquad \textbf{Equation 2-16}$$

2.4.3-2b Drain Cells.

The MODFLOW Drain (DRN) package was used to simulate headwater streams within Upper Kittitas County and other ephemeral and small streams within the model domain that were not included in the SFR coverage (Fig. 2-3). Drain cell spatial extent was decreased from the YRB-GFM to account for the increased SFR coverage. In both the YRB-GFM and UKC-GFM, drains added stability to the model and accounted for the generally gaining (water entering stream cells) headwater reaches. MODFLOW only allows simulated groundwater flow into a drain cell. The amount of water exiting via a drain cell is equal to:

$$QD_n = CD_n \times \left(HD_n - h_{i,j,k}\right) \qquad \textbf{Equation 2-17}$$

where QD is the flow from the aquifer into the drain cell (ft^3/day), CD is the drain conductance (ft^2/day), HD is the drain elevation (f), $h_{i,j,k}$ is the head in the cell containing the drain cell (f), and the subscript n is a drain number (Harbaugh, 2005) shows a simplified plot of this relationship. Note that K is not accounted for in drain cells. The UKC-GFM includes a total of 1,694 drain cells.

2.4.3-2c General-head Boundary.

The MODFLOW general-head boundary (GHB) package was used to simulate reservoir-aquifer exchange for the three reservoirs in the UKC-GFM: Keechelus, Kachess, and Cle Elum (Fig. 2-3). The USGS YRB-GFM uses specified head (reservoir stage) values taken from USGS 1:24,000-scale topographic maps, and keeps the stages steady over the 10 year model period. The UKC-GFM was updated with time variant reservoir stages, with stage values taken from daily records of reservoir stages (Reclamation) over the 10 year model period; daily values were averaged into monthly values and written into the GHB file.

2.4.3-3a Groundwater Pumping

Groundwater pumping in Upper Kittitas County (and the Yakima River Basin) was previously estimated for categories of use for 1992 to 2001 (Fig. 2-7) (Vaccaro and Sumioka, 2006). The eight pumping categories were: (1) irrigation, (2) groundwater claims, (3) self-supplied domestic (permit-exempt wells), (4) public water supply, (5) municipal use, (6) livestock, (7) commercial and industrial, and (8) hatcheries. Pumpage estimates (Fig. 2-8) were based on methods (Vaccaro and Sumioka, 2006; Vaccaro et al.,

2009) that varied by the category and primarily represent pumpage associated with groundwater rights.

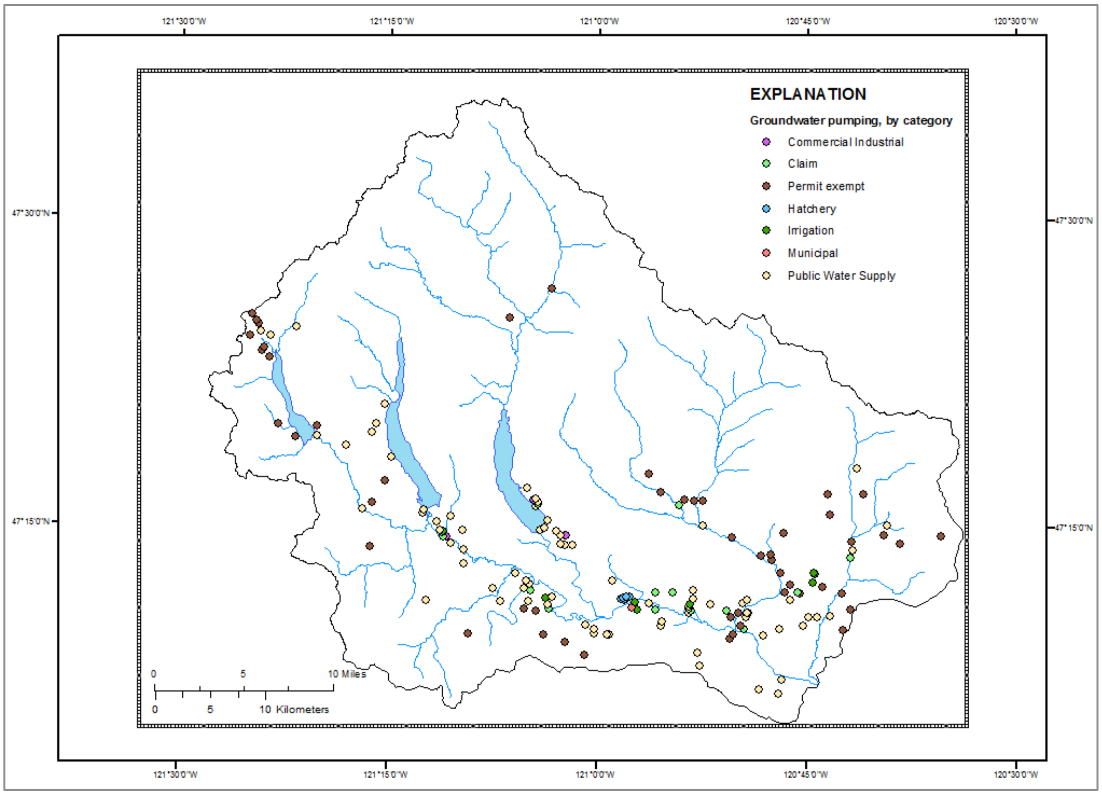


Figure 2-7. Map of pumpage coverage, by category.

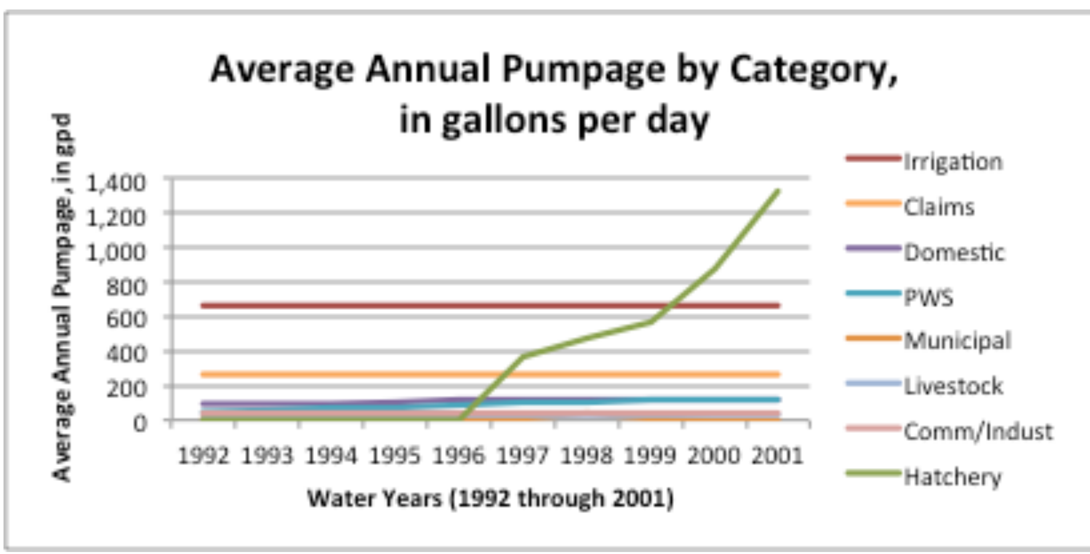


Figure 2-8. Graph of all pumpage entered into the Upper Kittitas County groundwater flow model for water years 1992 through 2001.

2.4.3-3b Groundwater Recharge

Groundwater recharge for Upper Kittitas County was estimated prior to this modeling thesis as part of the YRB-USGS (groundwater study). Two models in the U.S. Geological Survey's Modular Modeling System (Leavesley et al., 1996) were used to estimate recharge: the Precipitation-Runoff Modeling System (PRMS; Leavesley et al., 1983) and the Deep Percolation Model (DPM; Bauer and Vaccaro, 1987; Vaccaro, 2007). Input to the PRMS and DPM models includes topographic characteristics from digital elevation models (DEM); precipitation and air temperatures; soil properties from the State Soil Geographic (STATSGO) database (U. S. Department of Agriculture, 1994); land use and land cover (LULC) from various GIS and other databases; and irrigation application rates for irrigation districts (Kittitas Reclamation District in Upper Kittitas County) (Vaccaro and Olsen, 2007). The PRMS and DPM models "simulate snow accumulation and ablation, plant interception, evapotranspiration, surface runoff, infiltration, water storage in the root or soil zone, and recharge" (Vaccaro and Olsen, 2007, p.9). The Precipitation-Runoff Modeling System was applied to the wetter, forested upland areas, and "estimates were assumed to be the same for predevelopment and current LULC conditions" (Vaccaro and Olsen, 2007, p.9). The Deep Percolation Model was applied to more populated and agricultural areas, and estimated predevelopment and current recharge (Vaccaro and Olsen, 2007). For the PRMS and DPM models, potential recharge was defined as "water leaving the active root zone or, for barren soils, the bottom of the mapped soil column" after accounting for surface runoff and evapotranspiration (Vaccaro et al., 2009, p.38). That rate was then specified

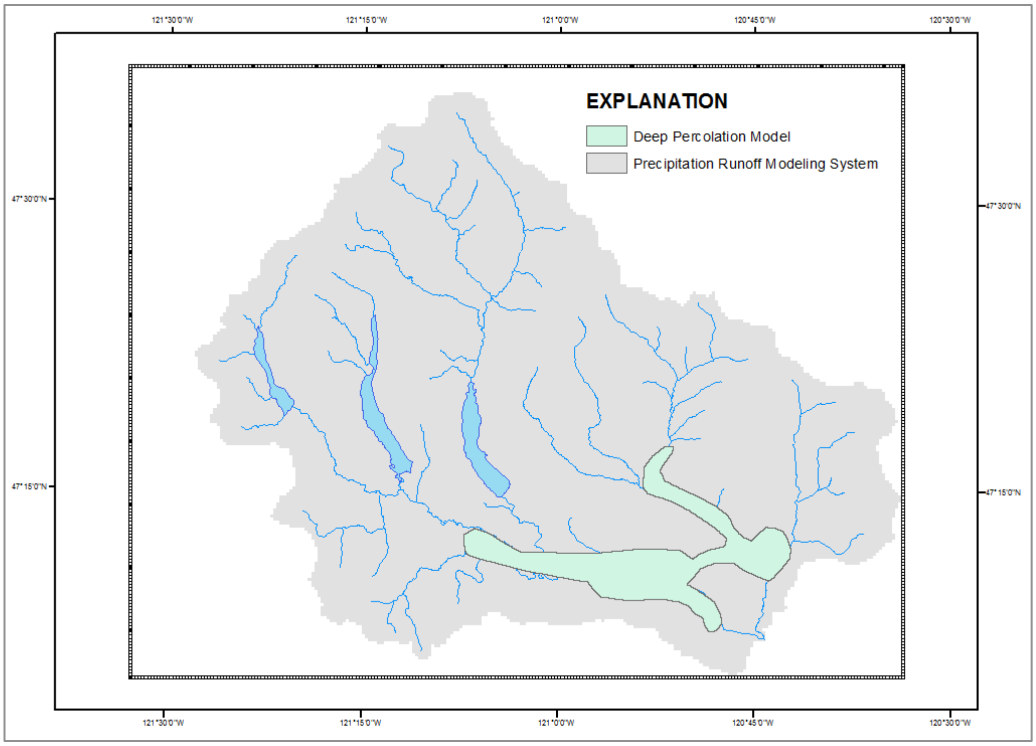


Figure 2-9. Areas modeled to estimate groundwater recharge for current conditions, Upper Kittitas County aquifer system, Washington (from Vaccaro and Olsen, 2007).

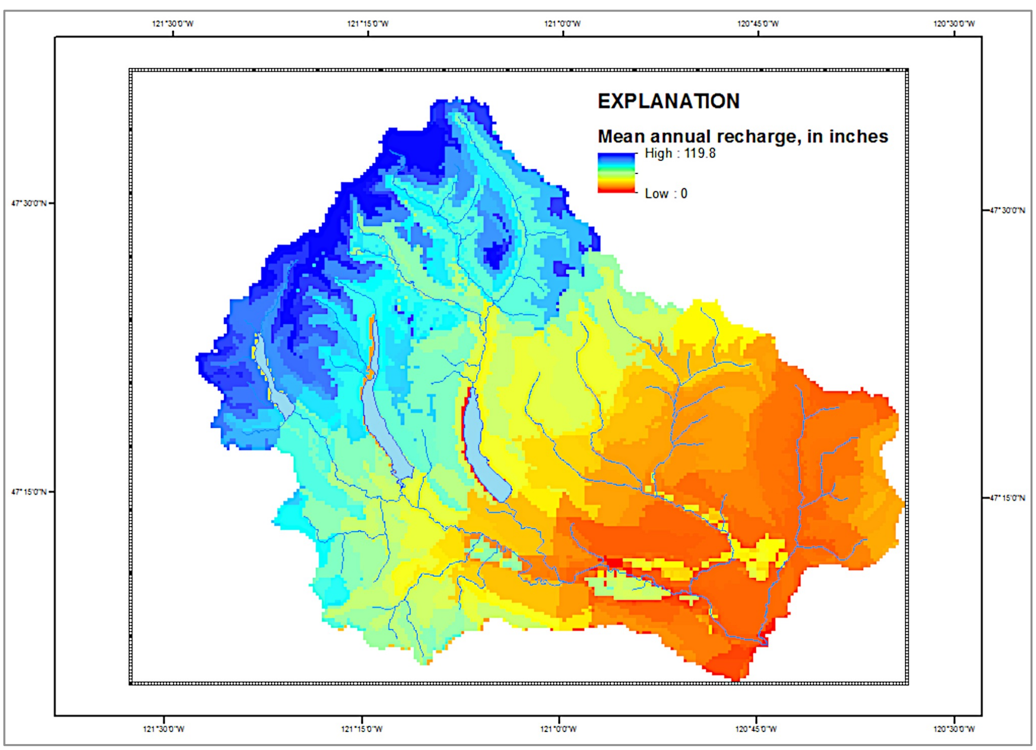


Figure 2-10. Spatial distribution of mean annual recharge for current conditions, 1960–2001, Yakima River basin aquifer system, Washington.

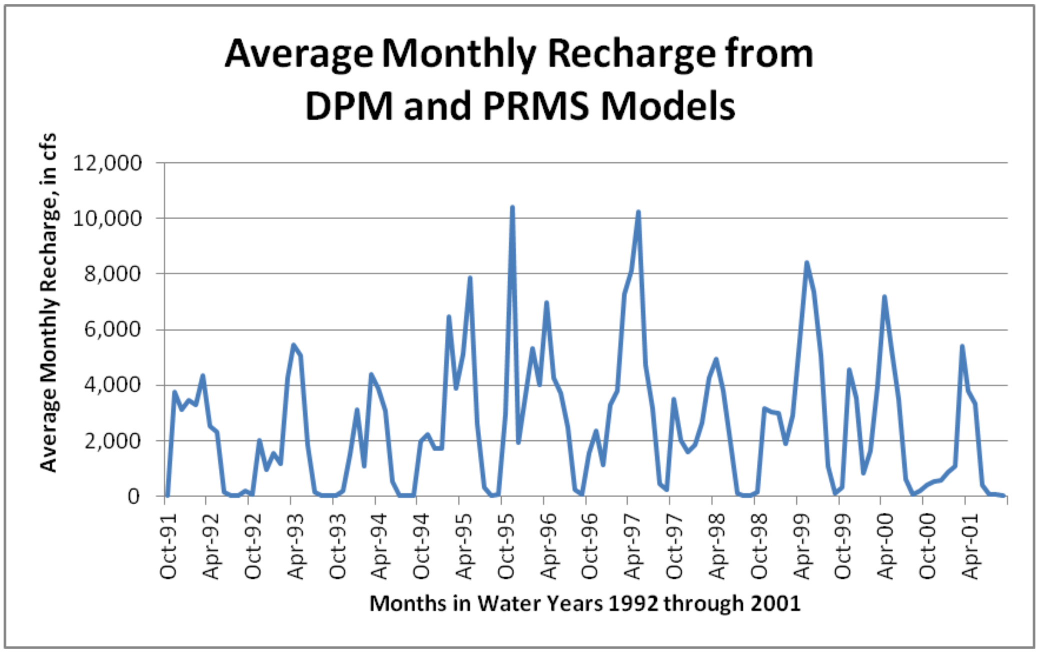


Figure 2-11. Average monthly recharge in Upper Kittitas County, water years 1992 through 2001, determined from PRMS and DPM models.

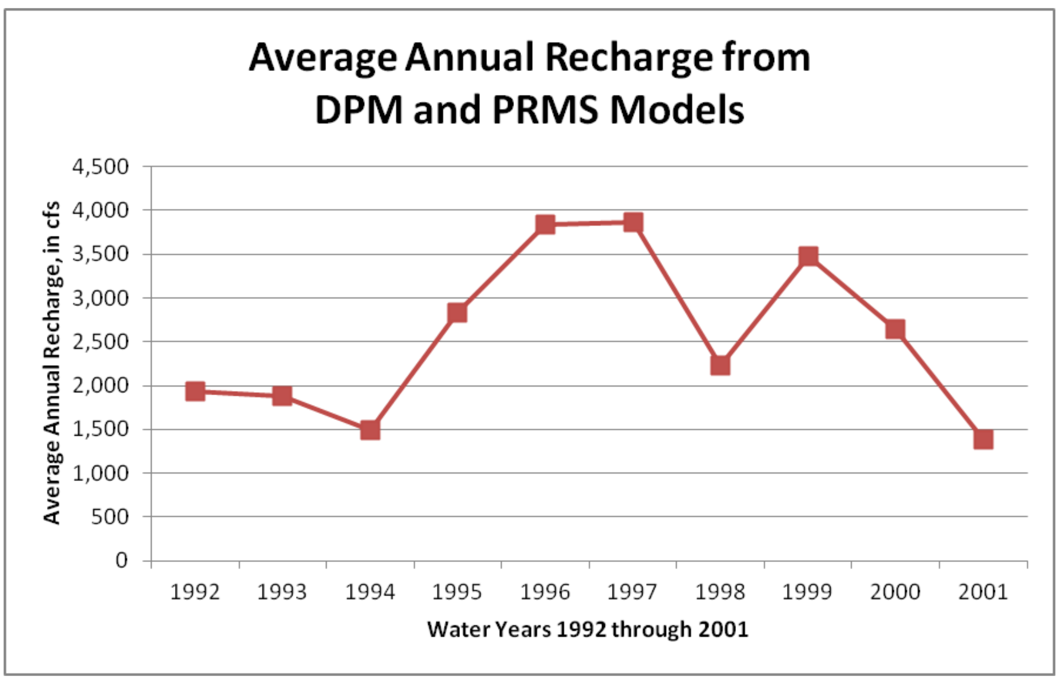


Figure 2-12. Average annual recharge in Upper Kittitas County, water years 1992 through 2001, determined from PRMS and DPM models.

as MODFLOW recharge and applied directly to the highest active model cell (layer 1 or 4).

2.4.3-3c Specified Stream Inflows

Monthly inflow to SFR2 segments for the 120 stress periods was estimated from: (1) measured streamflow, (2) simulated streamflow from watershed models (Mastin and Vaccaro, 2002). With model stability in mind, SFR2 coverage for the USGS Yakima Basin model was limited to the Yakima River and its major tributaries. As previously discussed, most UKC model SFR coverage has been extended further into smaller headland creeks, allowing for new diversion locations, and new streamflow routing through bedrock canyons. Five inflows are based on measured data and were used to calibrate the model; these include: (1) Yakima River near Martin, (2) Kachess River near Easton, (3) Cle Elum River near Roslyn, (4) Yakima River at Cle Elum, and (5) Teanaway River below Forks near Cle Elum. The inflows for smaller tributaries were also simulated, and were calculated from watershed models (Mastin and Vaccaro, 2002); these include: (1) Big Creek, Stream-gaging station, No. 12474001 (gaging stations are points to estimate flow for ungaged stations within the model area; station names and ID numbers were designated by Mastin and Vaccaro, 2002); (2) Cabin Creek, Stream-gaging station, No. 12475001; (3) Little Creek, Stream-gaging station, No. 12477601; (4) Swauk Creek near Cle Elum, Stream-gaging station, No. 12481001; and (5) Teanaway River below Forks, Stream-gaging station, No. 12480000.

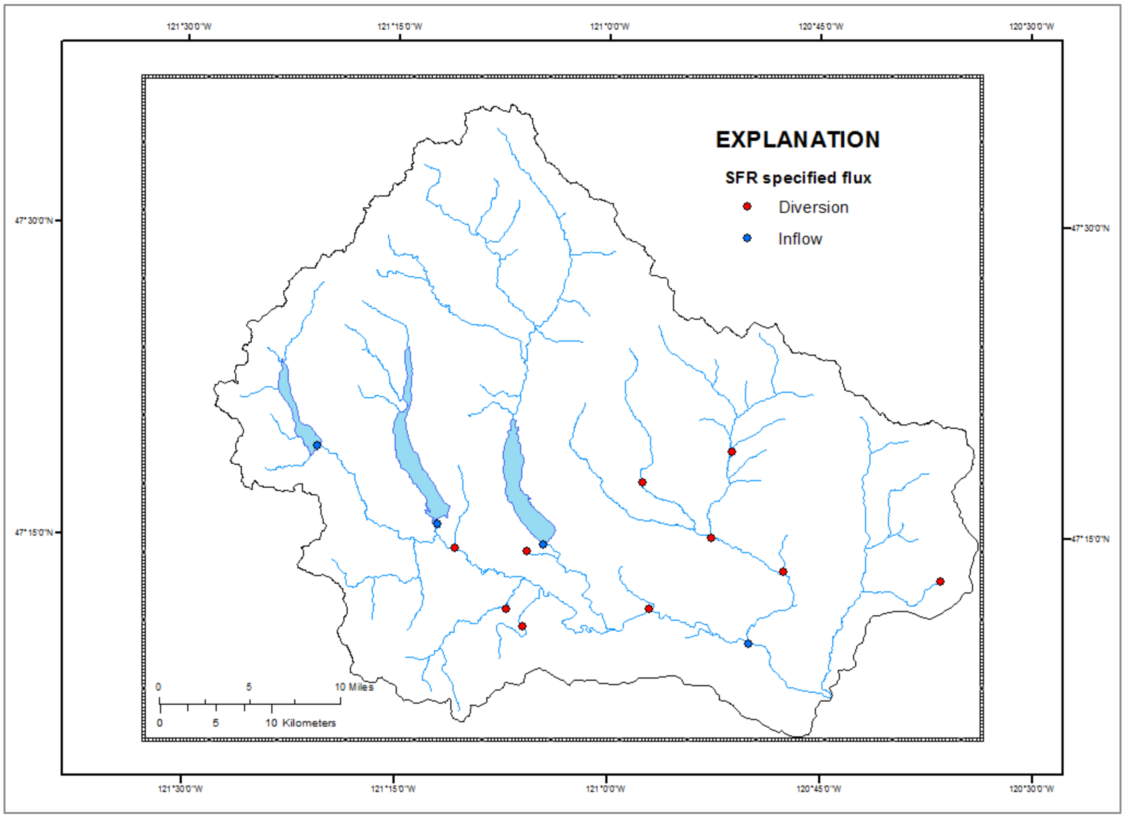


Figure 2-13. Locations of diversions and returns positioned within the Upper Kittitas County model.

2.4.5 Initial Model Hydraulic Properties

The initial hydraulic properties of horizontal hydraulic conductivity (Kx), vertical hydraulic conductivity (Kv), anisotropy (Kx:Kv), specific storage, and specific yield were assigned on the basis of values tabulated from previous studies (Vaccaro et al., 2009; Ely et al., 2011), and compilations of known conductivity values and ranges, i.e., from Heath (1987) and Fetter (2001). Minor adjustments were then made to parameter values to improve model fit. These adjusted values are considered the initial hydraulic properties for calibrating the UKC-GFM.

2.4.5-1 Horizontal Hydraulic Conductivity

Values for modeled hydraulic properties in the UKC-GFM are presented in Table 2-5. In the YRB-GFM (Ely et al., 2011) horizontal isotropy was assumed for the basin-fill sediments, and each model hydrogeologic unit was initially assigned one value for Kx; bedrock was set at one value and considered isotropic and homogeneous. In the UKC-GFM, values for the bedrock were adjusted to reflect mapped spatial variations in bedrock within the study area.

TABLE 2-5. INITIAL HYDRAULIC PROPERTIES FOR ALL MODEL LAYERS IN THE UPPER KITTITAS COUNTY GROUNDWATER MODEL, FOR INPUT DATA INTO THE UPW PACKAGE.

Hydraulic Property	**Value of Hydraulic Property**	**Parameter ID, UKC-GFM**
Conductances		
Drain conductance	500,000	drncnd
Lake (general head boundary) conductance	1.00+E06	ghbcnd
Stream conductance (Yakima River)	0.5	sfrcnd1
Stream conductance (tributaries to Yakima River)	0.1	sfrcnd2
Horizontal Hydraulic Conductivity (ft/d)		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	100	kx101
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	1	kx201
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	40	kx301
Layer 4 – Bedrock: At the surface (≤ 100 ft deep)	50	kx401
Layer 4 – Bedrock: Under basin-fill (≤ 100 ft deep)	5	kx402
Layer 5 – Bedrock: Beneath Quaternary deposits	1	kx501
Layer 5 – Bedrock: Grande Ronde Basalt and interbeds	10	kx504
Layer 5 – Bedrock: Volcanic unit	1	kx505
Layer 5 – Bedrock: Intrusive unit	0.5	kx506
Layer 5 – Bedrock: Sedimentary unit	1	kx507
Layer 5 – Bedrock: Metamorphic unit	1	kx509
Vertical Anisotropy, unitless (Vertical Hydraulic Conductivity in Parentheses, ft/d)		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	10 (10 ft/d)	kv111
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	160 (0.006 ft/d)	kv211
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	135 (0.296 ft/d)	kv311

TABLE 2-5, CONTINUED. INITIAL HYDRAULIC PROPERTIES FOR ALL MODEL LAYERS IN THE UPPER KITTITAS COUNTY GROUNDWATER MODEL, FOR INPUT DATA INTO THE UPW PACKAGE.		
Hydraulic Property	**Value of Hydraulic Property**	**Parameter ID, UKC-GFM**
Layer 4 – Bedrock: At the surface (-411) (≤ 100 ft deep)	1000 (0.05 ft/d)	kv411
Layer 4 – Bedrock: Under basin-fill (-412) (≤ 100 ft deep)	100 (0.05 ft/d)	kv412
Layer 5 – Bedrock: Beneath Quaternary deposits	10 (0.1 ft/d)	kv511
Layer 5 – Bedrock: Grande Ronde Basalt and interbeds	10 (1 ft/d)	kv511
Layer 5 – Bedrock: Volcanic unit	10 (0.1 ft/d)	kv511
Layer 5 – Bedrock: Intrusive unit	10 (0.05 ft/d)	kv511
Layer 5 – Bedrock: Sedimentary unit	10 (0.1 ft/d)	kv511
Layer 5 – Bedrock: Metamorphic unit	10 (0.1 ft/d)	kv511
Specific Storage		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	0.002	ss121
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	0.002	ss221
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	0.002	ss321
Layer 4 – Bedrock (≤ 100 ft deep)	0.002	ss421
Layer 5 – Bedrock	0.002	ss521
Specific Yield		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	0.02	sy131
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	0.02	sy231
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	0.02	sy331
Layer 4 – Bedrock (≤ 100 ft deep)	0.02	sy431

Horizontal isotropy was assumed for basin-fill hydrogeologic units one through three in the UKC-GFM, and each model hydrogeologic unit was initially assigned one value for Kx. The coarser grained basin-fill units, mostly in the Roslyn Basin, were assigned Kx values ranging from 40 ft/d for unit 3, lower coarse-grained (gravel) unit, to 100 ft/d for unit 1, the upper coarse-grained (gravel and sand) unit. For the fine-grained basin-fill unit, unit 2 (middle fine-grained basin-fill unit of sand and clay) mostly in the Roslyn basin, the initial Kx value was set at 1 ft/d (Table 2-5).

Similar to the YRB-GFM, a relatively thin (100 foot thick) upper part of the bedrock hydrogeologic units, model layer 4 in the UKC-GFM (model HGU 47 in the YRB-GFM), was incorporated into the UKC-GFM to represent the upper bedrock where hydraulic properties may vary in response to glacial loading, erosion, and exposure at the surface versus bedrock covered by basin-fill units. Different than the YRB-GFM, in order to add more variation to these properties in the upper 100 feet of bedrock, layer 4 was zoned so that bedrock exposed at the surface (zone -401) was assigned a Kx value of 50 ft/d, a value identical to the YRB-GFM, whereas upper bedrock beneath the basin-fill sediments (zone -402) was assigned a Kx value of 5 ft/d because covered bedrock may be less exposed or weathered.

The lower portion of bedrock, model hydrogeologic units 4 through 8 in model layer 5, were assigned initial Kx values based on their varying geologies. The Grande Ronde Basalt and interbeds, hydrogeologic unit 4 in the UKC-GFM, were assigned a Kx value of 10 ft/d (Table 2-5). Units 5 through 8 in the YRB-GFM were initially undifferentiated and assigned one Kx value of 0.1 ft/d; Vaccaro et al. (2009) state: "based on a review of the literature survey for hydraulic properties of bedrock; the 0.1 ft/d value is near the highest of reported bedrock values." Initial bedrock Kx values in layer 5 of the UKC-GFM were modified from the YRB-GFM, and varied via zonation based on the simplified surficial geologic map of Upper Kittitas County. For the UKC-GFM, hydrogeologic unit 5, the volcanic unit, and hydrogeologic unit six, the intrusive unit, were initially assigned Kx values of 1.0 ft/d and 0.5 ft/d, respectively, both within typical ranges for hydraulic conductivities for igneous rocks, fractured or unfractured (Heath, 1983). Hydrogeologic unit 7, the sedimentary unit, *Non-marine sedimentary rock*, was assigned a Kx value of 1.0 ft/d, again within an acceptable range for sedimentary rocks (Heath, 1983). Hydrogeologic unit 8, the metamorphic unit, was initially assigned a Kx value of 1.0 ft/d, within an acceptable range of hydraulic conductivity for (fractured) metamorphic rocks.

2.4.5-2 Vertical Hydraulic Conductivity

Vertical hydraulic conductivity (Kv) values were derived from vertical anisotropy ratios, of Kx:Kv. In the YRB-GFM, vertical anisotropy ratios were based on previous work by Vaccaro et al. (2009). Vertical anisotropy ratios were regionalized using only two initial ratios for the basin-fill units, with the ratio for coarse grained basin-fill units initially assumed to be 10:1, and the ratio for fine grained units initially assumed to be 100:1. These ratios make sense because, while layered sedimentary rocks may have relatively high horizontal hydraulic conductivity, the same sedimentary layers can cause resistance to flow in the vertical direction, causing Kx and Kv to differ considerably. In the UKC-GFM, initial vertical anisotropies in the basin-fill units were slightly adjusted within reasonable parameters from the YRB-GFM using trial and error methods, and ranged from 10:1 in unit 1 (gravel and sand), 135:1 in unit 3 (gravel), and 160:1 in unit 2 (silt and clay). For example, if layer 2 basin-fill (unit 2, fine grained silt and clay) has a Kx value of 1 ft/d and the vertical anisotropy ratio (Kx:Kv) for this unit is 160:1, then this means that unit 2 aquifer material is 160 times more conductive in the horizontal direction (Kx) than in the vertical direction (Kv). This yields a Kv value of 0.006 ft/d for unit 2. Applying this same technique to the remaining basin-fill units in the UKC-GFM produces vertical hydraulic conductivity values of 10 ft/d in unit 1 and 0.296 ft/d in unit 3 (Table 2-5).

Basalt and other bedrock units in the UKC-GFM were assigned Kv values that varied in the upper 100 feet of bedrock within model layer 4. The Kx:Kv ratios for upper bedrock ranged from 1,000:1 in the upper bedrock exposed at the surface, to 100:1 in the upper bedrock beneath the basin-fill sediments, producing a Kv value of 0.05 ft/d for all upper bedrock. The Kx:Kv ratios for the remaining bedrock materials in model layer 5 were all assigned Kx:Kv ratios of 10:1, yielding Kv values ranging from 0.05 ft/d for the intrusive unit, to 0.1 ft/d for the volcanic, sedimentary, and volcanic units, and 1 ft/d for the basalt unit (Table 2-5).

2.4.5-3 Storage Properties

Common specific yield values generally range from 0.02 to 0.30. Specific storage has dimensions of 1/L, with a general value of 0.0001 ft^{-1} or less (Fetter, 2001). Selected published values for most mapped HGUs were documented in Vaccaro et al. (2009), and these values were obtained from aquifer tests and groundwater-modeling studies. Initial constant values for the basin-fill, basalt, and bedrock units based on this information (Ely et al., 2011) were used for the YRB-UKC and considered for the UKC-GFM.

As in the YRB-GFM, both unconfined and confined conditions occur within the groundwater system. However, unlike the YRB-GFM, which only uses specific storage (S_s) terms, the UKC-GFM uses MODFLOW-NWT and the UPW package to better handle the drying and rewetting of model cells, allowing for both specific yield (S_y) and specific storage properties. The initial S_s value assigned to all basin-fill, basalt, and bedrock units was 0.002 ft^{-1}. The initial S_y value assigned to all basin-fill, basalt, and bedrock units 0.02 ft^{-1}.

2.5 Model Calibration and Sensitivity

Model calibration is the process in which hydraulic properties (model parameters) are adjusted to obtain a reasonable fit between simulated heads and fluxes and measured data. An integral component of the calibration process is conducting a sensitivity analysis, which provides information on the relative importance of the properties as measured by changes in model fit to measured data (Ely et al., 2011). During the calibration process, efforts were made to reduce residuals between simulated and measured data, while keeping the UKC-GFM accurate and reliable.

Streamflow observations were used as calibration points in the UKC-GFM (Fig. 2-13), and were based on mean monthly data (averaged from mean daily data) from gaging stations in Upper Kittitas County. Simulated streamflow observations for some smaller streams and tributaries were based on measurements from both active and discontinued gages, as well as simulated values from watershed models (Fig. 2-13) (Mastin and Vaccaro, 2002; Ely et al., 2011). In Figure 2-13, model streamflow observation numbers correspond to actual and previously modeled (Mastin and Vaccaro, 2002) stream gage sites: 1) Yakima River at RM 204, 2) Cabin Creek*, 3) Yakima River at RM 196, 4) Big Creek near mouth*, 5) Little Creek near mouth*, 6) Yakima River at

RM 186, 7) Cle Elum River above lake, 8) Cle Elum River near mouth, 9) Yakima River at RM 183 (at Cle Elum), 10) Yakima River at RM 177, 11) Teanaway River below forks, 12) Teanaway River near mouth, 13) Yakima River at RM 171 (near Horlick), and 14) Swauk near mouth*. Gages marked with an asterisk are previously modeled gages (Mastin and Vaccaro, 2002). Water levels measured in wells were used to develop head and head change observations for model calibration (Fig. 2-14). Later during this master's thesis, Spring of 2011, the USGS began a monthly inventory of wells in Upper Kittitas County, and new water levels for wells not currently in the UKC-GFM were measured. Eighty-three new bedrock wells (out of the 248 inventoried wells) were added to the 33 previous head observations, for a total of 116 hydraulic head observations. The 2011 bedrock hydraulic heads are in stress period 102 and represent March of 2000, a similar water year; note that this well inventory is outside of the model period. The inventoried wells are an important addition to the model because they provide more information about the less understood bedrock. All observations were assigned to the 15th day of the month, mid-month, which is appropriate because the model uses monthly stress periods and therefore monthly average stresses.

2.5.1 Calibration Approach

The model was calibrated using the iterative parameter estimation software package PEST (Doherty, 2010). "PEST uses a nonlinear least-squares regression to find the set of parameter values that minimizes the weighted sum-of-squared-errors objective function" (Ely et al., 2011, p.47). The weighted least-squares objective function S($\vec{b}$), used in MODFLOW can be expressed as (Hill, 1998, p.4):

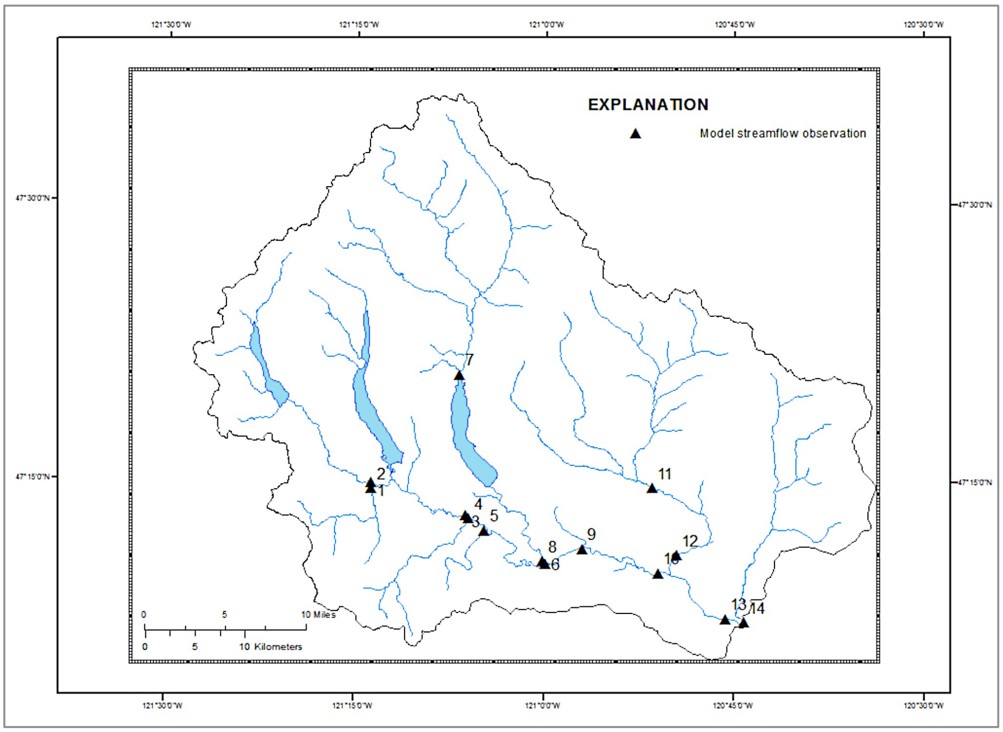


Figure 2-14. Locations of model streamflow observations, Upper Kittitas County aquifer system, Washington.

$$S(\underline{b}) = \sum_{i=1}^{ND} \omega_i [y_i - y'_i(\underline{b})]^2 + \sum_{p=1}^{NPR} \omega_p [P_p - P'_p(\underline{b})]^2 \qquad \textbf{Equation 2-18}$$

where: *b* is a vector containing values of each of the NP parameters being estimated; ND is the number of observations (called N-OBSERVATIONS in the UCODE documentation); NPR is the number of prior information values (called NPRIOR in the UCODE documentation); NP is the number of estimated parameters (called N PARAMETERS in the UCODE documentation); y_i is the i^{th} observation being matched

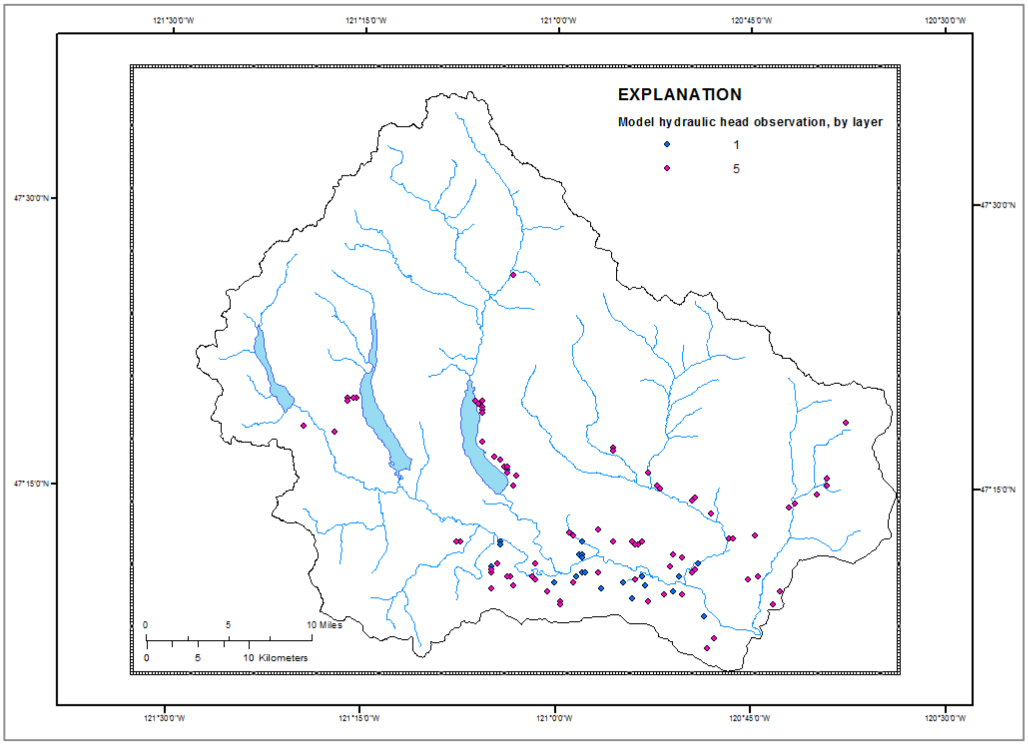


Figure 2-15. Location of model hydraulic head observations, Upper Kittitas County aquifer system, Washington. Layer 1 head observations are in basin-fill, while layer 5 head observations are in layer 5.

by the regression; $y'i(b)$ is the simulated value which corresponds to the i^{th} observation (a function of b); Pp is the p^{th} prior estimate included in the regression; $P'p(b)$ is the p^{th} simulated value (restricted to linear functions of b in UCODE and MODFLOWP); ωi is the weight for the i^{th} observation; and ωp is the weight for the p^{th} prior estimate. The differences $[yi – y'i(b)]$ and $[Pp – P'p(b)]$ are called residuals, and represent the match of the simulated values to the observations (Hill, 1998, p.4-5).

A total of 30 model parameters were specified. The parameters adjusted during calibration included Kx, Kx:Kv (vertical anisotropy), storage properties, and stream conductances. Model calibration was first conducted using a trial-and-error process during which model parameters were adjusted within reasonable ranges while ensuring that model predictions were in reasonable agreement with measured trends in groundwater levels and streamflow variations. Subsequent automated calibrations of the 30 estimated model parameters using parallel PEST were conducted using 116 head observations spanning the ten year simulation period (water years 1992 through 2001) and 720 monthly streamflow observations at six gage sites. Calibrations using both heads and flows were conducted with observation weights adjusted to ensure equal contribution by the two groups to the model objective function, as per recommended USGS guidelines (Doherty and Hunt, 2010).

PEST works to minimize the residuals in a groundwater model. The Objective Function (phi) is the sum of the squared weighted residuals, where residuals (r_i) are defined as:

$$r_i = (h_{calculated} - h_{observed}) \qquad \textbf{Equation 2-19}$$

and phi is defined as:

$$\Phi = \Sigma(w_i r_i)^2 \qquad \textbf{Equation 2-20}$$

where w_i is a weighting factor assigned to each observation. PEST's goal is to find the minimum value for the objective function. PEST tracks its own progress by following whether phi is increasing or decreasing. During calibration, contributions to phi from observation groups were manually assigned. All hydraulic heads made up approximately half (52%) of the contribution to phi. The remaining six streamflow observation groups made up the other half of the contribution to phi, with Cabin Creek, Big Creek, Little

Creek, Teanaway River near Forks, Swauk Creek, and Yakima River at Horlick equal to 8%, 8%, 7%, 9%, 8%, 8%, respectively.

2.5.1-1 Sensitivity Analysis

Sensitivity analysis during calibration assesses the effects of parameter values on simulated heads and streamflow, and develops useful nonlinear regressions (Hill, 1998; Hill and Tiedeman, 2003; Ely and Kahle, 2004; Ely and Kahle, 2012). "The ability to estimate a parameter value using nonlinear regression is a function of the sensitivity of simulated values to changes in the parameter value" (Ely and Kahle, 2004, p.31). The nonlinear least-squares regression equation for this process is (Hill, 1998; Ely and Kahle, 2004):

$$S(\vec{b}) = \sum_{i=1}^{ND} w_i \left[y_i - y'_i(\vec{b})\right]^2 \qquad \textbf{Equation 2-21}$$

where $\vec{b}$ is a vector containing values for each of the parameters being estimated, *ND* is the number of observations, y_i is the i^{th} observation being matched by regression, y'_i is the simulated value corresponding to the i^{th} observation, and w_i is the weight assigned to the i^{th} observation.

Parameter sensitivity reflects the amount of observation data available for parameter estimation. High parameter sensitivity means that there are adequate observation data to estimate the parameter value. Low parameter sensitivity means that there are insufficient observation data to estimate the parameter value and changing the parameter value will have little effect on the sum of squared errors. Parameter sensitivities are expected to be lowest overall for a well-calibrated model (Ely and Kahle, 2004).

2.5.2 Observations Used in Model Calibration

2.5.2-1 Water Levels, Water Level Changes, and Associated Errors

The hydraulic-head data used for calibration consisted of 116 water-level measurements from wells made between water years1992 and 2001, as well as some in 2011 (Gendaszek et al., 2014). Latitudes and longitudes for the well locations were determined by two methods. For the 33 wells with groundwater levels measured generally prior to 2000, wells were located by well drillers or as part of previous investigations that located numerous wells on 1:24,000 topographic quadrangles. For the 83 water levels measured during the 2000 and 2011 field effort, a Global Positioning System (GPS) with approximately 50 ft accuracy was used to determine latitude and longitude at wells. Water levels in wells were measured using a calibrated electric tape or graduated steel tape, both with accuracy to 0.01 ft. Land surface altitude was interpolated from the 10-m DEM. More bedrock water levels for Upper Kittitas County were used for calibration in the UKC-GFM than had previously been used for the YRB-GFM because the water levels from 2011 were measured after the YRB-GFM and incorporated into the UKC-GFM.

Observation weights are commonly assigned because there may be multiple types of observations, and/or there may be varying levels of accuracy or experimental error for the observations. While different weighting schemes were used during calibration, final sensitivities and weighting schemes are presented in this report. Model calibrations conducted using observations of different types require a weighting scheme that adequately represents the contribution to total model error of observations made in different measurement units. The 116 water level measurements contributed a model error measured in feet while the 720 streamflow observations contributed a model error measured in cubic feet per second (the larger of the two). Instead of distributing weights to reflect actual gages versus modeled streamflow measurements, or to reflect 2011 bedrock heads versus basin-fill heads, streamflow and hydraulic head observations used to calibrate the UKC-GFM were weighted by giving all observations similar influence to total model error (phi), with hydraulic heads equaling approximately 52 percent of phi and streamflow observations the remaining 48 percent of phi.

Potential errors for water level observations include averaged hydraulic head (water level) measurements over large screened intervals or multiple screened intervals; and folding, faulting, compartmentalization, and intraborehole flow. Another consideration when weighting water level observations used in model calibration has to do with the Spring (March) 2011 water levels. While these water levels were taken ten years after the model period, they provide more information about water in the bedrock below Upper Kittitas County, and are therefore valuable and are not assigned a lower weight than the water levels collected during the simulation period. To account for the associated errors, all water levels were assigned equal relative weights of 70.0.

2.5.2-2 Streamflow Observations and Errors

Streamflow observations used in model calibration were taken from six of the 14 sites at streams and rivers in Upper Kittitas County, and amounted to 720 total streamflow observations. Of these, two were measured stream gage sites from USGS and Reclamation stream gaging stations, while the remaining four sites were previously modeled (Mastin and Vaccaro, 2002) sites for ungaged small tributaries. During calibration, streamflow observations for actual gages were assigned relative weights of 0.000125 for Teanaway River below forks and 0.00025 for Yakima River at Horlick. Streamflow observations for the four modeled gages (Mastin and Vaccaro, 2002) were assigned relative weights of 0.00045 for Cabin Creek, 0.00075 for Big Creek, 0.0015 for Little Creek, and 0.0004 for Swauk Creek.

2.5.3 Model-Calculated Hydraulic Properties and Parameter Uncertainty

After using the PEST calibration process, the resulting parameter values were assessed for input into the UKC-GFM. Although PEST calibration allowed for a good fit between simulated streamflow and hydraulic heads and measured streamflow and hydraulic heads, it also generated unreasonable parameter values and caused the model to fail to converge (FTC). Therefore it became necessary to modify some parameters to be more consistent with previously published values without sacrificing too much model fit; these final adjusted parameters are presented in Table 2-6.

The final horizontal hydraulic conductivity (Kx) values for basin-fill sediments (units 1 through 3) remained relatively consistent with initial hydraulic parameters (Table

2-5). The Kx values for bedrock in Layer 4 changed, with bedrock exposed at the surface decreasing from 50 ft/day to 24.9 ft/day, and bedrock beneath basin-fill sediments decreasing from 5 ft/day to 0.5 ft/day. The bedrock Kx values decreased or remained the same in the Layer 5 zones. The greatest decrease occurs in the Grande Ronde basalt unit, from 10 ft/day to 5 ft/day between initial and final parameters. This value is within ranges presented in the YRB-GFM report (Ely et al., 2011) for this unit, which estimate mean, minimum, and maximum Kx values of 22.99 ft/day, 4.28 ft/day, and 90.97 ft/day, respectively, for the rubbly interflow zone. The remaining final bedrock Kx values for the separately zoned bedrock units range between 0.5 and 1.0 ft/day; while these values are not highly variable, the PEST sensitivity analysis, discussed later in this section, indicates that they are significant to the aquifer system beneath Upper Kittitas County.

Final vertical anisotropy ratios (Kv) for hydrogeologic units in all but Layer 5 decreased from initial values. According to the UKC-GFM, shallow exposed bedrock transmits water faster than deeper bedrock or bedrock beneath the basin-fill sediments.

Final storage property parameter values are the same as initial values; the sensitivity analysis discussed later in this section suggests that the storage properties of Layer 4 and 5 bedrock are significant when modeling hydraulic head and streamflow in the UKC-GFM.

The final parameter values are shown in Table 2-6, and the normalized composite scaled sensitivities (CSS) for all parameters to hydraulic head observations only and to combined streamflow observations only are shown in Fig. 2-16. Based on the weights

TABLE 2-6. FINAL HYDRAULIC PROPERTIES FOR ALL MODEL LAYERS IN THE UPPER KITTITAS COUNTY GROUNDWATER MODEL, FOR INPUT DATA INTO THE UPW PACKAGE.		
Hydraulic Property	**Value of Hydraulic Property**	**Parameter ID, UKC-GFM**
Conductances		
Drain conductance	500,000	drncnd
Lake (general head boundary) conductance	1.00+E06	ghbcnd
Stream conductance (Yakima River)	0.5	sfrcnd1
Stream conductance (tributaries to Yakima River)	0.1	sfrcnd2
Horizontal Hydraulic Conductivity (ft/d)		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	93.4	kx101
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	1.24	kx201
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	35.7	kx301
Layer 4 – Bedrock: At the surface (-411) (≤ 100 ft deep)	24.9	kx401
Layer 4 – Bedrock: Under basin-fill (-412) (≤ 100 ft deep)	0.5	kx402
Layer 5 – Bedrock: Beneath Quaternary deposits	0.5	kx501
Layer 5 – Bedrock: Grande Ronde Basalt and interbeds	5.0	kx504
Layer 5 – Bedrock: Volcanic unit	1.0	kx505
Layer 5 – Bedrock: Intrusive unit	0.5	kx506
Layer 5 – Bedrock: Sedimentary unit	0.5	kx507
Layer 5 – Bedrock: Metamorphic unit	0.5	kx509
Vertical Anisotropy, unitless (Vertical Hydraulic Conductivity in Parentheses, ft/d)		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	8.70 (10.74 ft/d)	kv111
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	133 (0.009 ft/d)	kv211
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	115.2 (0.310 ft/d)	kv311
Layer 4 – Bedrock: At the surface (-411) (≤ 100 ft deep)	112.9 (0.221 ft/d)	kv411
Layer 4 – Bedrock: Under basin-fill (-412) (≤ 100 ft deep)	1.2 (0.04 ft/d)	kv412
Layer 5 – Bedrock: Beneath Quaternary deposits	20 (0.025 ft/d)	kv511
Layer 5 – Bedrock: Grande Ronde Basalt and interbeds	20 (0.25 ft/d)	kv511
Layer 5 – Bedrock: Volcanic unit	20 (0.05 ft/d)	kv511
Layer 5 – Bedrock: Intrusive unit	20 (0.025 ft/d)	kv511
Layer 5 – Bedrock: Sedimentary unit	20 (0.025 ft/d)	kv511
Layer 5 – Bedrock: Metamorphic unit	20 (0.025 ft/d)	kv511
Specific Storage		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	0.002	ss121

TABLE 2-6, CONTINUED. FINAL HYDRAULIC PROPERTIES FOR ALL MODEL LAYERS IN THE UPPER KITTITAS COUNTY GROUNDWATER MODEL, FOR INPUT DATA INTO THE UPW PACKAGE.		
Hydraulic Property	**Value of Hydraulic Property**	**Parameter ID, UKC-GFM**
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	0.002	ss221
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	0.002	ss321
Layer 4 – Bedrock (≤ 100 ft deep)	0.002	ss421
Layer 5 – Bedrock	0.002	ss521
Specific Yield		
Layer 1 – Basin-fill: Upper coarse-grained (gravel and sand)	0.02	sy131
Layer 2 – Basin-fill: Middle fine-grained (silt and clay)	0.02	sy231
Layer 3 – Basin-fill: Lower coarse-grained (gravel)	0.02	sy331
Layer 4 – Bedrock (≤ 100 ft deep)	0.02	sy431

assigned to observation groups in the UKC-GFM, the parameters most sensitive to hydraulic heads are horizontal hydraulic conductivities (Kx) of the bedrock (Kx501, Kx504, Kx505, Kx507, and Kx509; all but the Tertiary Intrusive unit) in layer 5, Kx of layer 1 basin-fill (Kx101), and storage properties of the bedrock (Ss521). The high sensitivity values for bedrock Kx parameters show significance in assigning individual hydraulic parameter values for each of the simplified bedrock types, and indicate a dependence on these parameters when considering water levels in the bedrock. Parameter sensitivities for streamflow observations had different patterns and varied over two orders of magnitude, three less than for hydraulic head. The parameters most sensitive to combined streamflow observations are Kx of the bedrock (Kx401, Kx504, and Kx505), vertical anisotropy (Kv) of the bedrock (Kv511), and storage properties of the bedrock (Ss421 and Ss521). The sensitivity of bedrock Kx values to streamflow observations in layers 4 and 5 are reasonable because the streamflow observations have been combined for this sensitivity analysis, and the Yakima River near Horlick is part of the combined values; Yakima River at RM 171 (near Horlick) is the final point at which groundwater and surface water exits Upper Kittitas County, and therefore it makes sense that hydraulic properties affecting groundwater in the bedrock would be influential to this streamflow observation. As with parameter sensitivities for hydraulic heads, the Kx sensitivity values for layers 2 (silt and clay) and 3 (gravel) are lower than for layer 1 (sand and gravel), indicating that parameter estimation for the lower basin-fill layers would be difficult because the model observations are insensitive to the parameter values, and would not affect simulated streamflow. High CSS for Kv in layer 5 bedrock suggests the importance of the upward movement of groundwater in the bedrock to simulated heads and flows.

When separated into six separate streamflow observation groups (Table 2-7), the highest parameter sensitivity value is Kx401, horizontal hydraulic conductivity, for the Yakima River near Horlick, the point at which water leaves the study area. When comparing parameter sensitivities for each streamflow group, Kx401 is the highest sensitivity value for four out of the six streamflow groups, indicating that the surficial bedrock properties are significant to model outcomes in the UKC-GFM. Cabin Creek, Little Creek, Teanaway River below Forks, and Yakima River near Horlick streamflow are all sensitive to hydraulic properties of bedrock at the surface (i.e., Kx401). Big Creek streamflow is sensitive to Kx in the Miocene Volcanic unit, because its upstream portion cuts through this unit, whereas Little Creek and Cabin Creek do not. Swauk Creek (near mouth) streamflow is most sensitive to Kx in the Miocene Basalt (CRBG) unit, the unit which underlies the streamflow observation location as well as a portion of Swauk Creek upstream from that location.

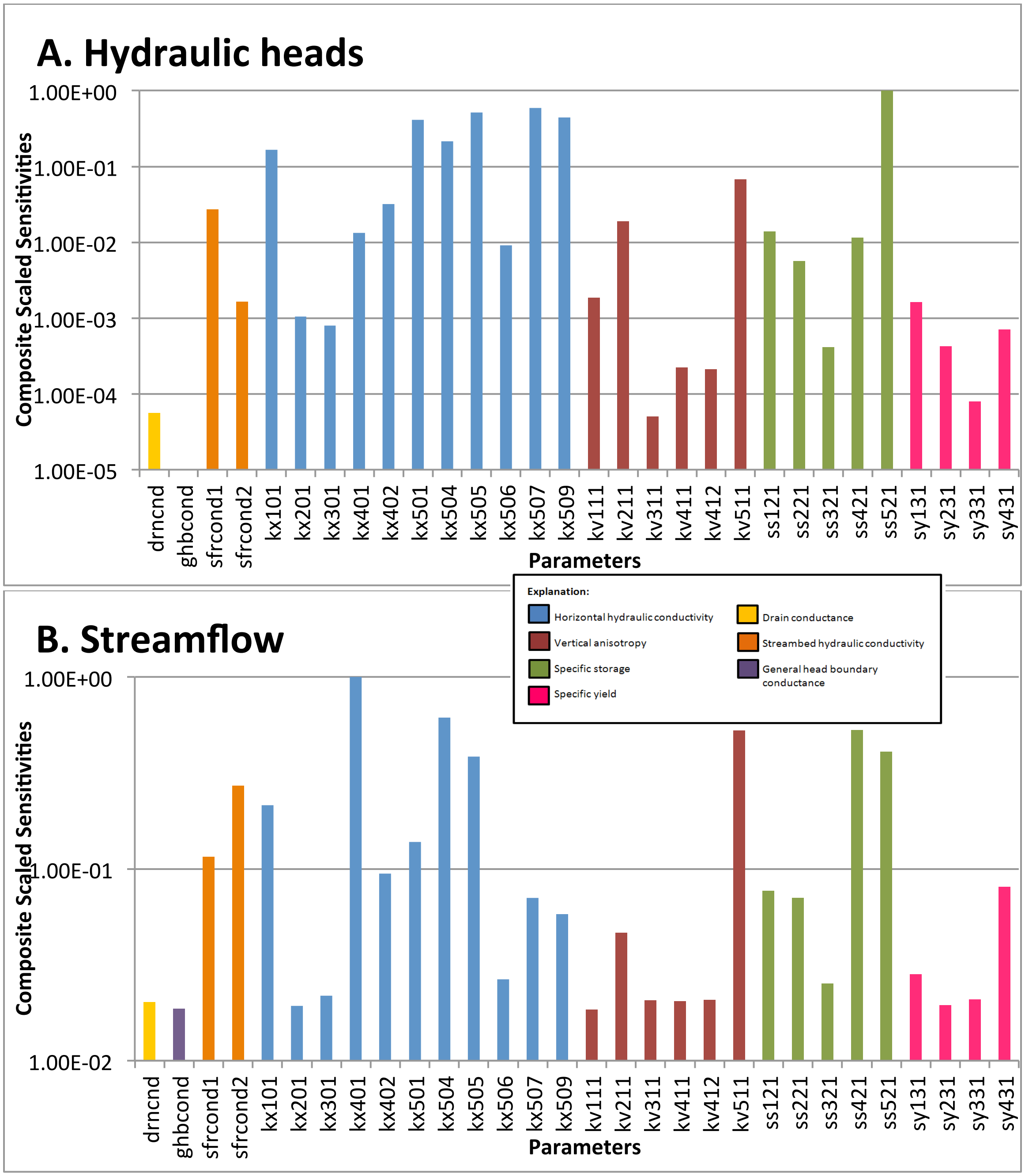


Figure 2-16. Normalized composite scaled sensitivities of final calibrated model parameters to A) hydraulic-head observations and B) combined streamflow observations, Upper Kittitas County aquifer system, Washington.

TABLE 2-7 COMPOSITE SCALED SENSITIVITIES FOR INDIVIDUAL STREAMFLOW GROUPS, DETERMINED USING PEST PROGRAM.						
Parameter name (ID)	**Streamflow Groups***					
	Cabin Creek	**Big Creek**	**Little Creek**	**Teanaway River below forks**	**Swauk Creek**	**Yakima River near Horlick**
drncnd	6.36	4.97	13.16	2.31	3.77	7.67
ghbcond	5.86	3.33	12.82	2.56	3.55	6.42
sfrcond1	9.91	21.39	12.59	7.53	3.87	98.08
sfrcond2	73.76	105.07	49.29	49.70	63.83	177.83
kx101	6.89	18.48	28.24	4.07	3.92	186.86
kx201	7.00	3.14	12.71	2.62	3.46	7.01
kx301	6.43	3.16	13.94	4.19	3.01	10.00
kx401	174.32	198.55	220.09	178.09	251.92	751.25
kx402	5.80	4.57	13.51	2.78	3.47	81.82
kx501	17.80	3.50	12.27	7.25	3.76	119.98
kx504	6.06	3.22	12.43	3.99	538.46	61.18
kx505	101.98	210.55	20.20	34.35	58.53	236.81
kx506	5.95	13.40	14.63	3.98	3.57	9.61
kx507	8.54	12.20	12.60	11.47	53.00	23.96
kx509	5.89	34.60	29.92	4.94	2.85	21.11
kv111	6.86	3.41	12.07	2.12	2.90	6.96
kv211	7.94	4.92	12.67	2.30	2.86	37.69
kv311	6.43	3.15	13.87	2.64	4.65	7.63
kv411	5.56	5.12	13.09	2.73	6.09	7.08
kv412	6.96	5.41	12.11	3.60	3.84	9.04
kv511	45.29	129.36	25.24	17.33	408.97	171.86
ss121	6.48	4.67	15.21	2.42	3.58	65.49
ss221	6.38	3.47	12.18	3.85	4.11	60.29
ss321	5.84	3.47	16.51	3.65	3.67	12.13
ss421	101.99	145.41	95.93	105.93	87.55	396.56
ss521	69.35	112.72	31.48	38.48	206.90	258.37
sy131	7.58	3.07	12.22	3.06	3.62	19.52
sy231	6.27	3.45	10.90	4.26	4.00	9.57
sy331	7.61	3.59	11.82	4.00	3.34	10.04
sy431	19.23	25.47	15.84	17.52	17.45	56.08

*The streamflow group names used for PEST runs in the "sensitivity file", in the order presented in this table, are: yraca_slms, yrab_slms, yral_slms, yratf_slms, yras_slms, and yrah_slms.

2.5.5 Transient Calibration Model Fit

2.5.5-1 Comparison of Simulated and Measured Hydraulic Heads

A plot of measured hydraulic heads as a function of simulated hydraulic heads is provided in Figure 2-17. For all 116 observation wells, the mean difference between simulated and measured hydraulic heads (residuals) is +73 feet, with 82 percent of simulated heads exceeding measured heads. A plot of measured versus simulated hydraulic heads should show heads normally distributed along a line of equal values with a slope of 1.0 and a y-intercept of zero. The hydraulic heads in the UKC-GFM fall along a straight line with a slope of 1.01 and a y-intercept of 61. As an acceptable standard for the calibration, "the root-mean-square (RMS) error of the difference between simulated and measured hydraulic heads in the [116] observation wells, divided by the total difference in water levels in the groundwater system (Anderson and Woessner, 1992, p. 241), had to be less than 10 percent to be acceptable" (Ely et al., 2011). The calibrated model produces an RMS error divided by the total difference in water levels of 1.5 percent, as calculated below:

First:

$$RMS = \sqrt{\frac{r_1^2 + r_2^2 + \cdots + r_n^2}{n}} \qquad \textbf{Equation 2-22}$$

Then:

$$\left(\frac{RMS}{total\ difference\ in\ water\ levels}\right) \times 100 \qquad \textbf{Equation 2-23}$$

where: r_1^2 through r_n^2 are the squared residuals at each of the observation wells, and n equals the number of observation wells, 116. The *"total difference in water levels"* is equal to the sum of the residuals, 8,569 feet. Figure 2-18 is a map of simulated groundwater levels from the calibrated UKC-GFM.

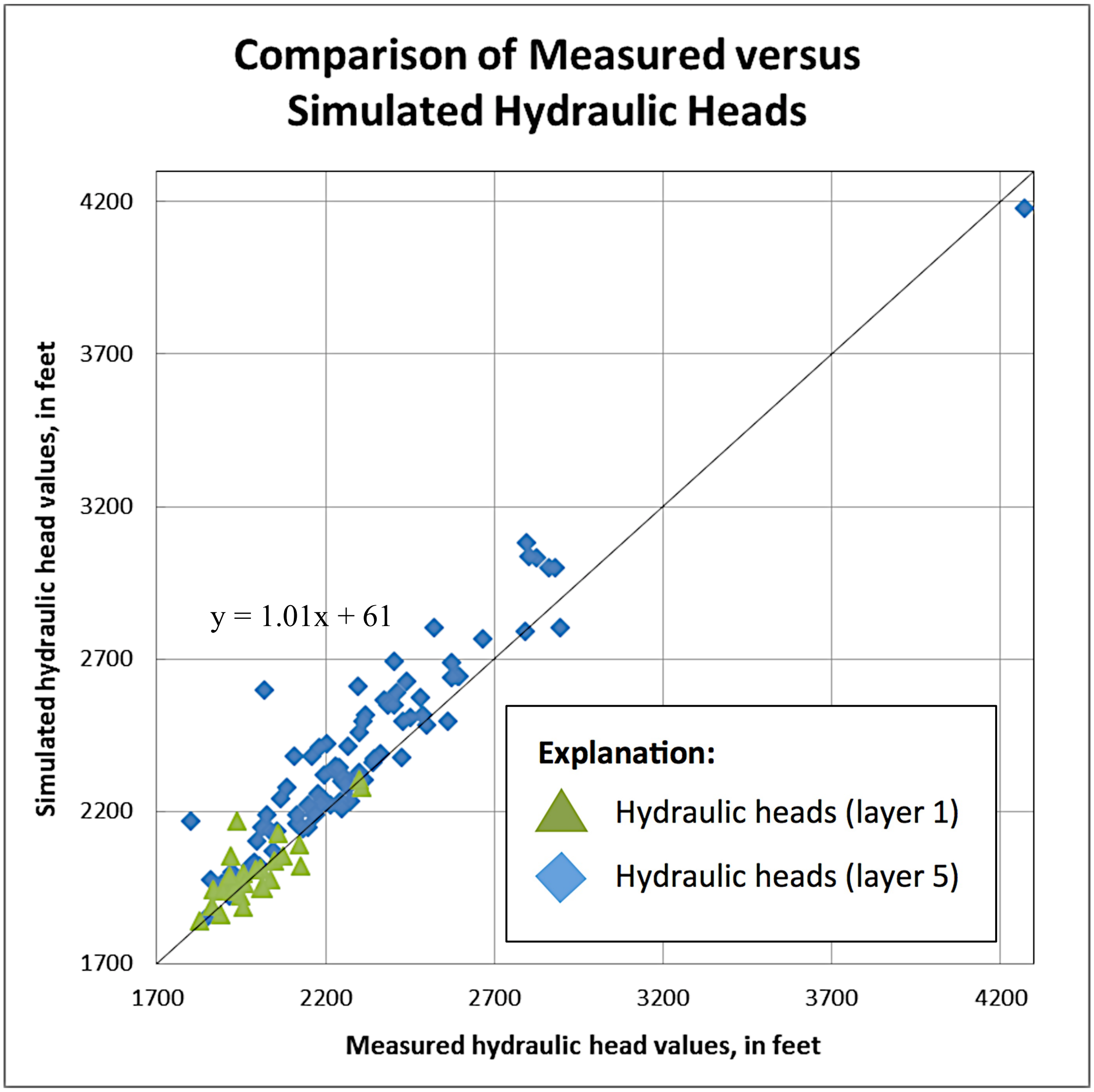


Figure 2-17. Measured hydraulic heads as a function of simulated hydraulic heads, Upper Kittitas County aquifer system, Washington.

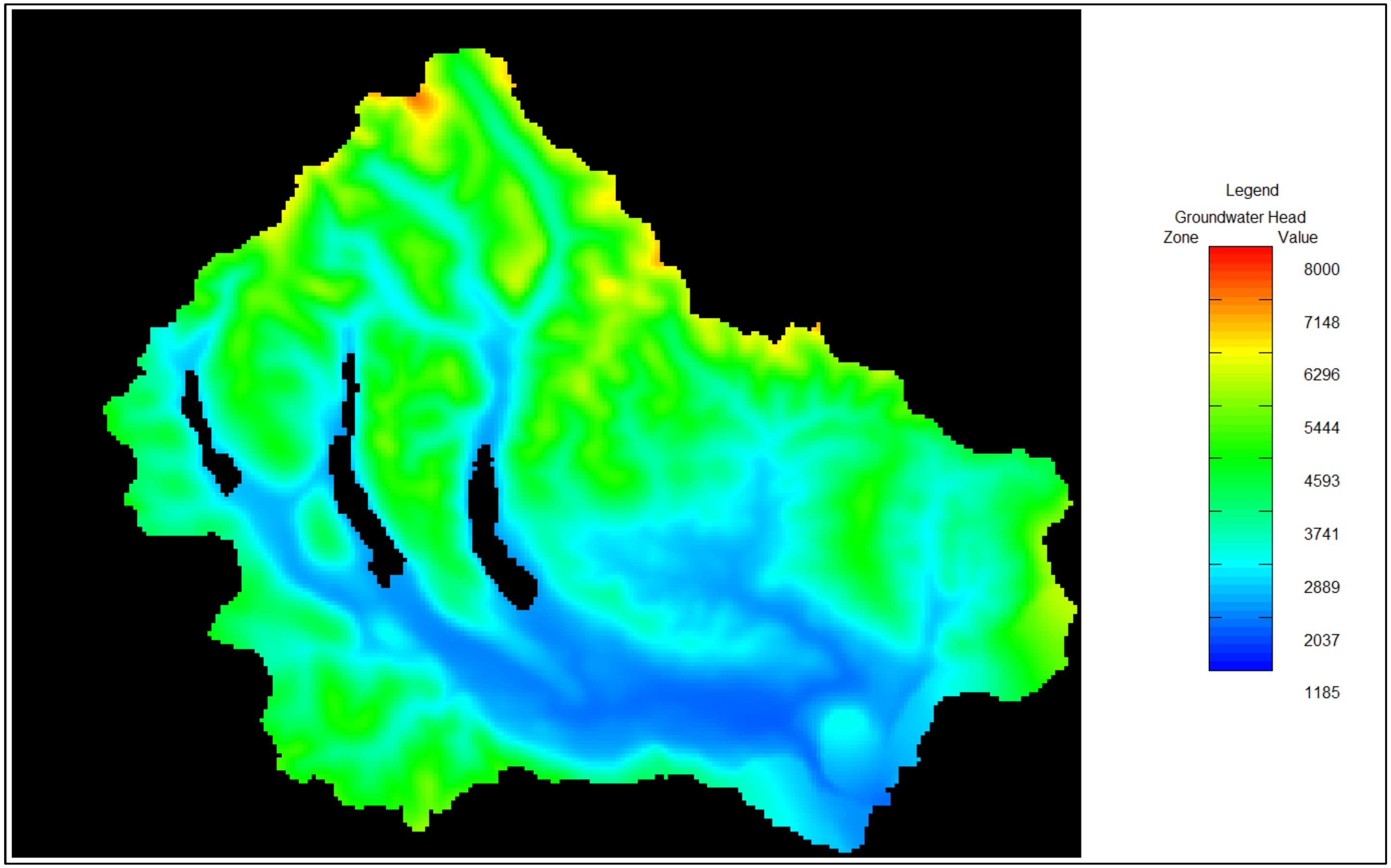


Figure 2-18. Map of simulated hydraulic heads for model layer 5, bedrock. Units are in feet.

2.5.5-2 Comparison of Simulated and Measured or Estimated Streamflow

Streamflow gains and losses are an important component of the simulated water budget; therefore it is important that simulated streamflow corresponds well to observed streamflow. Simulated stream leakage accounts for about 0.02 percent of total influxes into the model, including recharge and reservoir infiltration, for the 10 year cumulative water budget for total simulated flows into the aquifer system (streamflow losses), and three percent of the total simulated flows out of the aquifer system (streamflow gains).

A comparison of simulated and measured streamflow at selected sites in the study area provides information on the reliability of the UKC-GFM. The UKC-GFM was calibrated at seven of the sites in Figure 2-14, two sites along the Yakima River and five sites along tributaries. These sites include site numbers: (2) Cabin Creek*, (4) Big Creek near mouth*, (5) Little Creek near mouth*, (9) Yakima River at RM 183 (at Cle Elum), (11) Teanaway River below forks, (13) Yakima River at RM 171 (near Horlick), and (14) Swauk near mouth*. Gages marked with an asterisk are previously modeled gages (Mastin and Vaccaro, 2002). For the Yakima River, simulated and measured streamflow generally display a close correspondence for peaks and base flows (Fig. 2-19). At the Yakima River at RM 183 (at Cle Elum) and the Yakima River at RM 171 (near Horlick), percent differences for mean annual flows at the sites are 11 and 7 percent, respectively. For tributaries to the Yakima River, where water levels are less abundant, and data resolution is coarser, the timing of simulated streamflow peaks match measured streamflow peaks, but streamflow values are not matched. Percent differences for mean annual flows at tributaries range from 19 percent at Big Creek near mouth, to 49 percent at Swauk near mouth. Additionally, at tributaries, peak flows are under-simulated and base flows are over-simulated. The hydrograph match along the mainstem of the Yakima River is good because most of the streamflow is regulated by reservoir releases.

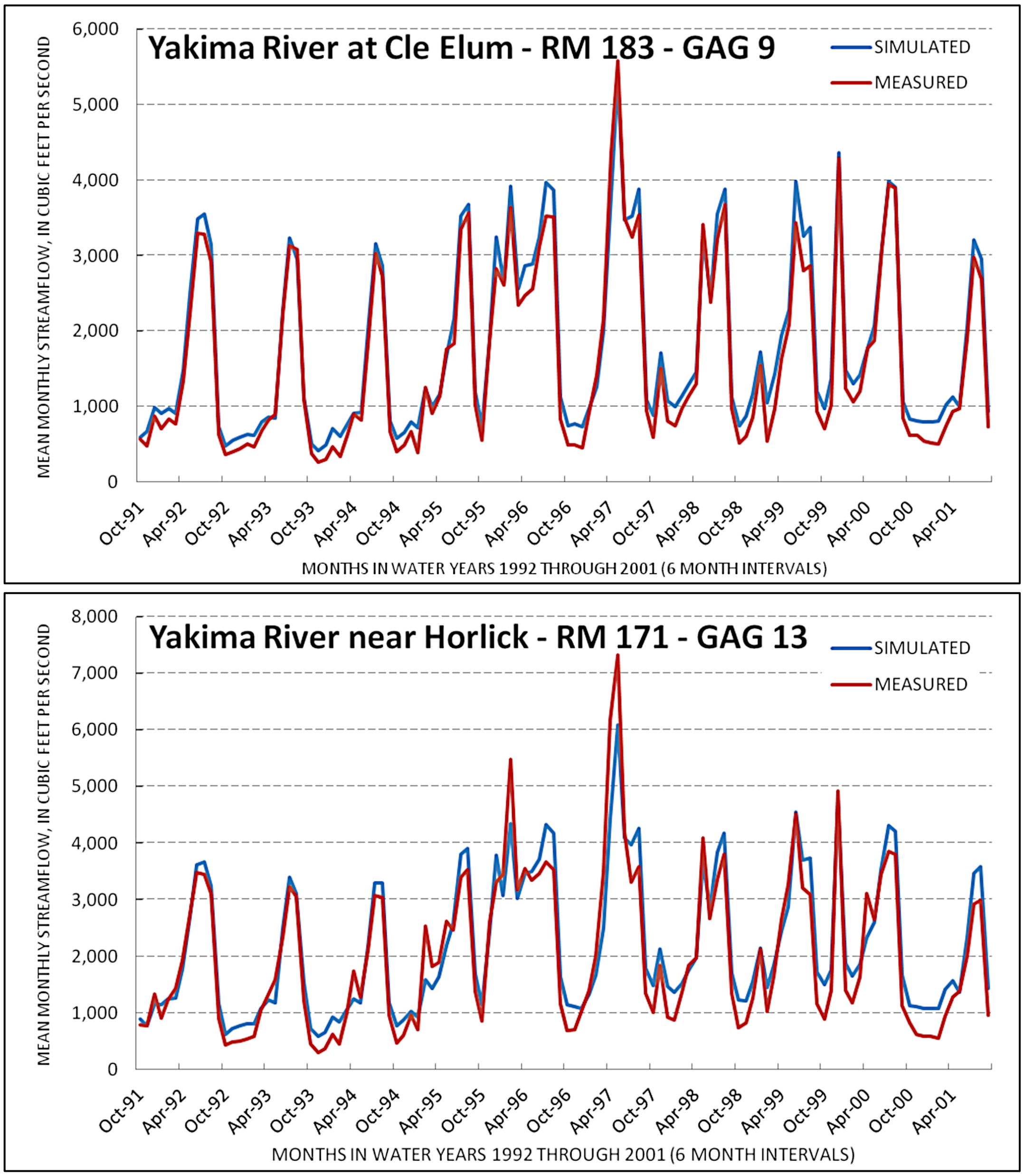
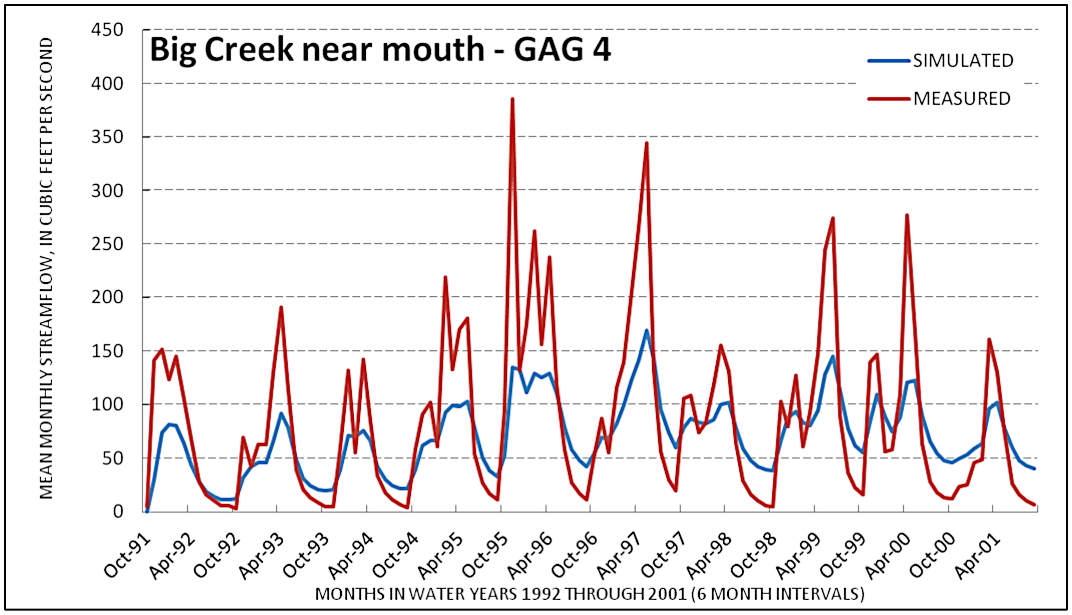


Figure 2-19. Simulated and measured mean monthly streamflow of the calibrated model, for the Yakima River at Cle Elum, the Yakima River near Horlick, as well as the Cabin Creek tributary.



2-19, continued. Simulated and measured mean monthly streamflow of the calibrated model, for the Yakima River at Cle Elum, the Yakima River near Horlick, as well as the Cabin Creek tributary.

2.6 Model Uncertainties and Limitations

2.6.1 Spatial and Temporal Limitations

The UKC-GFM was built using several established modeling techniques, as well as a robust set of data types to capture the groundwater flow system in Upper Kittitas County, and so it is a useful tool for analyzing the groundwater flow system; however, the model also contains some inherent uncertainties due to its structure, and is therefore limited in terms of uses and types of answers it can produce. The spatial organization of the UKC-GFM includes cells with lengths and widths equal to 1,000 feet. This means that elevations taken from a 10-meter digital elevation model (DEM) are averaged for each cell. Therefore, data for the inputs into the model, such as recharge from the DPM and PRMS models (Vaccaro and Olsen, 2007), pumpage (DOE and USGS; Vaccaro and

Sumioka, 2009), reservoirs (Reclamation), and diversions and returns (Reclamation) were also averaged in this way across the UKC-GFM. Additionally, data for pumpage and water levels in Upper Kittitas County were more concentrated along the Yakima River and major tributaries, so data and model simulation farther north and in the less populated areas of the study area are coarser due to less information or the absence of information there.

2.6.2 Input Uncertainties

Data on groundwater levels, surface water flow, pumpage, recharge, mapped hydrogeologic units, and hydraulic properties were taken from Jones et al. (2006), Vaccaro and Sumioka (2006), Vaccaro and Olsen (2007a), Jones and Vaccaro (2008), Vaccaro et al. (2009), and other sources, and are estimates of actual values. Groundwater level information collected for the study area during the study period was concentrated around river valleys and populated areas, which means that there are fewer water levels to provide information about groundwater in the bedrock. To strengthen the bedrock water level data, water levels from a Spring (March) 2011 inventory were added to the UKC-GFM for stress period 102 (March of 2000), a similar year to that of the Spring inventory. While outside the model period, the Spring 2011 water levels were useful for inputting data where it was previously unknown, and it was assumed that water levels in these areas have not varied significantly since the model period.

Streamflow data was available from Reclamation/USGS gaging sites for the Yakima River and major tributaries in Upper Kittitas County. Smaller tributaries in

Upper Kittitas County are ungaged, so watershed models were used to provide more data in these smaller stream bodies (Mastin and Vaccaro, 2002); uncertainties arise from the use of watershed models in the UKC-GFM, which include averaging precipitation, land cover, and geology data temporally and over 208-foot cell sizes, and amount to a standard error of estimate of 62 cfs for the smaller, watershed modeled tributaries.

Exempt (domestic) wells in Upper Kittitas County were handled by identifying the wells to their townships, ranges, and sections, positioning them at the center of census block polygons, and multiplying the number of wells per census block by 251 gpd; the gpd value for exempt pumpage was estimated for non-irrigated systems for the year 2000, and considered the best estimate available according to databases and contacts with water-system operators (Vaccaro and Sumioka, 2009). While this method is efficient for large model areas and it estimates the amount of exempt groundwater pumpage in Upper Kittitas County, it does not show exempt wells in known locations, upper bedrock streams for example, and it shows a spreading of exempt wells and their pumping affects in larger areas than reality because some census blocks in Upper Kittitas County span large areas but are not very populated. For this reason, the effects of exempt well pumpage are felt in the UKC-GFM, but are spatially averaged.

Modeled hydrogeologic units in the UKC-GFM are based on previous studies of basin-fill extent and depth (Jones et al., 2006), as well as spatially mapped surficial geology (Haugerud and Tabor, 2009) for the bedrock. With depth, bedrock hydrogeologic units follow a vertical line/boundary until reaching a no flow boundary at 500 feet asl. This means that modeled bedrock hydrogeologic units in the subsurface, and thus their modeled hydraulic properties (parameter estimates), do not correlate to well log records, as this amount of detail was beyond the scope of this master's thesis. This bedrock zonation scheme is an upgrade to the set-up of the YRB-GFM, and allows the UKC-GFM to provide information about how a variety of bedrock hydraulic properties affect the groundwater flow system, which is useful information as most of the study area is underlain by various types of bedrock. A combination of parameter estimation and a comparison of modeled hydraulic properties to literature values generated acceptable hydraulic parameter values. Recent work for the UKC-USGS (Gendaszek et al., 2014) has extensively compiled bedrock well log information for Upper Kittitas County, and produced cross-sections which provide more information about the bedrock in the subsurface. Future use of the UKC-GFM could incorporate the subsurface information about bedrock extent that is reported in the UKC-USGS.

2.7 Model-Derived Water Budget

The UKC-GFM can be used to derive components of the groundwater budget for the simulation period (water years 1992 through 2001). A hydrologic budget must obey the continuity equation, Equation 2-2. Groundwater budgets for each time step, as well as cumulative groundwater budgets for the UKC-GFM, are generated in MODFLOW's LIST file after the model is run. Instead of units of volume, groundwater budgets generated by MODFLOW use units of flux. Outflows are fluxes out of the aquifer/groundwater system, and inflows are fluxes into the aquifer. For example, recharge is considered an inflow relative to cell nodes, while pumping from wells is considered an outflow.

The resulting groundwater budget from the UKC-GFM is expressed in Equation 3-1. Groundwater budget components simulated by MODFLOW are in units of cubic feet per day (ft^3/d, cfd), hereafter converted to ft^3/s (cfs) for the following description of the UKC-GFM groundwater budget.

$$S_{in} + W_{in} + GH_{in} + SL_{in} + R = S_{out} + W_{out} + GH_{out} + SL_{out} + D, \quad \textbf{Equation 2-24}$$

where: subscripts 'in' and 'out' represent the flow of the budget component into and out of the groundwater system; S is groundwater storage; W represents well return flow and well pumpage; GH is general head boundary, or reservoir, inflow and outflow; SL is stream leakage inflow and outflow (streamflow); R is recharge to the groundwater system, calculated as potential recharge in previous DPM and PRMS modeling efforts (Vaccaro and Olsen, 2007); and D is drain outflow from the groundwater system (groundwater discharge to streams). In order to determine the volumetric budget (not in in terms of flux), multiply the flux value by the number of days during the 42-year model. For the UKC-GFM, net groundwater budget values provide a simplified groundwater budget equation:

$$S_{net} + R = W_{net} + GH_{net} + SL_{net} + D \qquad \textbf{Equation 2-25}$$

CHAPTER III

RESULTS AND DISCUSSION

3.1 Model-Derived Water Budget

In the simulated water budget for the UKC-GFM, the well pumpage component is very small relative to the total water budget. Based on the calibrated UKC-GFM, recharge and storage are primarily balanced by storage outflows from the groundwater system, by discharge (drains) to perennial streams and groundwater discharge (stream leakage) to the major tributary streams and rivers, and by head-dependent boundary ("general head boundaries," or reservoirs) outflows from the groundwater system.

The simulated water budget shows the variations in inflows and outflows in the UKC-GFM (Fig. 3-1, Fig. 3-2), with net outflows from the groundwater system represented as negative numbers along the y-axis in Figure 3-2. Net inflow (Fig. 3-2) from groundwater recharge, which drives the system, is approximately 932,800 ft^3/s per year and is the largest groundwater budget net inflow. Net inflows from storage are the second largest net budget component (Fig. 3-2), and are approximately 539,400 ft^3/s per year. The next largest budget component represents reservoirs, predominately groundwater sinks, meaning groundwater flows into the reservoirs (net groundwater budget outflows) on an annual average basis. The general head boundaries (GHBs, or reservoirs) budget values (Fig. 3-1, Fig. 3-2) show that there are both flows into and out of the system, although outflows are higher, which suggests that reservoir water is capturing snowmelt that would otherwise mostly go to streams, or reservoirs are discharging to streams directly, likely regulating streamflow more than groundwater.

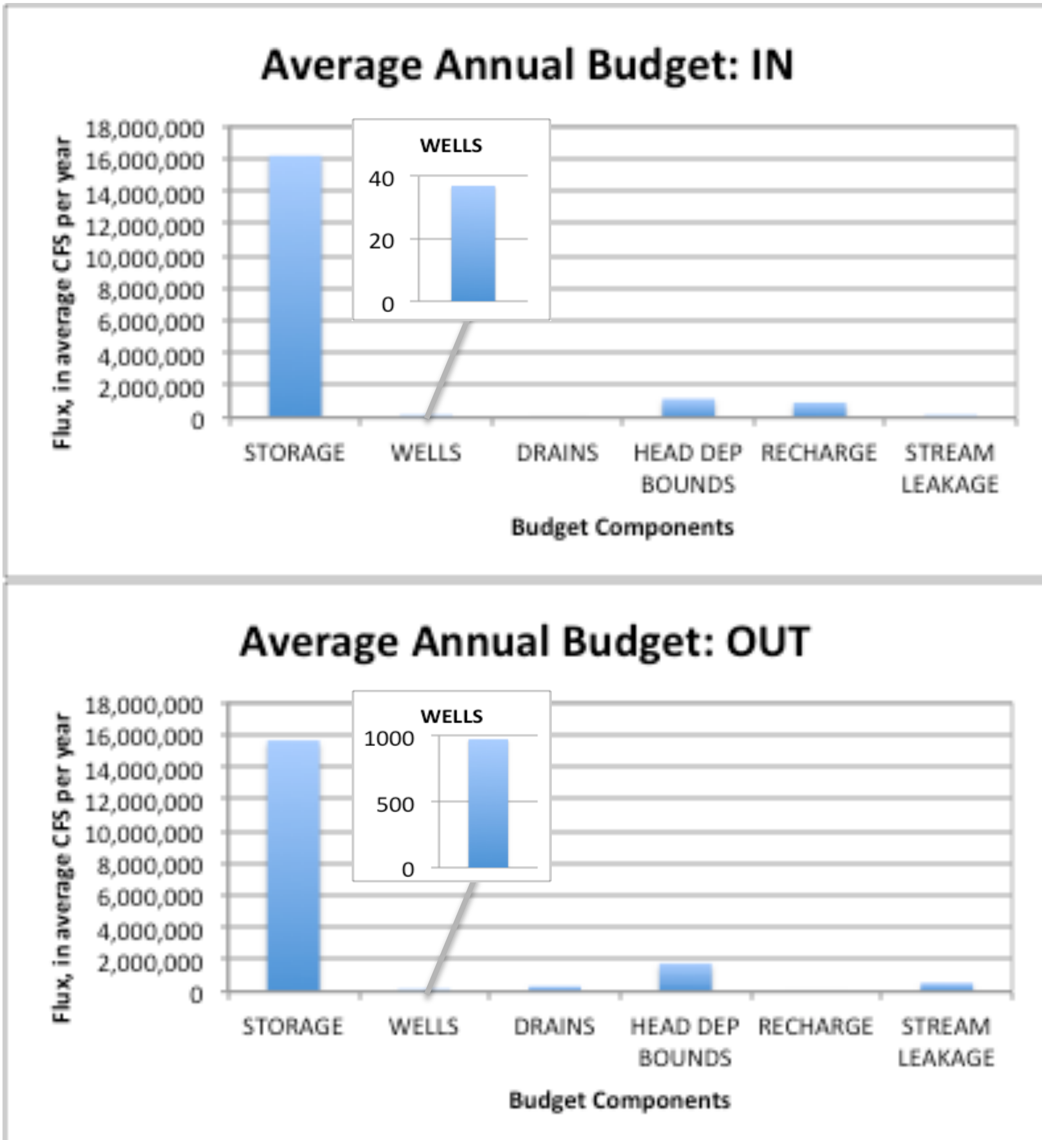


Figure 3-1. Simulated average annual groundwater budget for both inflows and outflows in the 10-year UKC-GFM, Upper Kittitas County aquifer system, Washington.

Groundwater discharge to streams (stream leakage outflows) (Fig. 3-1, Fig. 3-2) is approximately 544,800 ft^3/s per year, and is greater than stream leakage inflows, approximately 4,179 ft^3/s per year. Net stream leakage produces an outflow value of approximately 540,600 ft^3/s per year, and is the next largest net budget outflow component after general head boundaries. The low stream inflow into the groundwater

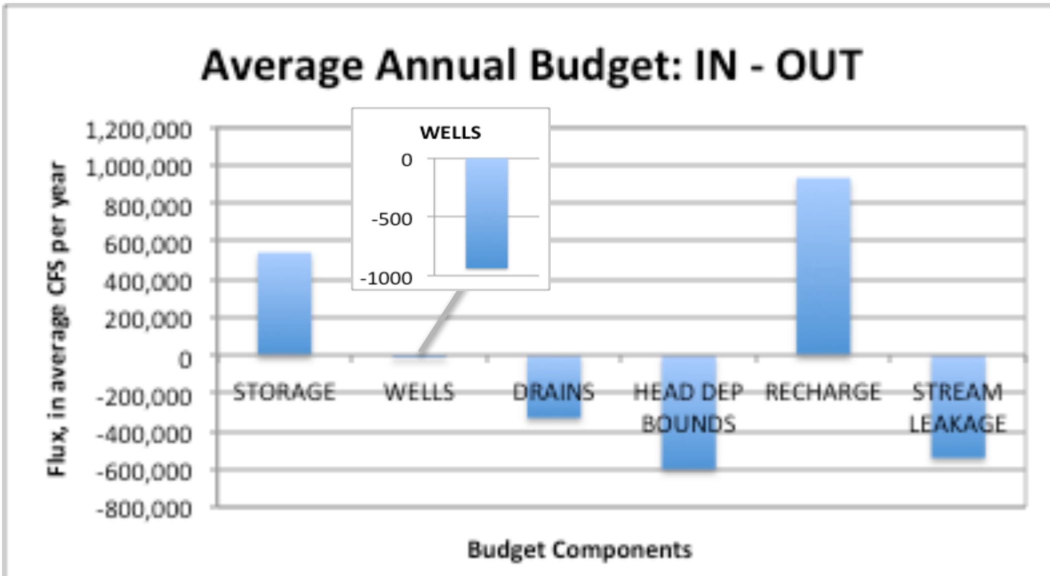


Figure 3-2. Simulated net average annual groundwater budget for inflows minus outflows in the 10-year UKC-GFM, Upper Kittitas County aquifer system, Washington.

budget suggests that streams are predominantly gaining and provide very little recharge to the groundwater system through losing reaches. The next largest net budget outflow component is drain outflow (Fig. 3-1, Fig. 3-2), which is the boundary condition that accounts for the groundwater discharge supporting streamflow in the humid uplands. Net groundwater discharge for the drains budget component is approximately 329,700 ft^3/s per year. Wells are the smallest net budget component, with a net outflow from the groundwater system of about 936 ft^3/s per year (Fig. 3-2). Outflows (pumpage) are approximately 973 ft^3/s per year, and inflows (septic returns) are 36 ft^3/year. The net wells budget component is the lowest budget component in the UKC-GFM, which is similar to the YRB-GFM (Ely et al., 2011), where the wells budget component is the third smallest after constant head (not a budget component in the UKC-GFM) and head-dependent boundaries. The small contribution of wells to the flow system can be explained because there are only 209 pumping wells by the end of the last model stress period (September 2001), which only cover a small portion of the study area, whereas the largest budget component, recharge, spans all of Upper Kittitas County.

The overall net (inflows minus outflows) groundwater budget components for the UKC-GFM balance accurately, within 0.01 percent, and represent the Upper Kittitas County groundwater system as accurately as is possible with the available information.

3.2 Model Applications (Scenarios)

Once calibrated, the UKC-GFM was given three model scenarios to assess the responses of the flow system in Upper Kittitas County to potential changes in stresses. Potential effects from model scenarios are assessed by comparing simulated output from the scenarios with simulated output from the calibrated base case UKC-GFM. All three scenarios were used to evaluate the impacts of stresses to the system for the ten-year model simulation period. The scenarios are:

Scenario 1: Existing Conditions Without All Pumping.

This scenario was performed in order to better understand the impacts of all pumping activities on surface water over the ten-year model simulation period. This scenario specifically addresses if pumping groundwater affects streamflow, and by how much. Instead of simulating a real world change that might happen to the watershed, this scenario is important because of the current groundwater moratorium imposed on all new well permits in Upper Kittitas County, which is in place because concerned senior surface water right holders worry that their rights have been depleted by groundwater pumpage. All pumping was removed from the model for this scenario.

Scenario 2: Decrease Recharge by 15 Percent.

This scenario was performed to better understand the impacts of potential climate changes on streamflow during the ten-year model simulation period. Scenario 2 specifically addresses if a decrease in recharge affects streamflow, and by how much. This scenario represents a potential realistic situation that might occur in the watershed. The decrease in recharge is based on previous work by Vaccaro (2010), in which a Deep Percolation Model (DPM) combined with climate inputs from five General Circulation Models (GCMs) produced an estimate for potential future conditions of 15 percent less recharge than current conditions. This scenario addresses what the impacts on surface water resources might have been if recharge had been 15 percent less during the ten year model simulation period. The only variable adjusted during this scenario was recharge.

Scenario 3: Increase Pumping by 15 Percent.

This scenario is a direct result of Scenario 2, and includes 15 percent more pumping, while using the same recharge values as in the base case UKC-GFM. It addresses the impacts on streamflow if water use in Upper Kittitas County were to increase for any reason, including climate change, population growth, or increased per capita domestic water use during the ten-year model simulation period. Scenario 3 specifically addresses if an increase in groundwater pumping affects streamflow, and by how much. Pumping at all wells was increased by 15 percent, which also affected septic returns in the study area.

A summary of scenario outcomes is displayed in Table 3-1.

TABLE 3-1. SIMULATED MEAN ANNUAL GROUNDWATER PUMPING AND STREAMFLOW FOR BASE CASE, AND MEAN ANNUAL CHANGE IN GROUNDWATER PUMPING AND STREAMFLOW FOR BASE CASE AND MODEL SCENARIOS, WATER YEARS 1992 THROUGH 2001, UPPER KITTITAS COUNTY AQUIFER SYSTEM, WASHINGTON.*

Scenario No.	Description	Ground-water Pumping (ft^3/s)	Change in pumping from base case (ft^3/s)	Streamflow (ft^3/s)		
				Yakima River at RM 183 (Cle Elum)	Yakima River at RM 171 (Horlick)	Little Creek near mouth
Base case	Calibrated model	973	--	1,820	2,180	20.9
Scenario 1	No pumping	0	-973	0.7	1.7	5×10^{-5}
Scenario 2	Decrease recharge by 15%	972	-1	-43	-81	-2.5
Scenario 3	Increase pumping by 15%	1,120	146	-0.1	-0.2	-3×10^{-5}

3.2.1 Scenario 1: Existing Conditions without All Pumping

The first scenario removed all groundwater pumping during the 10-year calibrated model simulation period. This scenario produced an increase in streamflow during the 10-year model period from the base UKC-GFM. Total (cumulative) eliminated pumping during this period was estimated at 9,730 ft^3/s in ten years, with mean annual pumpage of 973 ft^3/s per year. Comparatively the mean annual value for eliminated pumpage in the “no pumpage” scenario in the YRB-GFM is smaller, approximately 320 ft^3/s per year, because the YRB-GFM extends for a longer model period, 42 years, than the UKC-GFM and therefore incorporates water years with few wells and less pumpage. In the UKC-GFM, the mean annual difference in streamflow at Yakima River at RM 171 (Yakima River near Horlick, hereafter referred to as “Horlick”) is 1.7 ft^3/s (Table 3-1). The monthly difference in streamflow along the Yakima River between the calibrated UKC-GFM and the Scenario 1 streamflows increased in the downstream direction (Fig. 3-3); this is consistent with findings in the YRB-GFM (Ely et al., 2011), and supports the idea that flow is cumulative so effects to streamflow should increase downstream. For example, the monthly difference in streamflow at Yakima River at RM 204 was 9×10^{-3} ft^3/s in September of 2001, and increased to 4×10^{-1} ft^3/s at RM 186, and to 3.8 ft^3/s by RM 171 (Horlick). The simulated differences in streamflow also increased over time.

On a monthly basis, the largest increases in streamflow from the base model occurred from July to August, especially for the Yakima River at RM 183 (Yakima River at Cle Elum, hereafter referred to as “Cle Elum), 177, and 171 (Horlick); this reflects the downstream positions of these gages. Maximum monthly differences in streamflow exceeded the annual differences at gage sites, with the greatest monthly difference of 3.8 ft^3/s occurring at the Yakima River at RM 171 (Horlick) in September of 2001, with an annual difference of 2.9 ft^3/s at the same gage for water year 2001; the greatest annual difference of 3.1 ft^3/s occurred at Yakima River at RM 171 (Horlick) in water year 2000. The smallest monthly effects to streamflow occurred at two of the four tributaries, with average monthly values of 1×10^{-4} ft^3/s for Little Creek near Mouth, and 6×10^{-4} ft^3/s

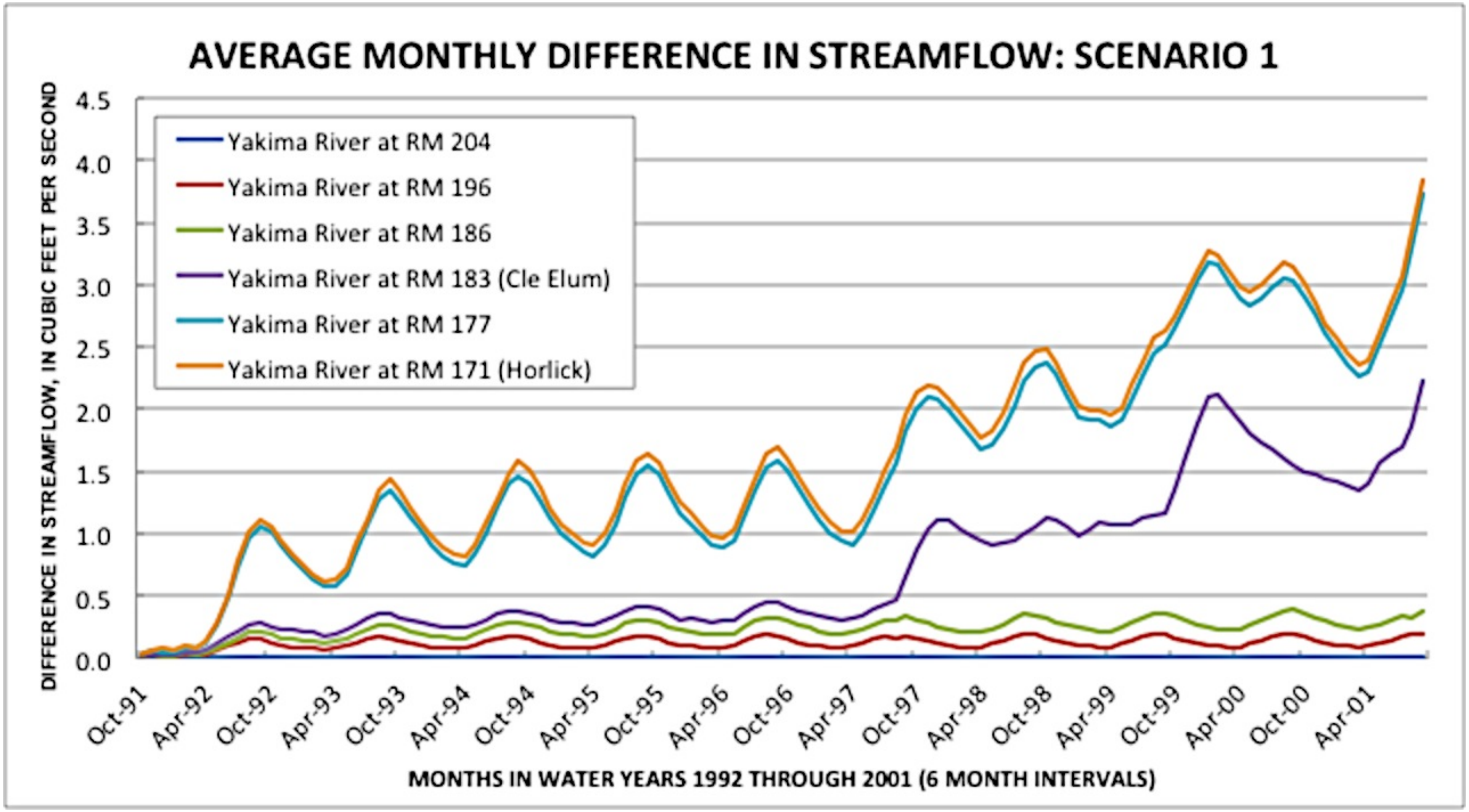


Figure 3-3. The difference in average monthly streamflow between existing conditions and existing conditions without groundwater pumping for Yakima River stream gages during the last ten water years (water years 1992 through 2001), Scenario 1, Upper Kittitas County aquifer system, Washington.

for Cabin Creek; the greatest monthly effects to streamflow for tributaries occurred at the Swauk Creek gage, with an average value of 8×10^{-2} ft^3/s. The average annual difference in streamflow for Little Creek near Mouth is 5×10^{-5} ft^3/s (Table 3-1). One explanation for the small effects of pumping to streamflow in small tributaries such as Little Creek is that less groundwater pumping occurs along Little Creek than along the Yakima River (Fig. 2-6), so a relatively smaller increase in streamflow is reasonable at Little Creek during Scenario 1. Additionally, there are fewer model hydraulic head observations (Fig. 2-14) used for calibration at this location than there are along the main stem of the Yakima River. Therefore data for calibration is coarse in Little Creek, and streamflow differences are more difficult to simulate in the UKC-GFM. The small tributary monthly changes were not plotted in Figure 3-3, which only displays Yakima River stream locations. On average, the smallest monthly effects to streamflow for Yakima River gages occurred at RM 204, the most upstream gage, with an average value of 7×10^{-3} ft^3/s. Small monthly change in streamflow occurred at the "Cle Elum River above lake" gage, with an average value of 4×10^{-3} ft^3/s. For all sites, average annual differences ranged from 4×10^{-3} ft^3/s (at Yakima River at RM 204 in water year 1992, to 3.1 ft^3/s at RM 171 (Horlick) in water year 2000, with the greatest annual difference of 2.9 ft^3/s at Horlick in water year 2001.

A visible trend in the Scenario 1 deviations from the base model (Fig. 3-3) occurs for Yakima River at RM 171 (Horlick) and Yakima River at RM 177, where there is a gap from RM 183 to RM 177, with an average difference of 0.9 ft^3/s. This happens because these two gages are downstream of the town of Cle Elum (Yakima River at RM

183 is the Cle Elum gage), so these gages therefore feel the effects of pumping more strongly due to the relative population density in Cle Elum compared to other gages along the Yakima River. In water year 1997, the sudden increase in streamflow for the Yakima River at RM 171 (Horlick), the Yakima River at RM 177, and the Yakima River at RM 183 (Cle Elum) occurs because the Cle Elum Fish Hatchery opened in 1997, and the hatchery installed new wells, which increased the effects of pumping to streamflow for streams near to, and downstream of, Cle Elum. Similar to the hydrographs for the base UKC-GFM (Fig. 2-17), peaks in monthly streamflow occur during warm months, April through September, and low flows occur in cool temperature months, October through March.

The UKC-GFM provides an approximate simulated value for the impacts of groundwater withdrawals to streamflow. Based on the annual difference produced by the UKC-GFM in Scenario 1, approximately 2.9 ft^3/s of streamflow are removed from the Yakima River by groundwater withdrawals in Upper Kittitas County at the end of the model simulation at the most downstream gage. While this value is relatively small, it is significant in terms of current Washington water law, specifically as it relates to the Washington Supreme Court Postema Decision, which is now a permanent Revised Code of Washington (RCW 90.40.035), and states that, "…to the extent that any underground water is part of or tributary to the source of any surface stream or lake, or that the withdrawal of groundwater may affect the flow of any spring, water course, lake, or other body of surface water, the right of an appropriator and owner of surface water shall be superior to any subsequent right hereby authorized to be acquired in or to groundwater."

To summarize RCW 90.40.035, groundwater pumping connected to junior water rights may not decrease surface water (streamflow), connected to senior water rights.

3.2.2 Scenario 2: Decrease Recharge by Fifteen Percent

Existing conditions with recharge decreased by 15 percent are presented in this scenario, and are compared to the base UKC-GFM conditions to assess the system's responses to change in recharge for potential near-future conditions. For this scenario all recharge in the UKC-GFM domain was decreased 15 percent, lowering total (cumulative) recharge in the base model from 9,330,000 ft^3/s to 7,930,000 ft^3/s in ten years (mean annual recharge decrease from 933,000 ft^3/s per year to 793,000 ft^3/s per year).

Scenario 2 streamflow decreased over the 10-year model period when compared to the base UKC-GFM, with monthly differences in streamflow becoming greater in the downstream direction (Fig. 3-4). The average monthly difference in streamflow at Yakima River at RM 204 (most upstream Yakima River gage) decreased by 6.5 ft^3/s in September of 2001, and by 47 ft^3/s at Yakima River at RM 171 (Horlick) in the same month and year. The greatest monthly difference in streamflow was a decrease of approximately 178 ft^3/s in May 1997 at Yakima River at RM 171 (Horlick). For all Yakima River sites, annual differences ranged from a decrease of approximately 6.7 ft^3/s (at Yakima River at RM 204 in water year 1992, to an annual decrease of 80 ft^3/s at RM 171 (Horlick) in water year 2001, with the greatest annual decrease of 146 ft^3/s at Horlick in 1997. Mean annual differences in streamflow between Scenario 2 and the Base model (Table 3-1) ranged from a decrease of approximately 2.5 ft^3/s at the Little Creek gage, a decrease of approximately 43 feet at the Yakima River at RM 183 (Cle Elum), and a decrease of approximately 81 ft^3/s at the Yakima River at RM 171 (Horlick).

Figure 3-4 displays the average monthly differences in streamflow between Scenario 2 (decrease recharge by 15 percent) and the base model, and illustrates the pattern of increased impacts to streamflow in the downstream direction. Compared to Scenario 1 results (Fig. 3-3), the Scenario 2 graph (Fig. 3-4) does not display as strong of a linear relationship over time. However, when a linear regression trendline is applied to the Yakima River at RM 171 gage (Horlick), the linear equation $y = -0.0147x + 438$ is produced, with a correlation coefficient of $R^2 = 0.183$. Furthermore, the trendline for the Yakima River at RM 196, a more downstream gage, is $y = -0.004x + 115$, with a correlation coefficient of $R^2 = 0.169$. Although R^2 values are low, these linear equations have negative slope values, and therefore demonstrate a trend in the data for overall decreases in streamflow at individual gages over time.

One explanation for the muted overall decrease in streamflow over time is that groundwater recharge in Upper Kittitas County, previously calculated by Vaccaro and Olsen (2007) (Fig. 2-9) decreases from west to east across the basin, so the results of Scenario 2 (Fig. 3-4) suggest that streamflow is sensitive spatially, in relation to recharge. Additionally, the greatest monthly difference in streamflow, a decrease of 178 ft^3/s at Yakima River at RM 171 (Horlick), occurred in May 1997 (Fig. 3-4) and not at the end of the model simulation; 1997 is a recorded above average recharge (or “wet”) year in the Yakima River Basin (Ely et al., 2011). Graph 3-5 displays the results as percent change in streamflow, over a six-point moving average of all monthly averages during water years 1992 through 2001. Percent change, or the percentage decrease in streamflow each month, was calculated as:

$$Percent\ change = \frac{[original\ number]-[new\ number]}{original\ number} \times 100 \qquad \textbf{Equation 3-1}$$

Since the graph is a six-point moving average, each point on the graph represents an average over six months; for example, the first point averages the monthly averages for Oct 1991 through March 1992. The moving average method was used to reduce the amount of data, thereby making trends stand out and reducing noise. If differences are converted to percent changes relative to total streamflow (Fig. 3-5), then the same general patterns in this graph persist and the May 1997 change is still the greatest. This suggests that the impacts of reduced recharge to streamflow are greater during wet years.

In summary, the calibrated UKC-GFM simulates an annual loss of 80 ft^3/s at the most downstream Yakima River gage, Yakima River at RM 171 (Horlick), by the end of the model simulation, water year 2001. Therefore, the model predicts that a 15 percent decrease in recharge in Upper Kittitas County would decrease streamflow in the Yakima River by approximately 80 ft^3/s by the end of the model simulation, before exiting the model area. This is a 4.7 percent decrease in streamflow from the base model, and is the greatest impact to streamflow when compared to Scenarios 1 and 3.

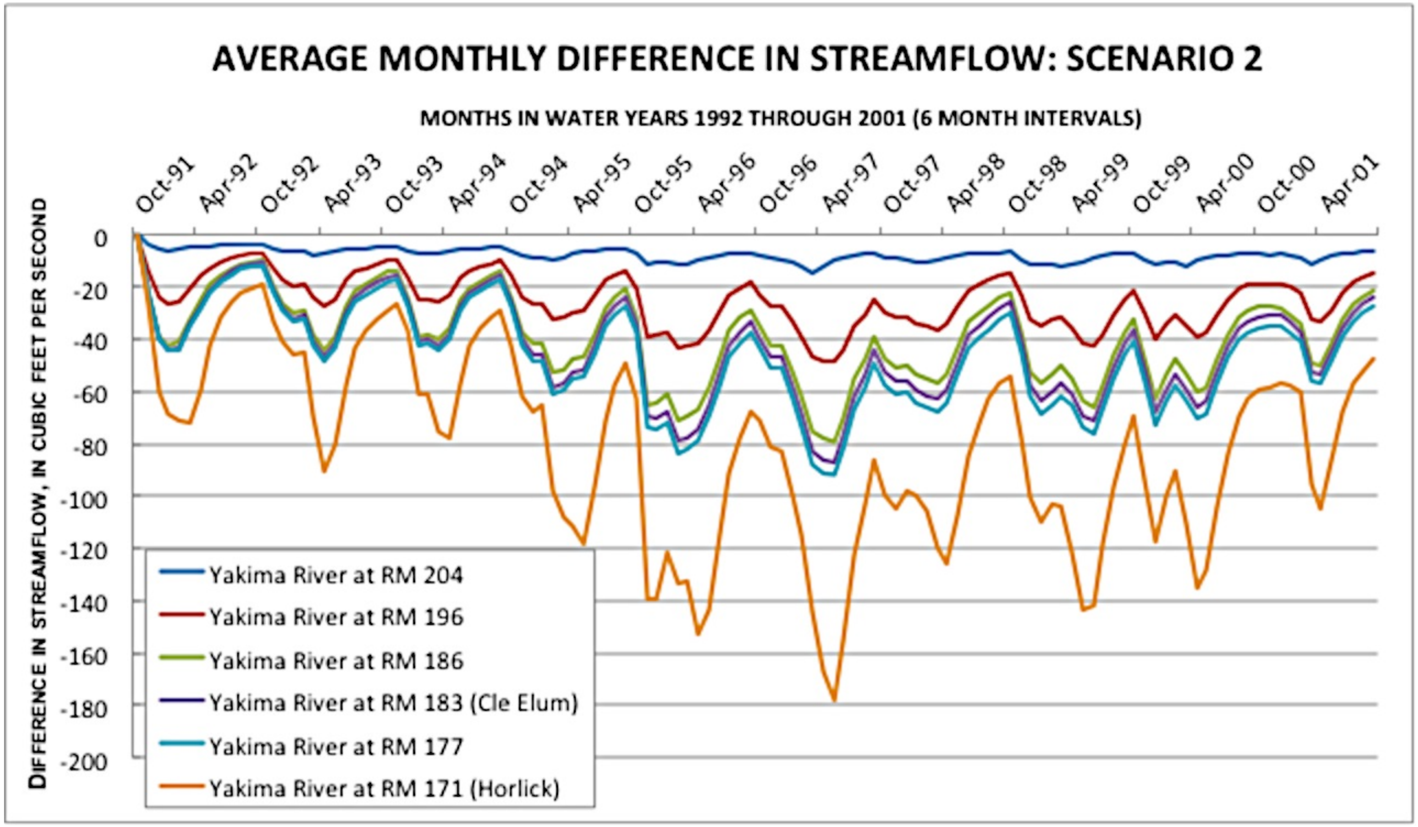


Figure 3-4. The difference in average monthly streamflow between existing conditions and existing conditions with recharge decreased by fifteen percent during the last ten water years (water years 1992 through 2001), Upper Kittitas County aquifer system, Washington.

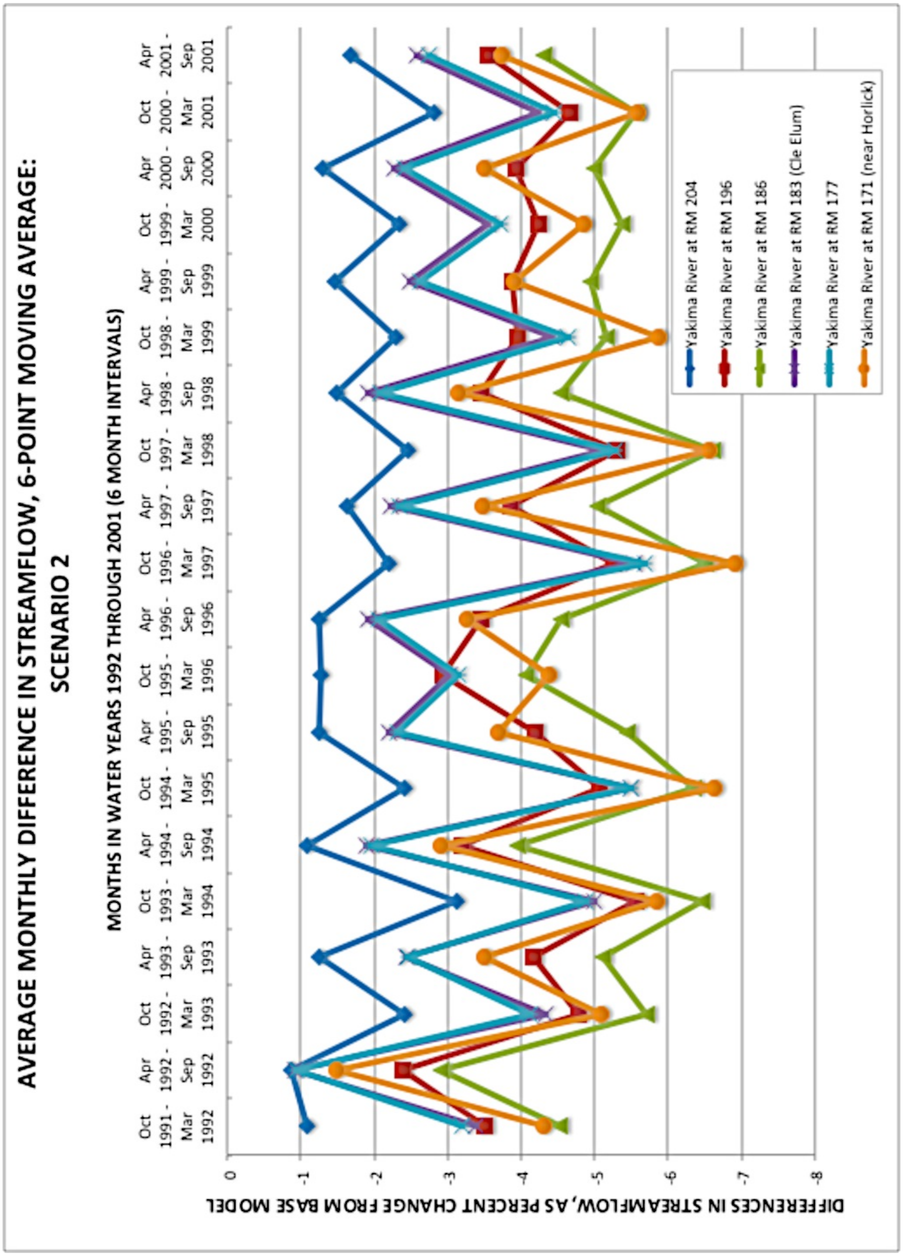


Figure 3-5. The percent change in average monthly streamflow between existing conditions and existing conditions, with recharge decreased by fifteen percent during the last ten water years (water years 1992 through 2001), Upper Kittitas County aquifer system, Washington. Time is plotted as a six point (six month) moving average.

3.2.3 Scenario 3: Increase Pumpage by Fifteen Percent

Scenario 3 assesses impacts to streamflow under existing conditions with pumpage increased by 15 percent, as compared to the UKC-GFM base case. This scenario demonstrates the system's response and sensitivity to the stresses of increased pumping if needed. Such pumpage is a potential response to Scenario 2, where recharge is decreased by 15 percent, but this scenario keeps recharge at base case levels, and assesses increased pumpage separately to exhibit the system's response to only the increase in pumpage. Combining both the decreased recharge and increased pumpage scenarios would demonstrate a very conservative worst-case scenario; such a combined scenario was not performed because the impacts of decreased recharge would dominate the scenario.

For Scenario 3, groundwater pumping was increased 15 percent, raising total (cumulative) pumping from the base model, about 9,730 ft^3/s in ten years (mean annual pumping of 973 ft^3/s per year), to 11,200 ft^3/s in ten years (mean annual pumping of 1,119 ft^3/s per year) for Scenario 3. Overall streamflow in Scenario 3 decreased due to increased pumping over the 10-year model period when compared to the base UKC-GFM. Similar to Scenario 1, impacts to streamflow intensified in the downstream direction and over time (Fig. 3-6). For example, the average monthly differences in streamflow during September of 2001 were decreases of 1×10^{-3} ft^3/s at Yakima River at RM 204, 6×10^{-2} ft^3/s at RM 186, and finally 6×10^{-1} ft^3/s by RM 171 (Horlick, the most downstream gage), which is the maximum monthly difference for this scenario.

On a monthly basis, the largest decreases in streamflow generally occurred from July to August, especially for the Yakima River at RMs 183 (Cle Elum), 177, and 171 (Horlick), all downstream gages. Maximum average monthly differences in streamflow exceeded the annual differences at gage sites, with the greatest monthly difference, a decrease of approximately 6×10^{-1} ft^3/s, occurring at Yakima River at RM 171 (Horlick) in September of 2001, with an annual decrease of 4×10^{-1} ft^3/s at the same gage for water year 2001; the greatest annual difference of 5×10^{-1} ft^3/s occurred at Yakima River at RM 171 (Horlick) in water year 2000. On average, the smallest monthly effects to streamflow occurred in tributaries (not plotted in Figure 3-6), with average monthly decreases of 1×10^{-3} ft^3/s for Little Creek near Mouth and Big Creek near Mouth, and $4x10^{-2}$ ft^3/s for Swauk Creek.

Similar to the Scenario 1 results (Fig. 3-3), a trend in the Scenario 3 deviations from the base model (Fig. 3-6) occurs for Yakima River at RM 171 (Horlick) and Yakima River at RM 177, where both river miles (gages) jump in values from the more upstream Yakima River at RM 183. This again relates to the proximity of these two gages to the more populated town of Cle Elum. Additionally, similar again to Scenario 1 results, the sudden increase in 1997 in streamflow for the Yakima River at RM 171 (Horlick), the Yakima River at RM 177, and the Yakima River at RM 183 (Cle Elum) occurs due to the opening of the Cle Elum Fish Hatchery in 1997.

Based on Scenario 3 results, a simulated moderate 15 percent increase in pumping within Upper Kittitas County removes approximately 4×10^{-1} ft^3/s of streamflow annually at the most downstream gage, Yakima River at RM 171 (Horlick), by the end of the model simulation period, water year 2001. Although small, this result is relevant because the law RCW 90.40.035 states that groundwater pumping may not impinge upon surface water right holders, who are senior to groundwater right holders; the UKC-GFM provides an approximation of potential impacts to streamflow if further allocation of groundwater becomes necessary due to potential future changes in climate that decrease recharge by 15 percent, or due to the building of new developments in the study area. Additionally, scenarios similar to Scenario 3 can also represent situations involving the differences between current water use rates and current water rights. For example, an exempt well is allowed 251 gpd; however, people typically use less than their full water right, but are legally allowed to pump the full amount.

Given the effects of groundwater pumping to streamflow, as simulated in Scenario 3, future work to better understand this connection could involve the use of particle tracking. Particle tracking, or particle backtracking, can be applied to existing groundwater models in order to determine flow paths and flow times from groundwater locations (wells) back to simulated source areas for the wells at land surface. The particle tracking technique was previously applied to the YRB-GFM by Bachmann (2015) to determine potential surface contributing zones of nitrate concentrations in groundwater samples from wells in the lower Yakima River Basin. Particle tracking for Upper Kittitas County could place particle starting points in groundwater wells in model cells of the UKC-GFM, and then follow the groundwater flow pathlines backwards in time to their endpoints (source areas). Such groundwater flow paths might reveal more about a groundwater well's connectivity to recharge from the water table, and/or connectivity to the Yakima River and its tributaries. Another potential starting point for particles in the UKC-GFM is the most downstream location of the model, near the Yakima River at RM 171 gage (Horlick); backtracking particles from the streambed near Horlick gage could reveal a simulated flow path and particle history for how water accumulates at the end of the model. Particle tracking could also reveal travel times through varied aquifer materials; for example, Bachmann (2015) observed shorter simulated groundwater flow travel times through basin fill sediments than in basalt or bedrock material.

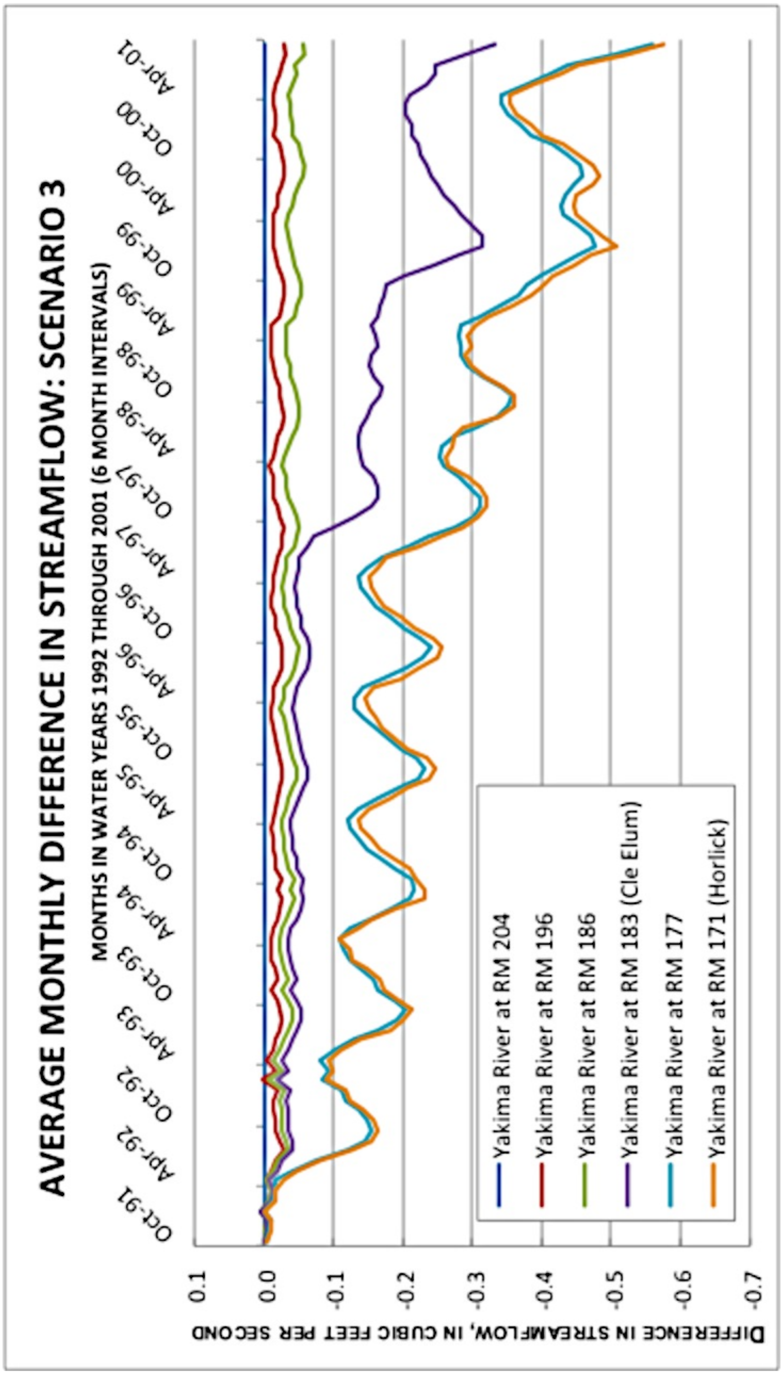


Figure 3-6. The difference in average monthly streamflow between existing conditions and existing conditions with pumping increased by fifteen percent for Yakima River stream gages during the last ten water years (water years 1992 through 2001), Scenario 3, Upper Kittitas County aquifer system, Washington.

3.3 Effects of Climate Change on Upper Kittitas County

Scenario 2, in which recharge in Upper Kittitas County is decreased by 15 percent, represents a relatively conservative estimate of future climate change in Upper Kittitas County. The recharge estimate is based on the Deep Percolation Model (DPM) of Bauer and Vaccaro (1990), which uses climate predictions from General Circulation Models (GCMs). Based on the same predictions, Vaccaro (2010) applied a moderate 15 percent decrease in recharge to models of the Columbia Plateau aquifer system (Vaccaro, 1999; Hansen et al. 1994) in Washington, which is near Upper Kittitas County. The predicted 15 percent decrease for future potential groundwater recharge, when applied to the Columbia Plateau aquifer model, resulted in potential water level declines of over 100 feet. Such water level declines would necessarily impact river levels, thereby impacting surface and groundwater rights as well as river habitats.

Vaccaro's (2010) study and Scenario 2 are relevant because additional reports and studies predict climate change impacts to the hydrologic system in the Pacific Northwest. Mantua et al. (2010) writes that mean annual temperatures for the Pacific Northwest will increase by approximately 3.2 degrees Celsius (when compared to the 1980s) by the 2080s. As a result of this change, by the 2080s, snow water equivalent (SWE) from glaciers and snowpack in the Cascade Mountains will decrease by 56 to 70 percent, and SWE in the Yakima River Basin will decrease by 67 to 80 percent (Elsner et al., 2010). This means that streamflow in areas such as Upper Kittitas County will become dependent on rainfall instead of snowmelt, as is currently true. Additional impacts to streamflow include changes in the timing and quantity of seasonal flows. Specifically, unregulated rivers and streams will have flows that peak higher and earlier in spring months, and will also have warmer surface water temperatures with lower water levels in summer months. Climate change in Upper Kittitas County will also impact fish; Chinook salmon and Steelhead are both present in the Yakima River. In addition to lowering instream flows, by the 2080s the increase in stream temperatures in the Columbia Plateau aquifer system is predicted to reach weekly average temperatures greater than 21 degrees Celsius, which is dangerous for salmon, which survive best in stream temperatures at or below 15 degrees Celsius (Osborn, 2012).

The results of Scenario 2 suggest that potential future climate change that causes a 15 percent decrease in recharge will result in a significant decrease in streamflow in all rivers. In the Yakima River sites at RM 183 (Cle Elum) and RM 171 (Horlick), this amounts to a 2 to 4 percent decrease in mean annual streamflow (Table 3-1). At Little Creek, which represents many of the small tributaries in the area, the mean annual streamflow is reduced by approximately 12 percent. Given that surface water is entirely appropriated within the Yakima River Basin and that some surface water rights are on small tributary streams, water resource planners should consider this result. For example, if a priority is to maintain instream flows for fish passage and to maintain healthy stream ecology, surface water withdrawals would need to be reduced.

CHAPTER IV

SUMMARY AND CONCLUSIONS

A transient numerical model was developed in order to assess the groundwater flow system of Upper Kittitas County, Washington. The Upper Kittitas County Groundwater Flow Model (UKC-GFM) simulates groundwater and surface water in the northern Yakima River Basin; the Yakima River Basin is a larger area previously modeled by the U.S. Geological Survey (USGS) (Ely et al., 2011). The UKC-GFM was constructed using the USGS finite-difference modeling program, MODFLOW-NWT (Niswonger et al., 2011). The UKC-GFM is made up of 1,000-foot cells that together form 195 rows and 246 columns. Temporal discretization for the UKC-GFM is a daily time step. There are five model layers and 11 hydrogeologic units within the UKC-GFM. The Yakima River and its major tributaries are included as streamflow-routing cells, and smaller tributaries are included as drain cells. Recharge was estimated during a previous model study (Vaccaro and Olsen, 2007). Groundwater pumping values were also estimated in a previous study (Vaccaro and Sumioka, 2006).

The UKC-GFM was calibrated to transient observed conditions for the 10-year period October 1991 through September 2001, a total of 120 monthly stress periods. Model calibration included comparisons of simulated versus observed water levels and streamflow, using trial and error methods and parameter-estimation software (PEST; Doherty, 2010). At 116 well measurement points, the average difference between simulated and measured hydraulic heads (residuals) is +73 feet, and the RMS error of the difference between simulated and measured hydraulic heads divided by the total difference in water levels is equal to 1.5 percent, which is an acceptable calibration standard. Therefore, the model does a good job of simulating the water table. Annual differences (percent differences) for measured and simulated streamflow at seven sites ranged from 7 to 11 percent along the Yakima River, and ranged from 19 to 49 percent along tributaries.

Three model scenarios were applied to the UKC-GFM to assess the system's reactions to stresses, specifically pumping and recharge. The three scenarios removed all pumping (Scenario 1), decreased recharge by 15 percent (Scenario 2), and increased pumping by 15 percent (Scenario 3). In Scenario 1, the annual difference in streamflow at the Yakima River at RM 171 (Horlick), the most downstream gage in Upper Kittitas County, was an increase of approximately 2.9 ft^3/sec in 2001, with a monthly average increase of 3.8 ft^3/sec in September of 2001, the final month and year of the simulation period. In Scenario 2, the annual difference for the same stream gage was a decrease of approximately 80 ft^3/sec in 2001, with a monthly average difference of 47 ft^3/sec in September of 2001; the greatest monthly average difference for the Horlick gage in Scenario 2 is a decrease of 178 ft^3/sec in May of 1997 (not linear over time). In Scenario 3, the annual difference for the same stream gage was a decrease of approximately 4×10^{-1} ft^3/sec in 2001, with an average monthly difference of 6×10^{-1} ft^3/sec in September of 2001.

The application of scenarios to the UKC-GFM allowed for a better understanding of the relationships between both the flow system and water availability within Upper Kittitas County. Based on results from the three applied scenarios, climate change stresses have a greater potential impact on simulated base streamflow than pumping stresses, with the annual difference in streamflow at Yakima River at RM 171 (Horlick) during the final stress period (water year 2001) in Scenario 2 (15 percent decrease in recharge) producing a 4.7 percent decrease in streamflow, and Scenario 1 (all pumping removed) producing a 0.17 percent increase in streamflow.

Water resources in Upper Kittitas County are considered over allocated. Additionally, the current Upper Kittitas Groundwater Rule (Chapter 173-539A WAC) halts the drilling of new unmitigated domestic ("exempt") groundwater wells in Upper Kittitas County, and water law RCW 90.40.035 states that groundwater rights may not impinge upon senior surface water rights. Therefore, a pumping scenario that simulates an increase in streamflow when groundwater pumping is removed (Scenario 1) is important because it provides Kittitas County lawmakers with a tool to approximate how overall groundwater pumping affects streamflow. A scenario that simulates a decrease in streamflow when recharge is decreased by 15 percent (Scenario 2) suggests that surface water withdrawals may need to be reduced in the future if surface water resources and target flows for fish are to be maintained. A scenario that simulates a decrease in streamflow when pumping is increased 15 percent (Scenario 3) highlights the importance of the current rules surrounding groundwater appropriation in Upper Kittitas County, and provides an approximation of how potential future development or population growth that requires new groundwater rights impacts streamflow. Scenario 3 also addresses how an increase in groundwater pumping due to a conservative decrease in groundwater recharge (Scenario 2) could impact streamflow. Based on model calibration and results from the three scenarios, the UKC-GFM is a useful tool for understanding the groundwater flow system as a whole, and assessing stresses such as groundwater pumping and climate change that reduces groundwater recharge.

Future studies in Upper Kittitas County could include the use of particle tracking to backtrack a simulated groundwater flow path from a groundwater well in the UKC-GFM to its source area from the water table, or to the Yakima River and/or its tributaries. Another future study might further investigate bedrock in Upper Kittitas County because, in section 2.5.3 of this report, it was determined that the calibration of hydraulic heads and streamflow in the UKC-GFM is sensitive to bedrock parameters, especially those relating to hydraulic conductivity. An example future study could re-model subsurface bedrock boundaries in the UKC-GFM, based on newly delineated bedrock boundaries from well log lithology information for Upper Kittitas County (Gendaszek et al., 2014). Finally, faults, fractures, folds in bedrock, and corresponding hydraulic conductances, could be simulated in the UKC-GFM through application of the horizontal flow barrier (HFB) package, in order to determine the extent to which these model properties act as barriers or conduits to groundwater flow.

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