Hydrology of the Hangman Creek Watershed (WRIA 56), Washington and Idaho

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Executive Summary

Water resources inventory area (WRIA) 56 encompasses the Hangman (Latah) Creek watershed in Washington, with headwaters in Idaho. The basin covers 431,220 acres and contains approximately 222 miles of perennial streams. The headwaters in Idaho lie at an elevation of about 3,600 feet above mean sea level, and at its confluence with the Spokane River the elevation is 1,720 feet above mean sea level.

The geology varies considerably within the basin. The primary geological units include, from oldest to youngest: 1) crystalline basement rocks of meta-sedimentary and igneous plutonic origin that underlie the entire region and occur in the higher peaks, 2) widespread horizontally-bedded volcanic rocks consisting of basalt flows separated by laterally discontinuous sedimentary interbeds, and 3) unconsolidated surficial deposits consisting primarily of flood-deposited sand and gravel and the wind-deposited silts that comprise the rolling hills characteristic of the Palouse.

An unconfined aquifer exists in the sand and gravel deposits in the lower portion of WRIA 56, below the confluence of Rock and California Creek. The water table in this aquifer unit is strongly connected to, and is influenced by, the stage of flow in Hangman Creek. Groundwater discharge from the Hangman valley aquifer and into the lower Spokane aquifer is almost 13 cubic feet per second. However, the most prolific and important aquifer in WRIA 56 is contained within the Columbia River Basalts where multiply stacked confined or semi-confined aquifers are accessible through deep wells. Due to its limited recharge potential within WRIA 56, the basalt aquifer system may be impacted by increasing groundwater withdrawals into the future.

The climate in WRIA 56 is generally very warm and dry in the summer and cool and moist during the winter. Because of the large range in elevation in the watershed significant variation in precipitation occurs, from less than 16 inches/year in the lower part of the basin that is sub-arid, to more than 40 inches/year in the upper part that is sub-humid. Area-weighted calculations of evapotranspiration in the watershed, when compared to the areal distribution of precipitation, show that there is a moisture surplus of 173,882 acre feet per year. This excess water is free to either run off into surface streams, or to infiltrate into the ground to recharge shallow and/or deep aquifer systems.

Surface water appropriations in WRIA 56 have the potential to impact stream flows during the summer months, especially in the Lower Hangman and Marshall/Minnie Creek sub-basins. Groundwater mining is certainly a high potential, particularly in the Lower Hangman and Marshall/Minnie Creek sub-basins where water right allocations from groundwater greatly exceed the recharge rate. Allocated surface water rights are 3.9% of the total annual average stream flow in WRIA 56, while allocated surface water and groundwater rights are 19.7% of the average annual stream flow.

Introduction

The Hangman (Latah) Creek watershed, also known as WRIA (water resource inventory area) 56, is facing a future with numerous water-related issues. Increasing urbanization and changing land use practices is placing growing pressure on water development versus protection of stream flows and related stream and riparian habitat. The Spokane County Conservation District (SCCD) is the lead agency responsible for watershed planning, facilitated by a grant obtained through the Washington State Department of Ecology (grant number G0000101). This study and report are prepared in fulfillment of a contract between SCCD and Eastern Washington University. Walt Edelin and Rick Noll at SCCD were particularly instrumental in overseeing this technical work.

Purpose and Objectives

The primary purpose of this study is to review pertinent hydrologic and geologic literature and establish a general water balance for the Hangman (Latah) Creek watershed (WRIA 56). The study area includes all of the land within the watershed which spans two states and four counties: Spokane and Whitman Counties in Washington and Benewah and Kootenai Counties in Idaho.

The specific tasks/objectives in the scope of work are:

1. Delineation of watershed boundaries used for the water balance calculations
2. Determine groundwater flow within and leaving the basin
3. Estimate direct recharge from precipitation
4. Determine the impact of irrigation on groundwater recharge
5. Evaluate the potential for numerical modeling of the study area

Data Sources

Much of the information in this report is gleaned from numerous published sources and agency records. The primary data used in this study is attributed to:

SCCD	Spokane County Conservation District
NRCS	Natural Resources Conservation Service
USGS	U.S. Geological Survey
NOAA	National Oceanographic and Atmospheric Administration
IDWR	Idaho Department of Water Resources
WDOE	Washington Department of Ecology

General Basin/Watershed Description

The Hangman Creek drainage basin is located in eastern Washington and northern Idaho, and comprises 431,220 acres, with 64% (276,803 acres) in Washington and 36% (154,417 acres) in Idaho. Approximately 222 miles of perennial streams occupy the basin, with the largest tributaries to the mainstem being Rock Creek and California Creek (SCCD, 1994). The mainstem of Hangman Creek itself is tributary to the Spokane River with its confluence at the intersection of the Lower Spokane (WRIA 54) and Middle Spokane (WRIA 57) reaches.

The headwaters in Idaho lie at an elevation of about 3,600 feet above mean sea level, and at its confluence with the Spokane River the elevation is 1,720 feet above mean sea level. Along its course, Hangman Creek flows from mountainous topography, across rolling hills in the Palouse, then into deep and narrow basalt canyons, and ultimately into a broad alluviated valley as it joins the Spokane River (SCCD, 1994).

The basin contains a wide variety of land uses, including cropland, forest and range land in the upper part of the basin, to smaller residential parcels and intensely urbanized areas in the lower basin. The stream channel has undergone significant changes in historical times, including straightening and channelization, and the riparian areas are increasingly affected by encroaching roadways and other structures that require stream bank stabilization (SCCD, 1994).

The climate in WRIA 56 is generally very warm and dry in the summer and cool and moist during the winter. Because of the large range in elevation in the watershed significant variation in precipitation occurs, from less than 16 inches/year in the lower part of the basin that is sub-arid, to more than 40 inches/year in the upper part that is sub-humid (SCCD, 1994).

Sub-Basin Geology and Hydrogeology

In cooperation with the SCCD, the entire WRIA 56 watershed was divided into five smaller sub-watersheds/basins (Figure 1). These include the following, from largest in area to the smallest:

	Area (square miles)	**Area (acres)**
Upper Hangman	334.9	214,383
Rock Creek	179.0	114,589
California Creek	24.9	15,942
Lower Hangman	71.8	45,947
Marshall/Minnie Creek	63.1	40,359

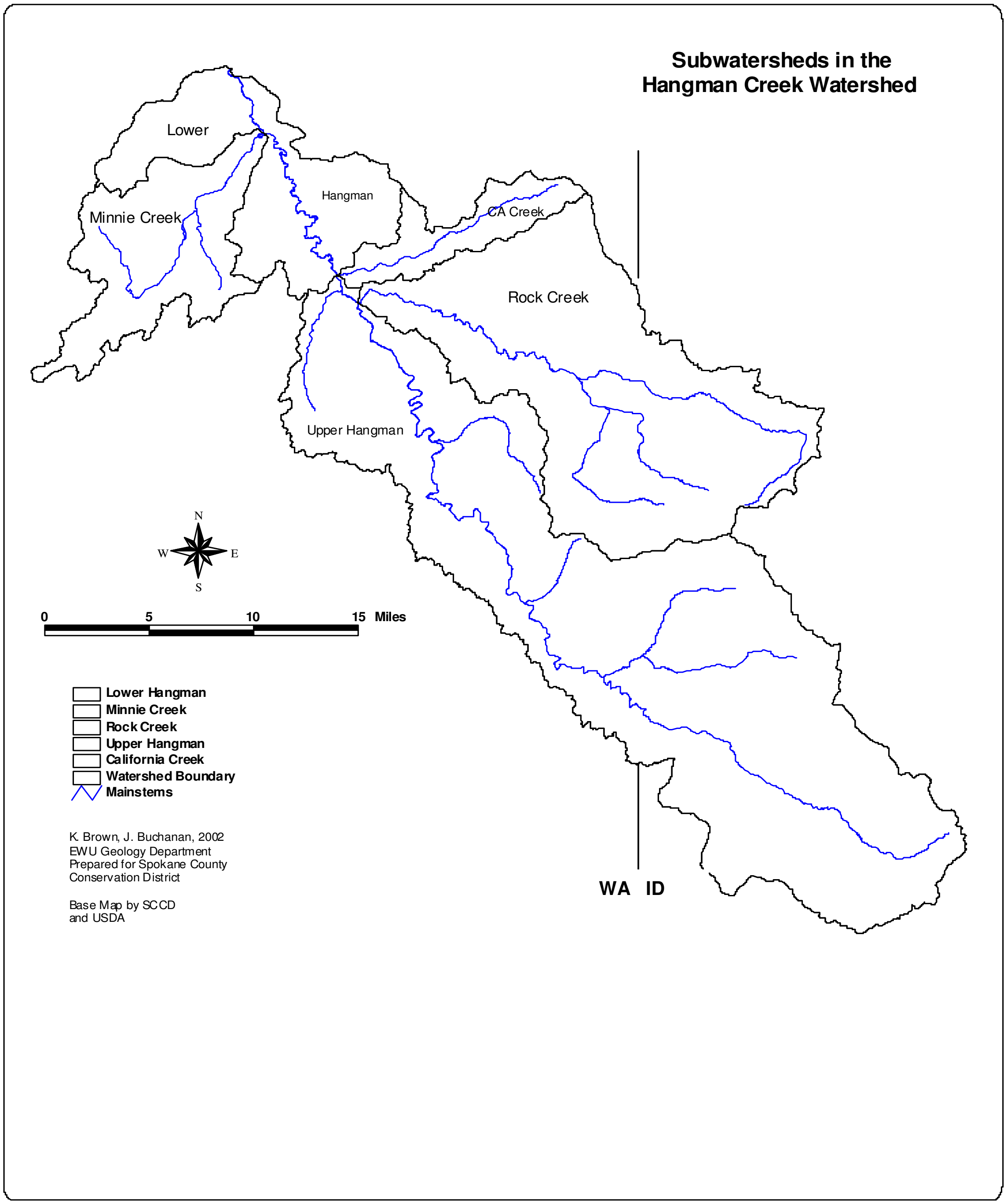

Figure 1. Map showing overall area of WRIA 56 including five sub-watersheds/basins.

Within the overall WRIA 56 basin, the geology varies considerably. There are several important geologic units that occur within the study area. The primary units are from oldest to youngest:

1) crystalline basement rocks of various compositions that underlie the entire region and core the numerous hills and steptoes (peaks surrounded by basalt lava),

2) widespread horizontally-bedded volcanic rocks consisting of basalt flows separated by laterally discontinuous sedimentary interbeds that form the relatively flat surfaces of the Columbia Plateau region, and

3) overlying unconsolidated surficial deposits consisting primarily of flood-deposited sand and gravel and the wind-deposited silts that comprise the rolling hills characteristic of the Palouse.

Crystalline Basement Rocks

The underlying basement rocks in WRIA 56 consist of several different types of rocks, most easily observed where they crop out in the higher peaks or where exposed in some stream canyons. Much of the basement consists of sedimentary rocks of the Precambrian age Belt Supergroup that have undergone low-grade metamorphism during intrusion by Mesozoic and Tertiary age quartz monzonite and granodiorite (granite) plutons (Griggs, 1976; Stoffel and others, 1991).

Depth to basement rock varies in the study area from zero to 1,555 feet or more. Drillers' logs of Cheney water wells 4 and 5 show that quartzite is encountered at 1,555 and 1,191 feet beneath the ground surface respectively. A water well three miles west of Cheney bottoms in granite at a depth of 516 feet beneath the ground surface. Where these rocks are exposed on the surface, they are usually deeply weathered and decomposed to a coarse sand and gravelly texture.

Columbia River Basalt and Latah Formation

The most ubiquitous rock in WRIA 56 is the Columbia River Basalt that was deposited during the Miocene (specifically, 12 to 17 million years ago). These rocks are the product of numerous volcanic eruptions of very fluid lavas in southeastern Washington and northeastern Oregon that flowed throughout the Columbia Plateau, resulting in deposits hundreds to thousands of feet in thickness that are regionally widespread (Swanson and others, 1975; Griggs, 1976). They are typically gray to black in color (red to orange when weathered) and vertically jointed and fractured.

A single basalt flow unit is typically several tens of feet in thickness, and exhibits a set of distinct morphologic elements that may sometimes be discerned in drillers' logs. The interior of a flow is typically dense, with vertical columnar jointing that developed during the cooling and crystallization of the flow. This section of the flow is termed the entablature if the columns are relatively thin, or termed the colonnade if the columns are well formed. A vesicular zone several feet thick usually develops on top of the flow as volatile gasses escape during cooling. In addition, the flow top may be weathered and rubbly (Mangan and others, 1986).

The basalts are multi-layered and contain interbeds consisting of semi-consolidated sand, silt and clay that reflect surficial deposition in streams and lakes during periods of quiescence between eruptions of basalt. These interbeds, known formally in this area as the Latah Formation, crop out in only a few locations due to their weak strength. Interbeds are usually less than ten feet in thickness and are laterally discontinuous. Basalt flows in the study area range in thickness from a few feet where they onlap the pre-Miocene steptoes to more than 1,500 feet in the deepest water well (Cheney well no. 4).

Stratigraphically, the Columbia River Basalts have been formally subdivided into different flow units (formations), and in WRIA 56 two recognized flows are present: the Wanapum and Grande Ronde Basalts (Drost and Whiteman, 1986). The Grande Ronde Basalts are older than the Wanapum Basalts and hence occur stratigraphically lower in the section. The contact between the two formations usually occurs between 2,100 and 2,200 feet in elevation in the Spokane area (Deobald and Buchanan, 1995).

Unconsolidated Surficial Sedimentary Deposits

The present surface above the Columbia River Basalts is covered by unconsolidated deposits consisting of thin soils of silt, sand and gravel. During the Pleistocene (0.01 to 1.6 million years ago) eastern Washington was periodically scoured by catastrophic outburst floods originating in northern Idaho due to the failure of glacial ice dams in the Clark Fork drainage. WRIA 56 was certainly affected by this extraordinary geologic event, as flood waters poured over the divide between Lake Coeur d'Alene and into Rock and California Creek.

Geologic mapping by Joseph (1990) and Stoffel and others (1991) shows these unconsolidated deposits exist in Hangman valley, and these deposits are in contact with similar ones in the lower Spokane valley. The sedimentary unit mapped in Hangman valley is described as consisting of glaciolacustrine (lake) and flood deposits containing silt and clay interbedded with coarser sand to gravel material (Joseph, 1990). Along Hangman Creek cyclic bedding between the coarse and fine sediments can be observed, and this pattern is speculated to exist in the subsurface but few well logs describe the stratigraphy in any detail. Recent work by Hamilton and others (2002) provides additional information on these deposits in the lower part of WRIA 56. This cyclic bedding is believed to be the product of periodic outburst floods from Glacial Lake Missoula entering the quiet waters of Glacial Lake Columbia that existed in the Spokane and Hangman valleys at the same time (Atwater, 1986; Molenaar, 1988). Since the energy of the floods was greater down the main Spokane valley, the finer-grained lake sediments there are mostly scoured away, leaving a coarser deposit of coarse sand and gravel. Nonetheless, these generally granular deposits exist in both valleys and are clearly contiguous with one another in map view.

Seismic reflection surveys performed during the delineation of wellhead capture areas for Fairchild Air Force Base (Buchanan and McMillan, 1997) fixes the third dimension of the aquifer geometry as it exists in Hangman and Marshall valleys. Both valleys appear to be trough-shaped and filled with 300 feet or more of sedimentary deposits sitting on top of competent bedrock at depth.

Also during the Pleistocene, finer-grained sediments blown by the wind from the glaciated terrain to the north, settled in the region resulting in the rolling hills typical of the Palouse. In many places these hills have been scoured by the outburst floods resulting in streamlined shapes when viewed from the air. The silts (eolian loess) comprising the Palouse hills range from a few tens of feet to no more than one hundred feet in thickness and are formally recognized by geologists as belonging to the Palouse Formation. This formation is best developed in the upper parts of WRIA 56, specifically in the upper Hangman and California Creek sub-basins.

Lastly, adjacent to the present-day river channels, these flood- and wind-laid sediments have been eroded and re-deposited as alluvium. The most notable occurrence of this alluvial material is in the lower part of WRIA 56, below the confluence of Rock and California Creek.

Aquifer Characteristics

An aquifer is defined as any geological material that stores and transmits groundwater in economic quantities. Several aquifers can be identified in WRIA 56 that are related to the geologic units identified in the preceding section, in fact, all lithologies contain groundwater to some degree. After examining nearly 800 water well records in the basin, Table 1 summarizes these major water-bearing units, and they are described in some detail below.

Unconsolidated Sand and Gravel Aquifer

A significant unconfined aquifer exists in the sand and gravel deposits in the lower portion of WRIA 56, below the confluence of Rock and California Creek. The water table in this aquifer unit is strongly connected to, and is influenced by, the stage of flow in Hangman Creek. The mainstem of Hangman Creek, below California Creek to its mouth, is an effluent (gaining) type stream based on this relationship with the adjacent groundwater system as observed by periodic groundwater level measurements in nearby wells during this study. Table 1 summarizes the characteristics of this important aquifer in WRIA 56.

Few water wells penetrate this aquifer unit through its entire thickness (Hamilton and others, 2002). Seismic reflection work along Meadowlane Road in the lower part of WRIA 56 (Buchanan and McMillan, 1997) suggests that the base of the alluvial aquifer in the center part of Hangman valley is about 1,400 feet MSL. This transect does not terminate against bedrock at either end so the cross-sectional area of the aquifer cannot be determined.

Table 1. Characteristics of major aquifer units in WRIA 56.

Aquifer unit	Host material	Aquifer type	Range in well depths minimum ft	maximum ft	Hydraulic conductivity ft/day	Typical range in well yields gpm
Basalt aquifer	Columbia River Basalts and Latah Formation (Miocene age) GW usually occurs in permeable interbeds and in vesicular zones.	confined to semi-confined	50	1,400	10^{-7} to 10^{2}	10s to 1,000s
Basement aquifer	pre-Miocene age crystalline rocks (various igneous and metamorphic rocks) GW usually occurs in fractures and in weathered zones.	confined to semi-confined	100	800	10^{-7} to 10	<10
Sand and gravel aquifer	unconsolidated sand and gravel (Pleistocene age)	unconfined	60	355	10^{-2} to 10^{3}	10s to 100s
Shallow water-bearing zones	unconsolidated soils above bedrock – not characterized in this study	perched	NA	NA	unknown	unknown

Notes:
Range in well depths derived from review of existing drillers' logs for water wells in the basin.
Hydraulic conductivity values from the technical literature.
Well yield range from drillers' logs.
Kh:Kv in basalt aquifers estimated to be 2,500:1 or greater.
Data sources: IDWR and WDOE

However, the saturated thickness in this part of the valley is more than 350 feet with the water table in the unconfined aquifer at about 1,820 feet MSL.

Another seismic transect along West 15th Avenue in the Vinegar Flats area and on the South Hill along West 14th Avenue provide a good, constrained cross-sectional view of the Hangman valley aquifer just before it connects to the western end of the Spokane aquifer (Buchanan and McMillan, 1997). The base of the alluvial aquifer resides at about 1,400 feet MSL, resulting in a saturated thickness of about 330 feet at its thickest part. The western edge of the aquifer terminates against basalt bedrock on the left (west) bank of Hangman Creek, while the eastern edge abuts a gradually rising weathered basalt bedrock surface up onto the South Hill. The water table lies at an elevation of 1,730 ft. MSL. This cross-section of the saturated area of the aquifer in this area is determined to be about 312,900 square feet.

The slope of the unconfined groundwater surface, or hydraulic gradient, in Hangman valley is closely related to the elevation of Hangman Creek as described above. Given this relationship, the hydraulic gradient in the Hangman valley aquifer is about 0.002, with a slope to the north. The groundwater flow rate can be calculated as being the product of hydraulic conductivity, hydraulic gradient, and cross-sectional area of the aquifer. Assuming a hydraulic conductivity of about 500 ft/day, and using the gradient and areas discussed above, calculations show that about 6.6 cubic feet per second of groundwater flow is moving from Marshall valley and into Hangman valley. Furthermore, about 12.7 cubic feet per second of groundwater throughflow is occurring from Hangman valley and into the lower Spokane valley at the confluence (Buchanan and McMillan). Therefore, since no physical barriers to groundwater flow have been discovered in the subsurface that would preclude the movement of groundwater from the Hangman valley aquifer and into the lower Spokane aquifer, almost 13 cubic feet per second of groundwater recharge is occurring from Hangman valley to the lower Spokane aquifer. This amount of groundwater discharge from WRIA 56 lies within the range described earlier by Bolke and Vaccaro (1981).

Elsewhere in WRIA 56, small, locally discontinuous unconfined and perched water-bearing strata exist in some locations in the variety of sediments that mantle the bedrock. Such zones occur in the riparian areas in the upper part of the watershed where some alluvium is present adjacent to the streams. Although these areas have potentially high porosity and permeability, the saturated thickness is typically less than ten feet and as such, these bodies of shallow groundwater respond immediately to periods of drought through rapid lowering of the water table. As a result, these shallow and perched water-bearing zones are not considered reliable for long term supplies of great quantities of groundwater, but may be sufficient for a domestic water supply. In addition, while the silts comprising the Palouse Formation retain significant amounts of infiltrated water, their permeabilities are usually very low, precluding them from definition as a viable aquifer. These small ground-water bearing zones are entirely uncharacterized in this study of WRIA 56.

<u>Basement Rock Aquifer</u>

Groundwater can also occur in the basement rocks where they are deeply weathered or jointed, or along the basalt/basement contact. Because of the crystalline nature of these rocks, quartzite and granite, porosity is usually low and permeability is limited as it is a function of the interconnectedness of the joints or the degree of weathering of the bedrock (Driscoll, 1986). At best, this aquifer may yield only several gallons of water per minute, and wells penetrating this aquifer will only yield water until the fractures in close proximity to the well are drained (Olson and others, 1975). Table 1 summarizes some of the characteristics of this aquifer in WRIA 56.

It is important to note that very few wells are developed in this aquifer in WRIA 56 due to its poor potential. It is surprising to note that Cheney water wells no. 4 and 5 are developed in the basement quartzite. Normally this lithology does not yield quantities of groundwater in sufficient quantities to municipal wells. With time yields may decrease to these wells as groundwater recharge to this deep hydrostratigraphic unit is limited. In fact the city has encountered a variety of problems in each of these wells that may be related to the quartzite aquifer.

Columbia River Basalt Aquifer

The most prolific and important aquifer in WRIA 56 is contained within the Columbia River Basalts. Since the basalt flows are generally multilayered, and many of the flows are interlayered with coarse sedimentary deposits of the Latah Formation, groundwater generally occurs in abundance in the porous vesicular zones between the flows or in the sedimentary interbeds thereby creating multiply stacked confined or semi-confined aquifers accessible through deep wells. Again, groundwater may also occur in abundance at the contact between the basalt and the underlying basement rock (quartzite and granite).

Most groundwater occurs within the vesicular zone that defines the top of a single basalt flow since it is usually quite permeable and porous; if the flow top was weathered prior to burial by the next succeeding flow, porosity and permeability may be further enhanced. Several statistics are offered below to indicate the great range of hydraulic properties one can encounter in basalt aquifers. The porosity of the vesicular zone in the basalts ranges from 10 to 50 percent. Transmissivity ranges from 100,000 to 40,000,000 gallons per day per foot (over the entire vertical saturated thickness of the aquifer), and hydraulic conductivity (permeability) ranges from 8,000 to 70,000 gallons per day per square foot making these rocks some of the most prolific, *and most variable and unpredictable*, aquifers (Fetter, 1994). The potential yield of groundwater from aquifers in the Columbia River Basalts ranges from 500 to 100,000 cubic meters per day (Driscoll, 1986). These water-yielding target zones account for less than six percent of the upper 1500 feet of the Columbia River basalts in eastern Washington (Newcomb, 1972). In fact, two water wells may be drilled to equal depth in the basalts within close proximity to one another, and as indicated in the range of hydraulic properties outlined above, may exhibit significantly different yields. Table 1 summarizes the important characteristics of this aquifer in WRIA 56.

Water reaches the interflow zones and recharges the aquifers by either percolating downward through the vertical columnar jointing structures in the overlying basalt flows or by lateral groundwater inflow (Luzier and Burt, 1974). Vertical permeability is usually several orders of magnitude lower than that in the interflow zones so recharge through vertical infiltration is very slow. Most of the deep confined basalt aquifers on the Columbia Plateau are recharged almost entirely through lateral groundwater inflow or through vertical exchange.

Occurrence and movement of groundwater in the Wanapum and Grande Ronde hydrostratigraphic units has been described regionally by Drost and Whiteman (1986). Within WRIA 56, the Grande Ronde flow forms the deepest hydrostratigraphic unit in the basalts and probably receives most of its recharge via the overlying Wanapum Formation. Aquifers in the Grande Ronde unit are mostly confined. The uppermost significant water-bearing basalt aquifer in WRIA 56 is the Wanapum flow, and in many places in the watershed this flow crops out on the land surface or is covered by a thin veneer of soil, alluvium, or the Palouse Formation. Recharge to this unit comes primarily from direct precipitation and infiltration on weathered outcrop surfaces. It is groundwater in the Wanapum hydrostratigraphic unit that is responsible for flow to the small springs that occur naturally in the surrounding area. The hydraulic gradient in both basalt hydrostratigraphic units controls the direction of groundwater flow, and is shown in Figure 2. Generally, groundwater flow is toward the main Hangman Creek valley, though it does not discharge to the stream itself. The groundwater surface is graded toward the main stream valleys in WRIA 56, though the groundwater surface lies beneath the streams at a depth of more than 80 feet in the upper part of the watershed (above the confluence of California Creek). Because of this relationship, Hangman Creek appears to be a losing (influent) stream in the Upper Hangman sub-basin. It is believed that the groundwater in the basalt system is discharging to an underlying structure, either a suspected fault (Hamilton and others, 2002) or a buried linear structure (lineament), that in turn may convey the groundwater to deeper strata or towards the north-northwest where it may eventually discharge into the alluvial reach in the lower Hangman sub-basin.

A projected longitudinal profile of the mainstem of Hangman Creek (Figure 3), and the underlying groundwater surface in the adjacent aquifers, shows this separation in the upper part of the watershed. Below Rock Creek, the groundwater surface lies at an elevation above the stream, and this is where numerous springs discharge from the basalts and sustain low flows in Hangman Creek during the dry summer season. Further down valley, the groundwater surface in the sand and gravel aquifer is strongly coupled to the stream stage as discussed previously. This effluent reach is also depicted in Figure 3.

Due to its limited recharge potential within WRIA 56, the basalt aquifer system may be impacted by increasing groundwater withdrawals into the future. In a subsequent section on water use within WRIA 56, it is clear that most irrigation in the basin is derived from groundwater sources in the basalt aquifers. Well interference (a pumping well affects water levels in another nearby well) and groundwater level decline are potential problems given this scenario.

Groundwater level monitoring of this important aquifer system is of paramount importance, and will require periodic measurements of existing wells, and perhaps the installation of dedicated monitoring wells. Fortunately, groundwater withdrawals from the basalt aquifer system in the upper parts of WRIA 56 will have minimal impacts on stream flow as best as this study can determine at this time.

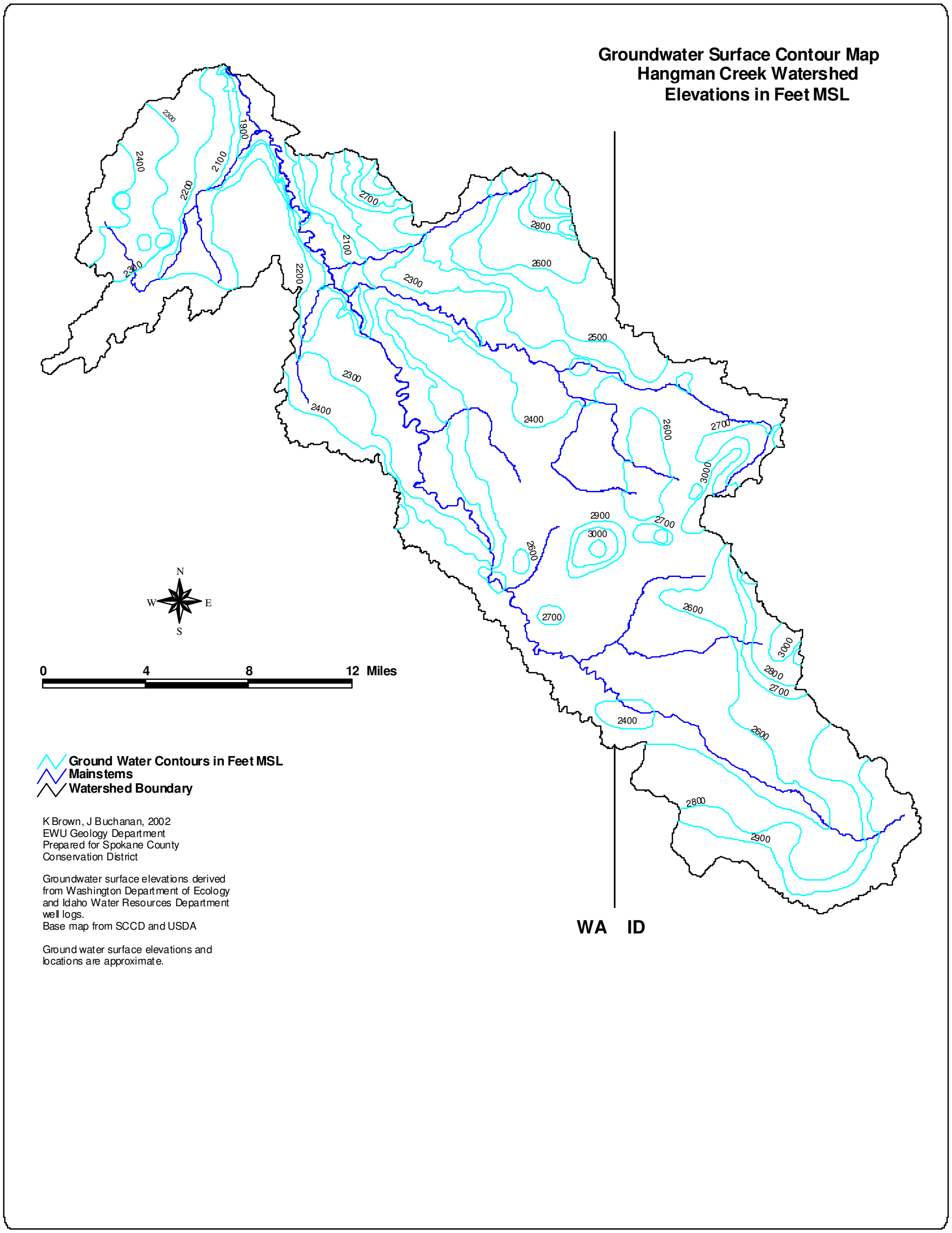

Figure 2. Map showing the groundwater surface in WRIA 56 based on review of about 800 water well records from IDWR and WDOE.

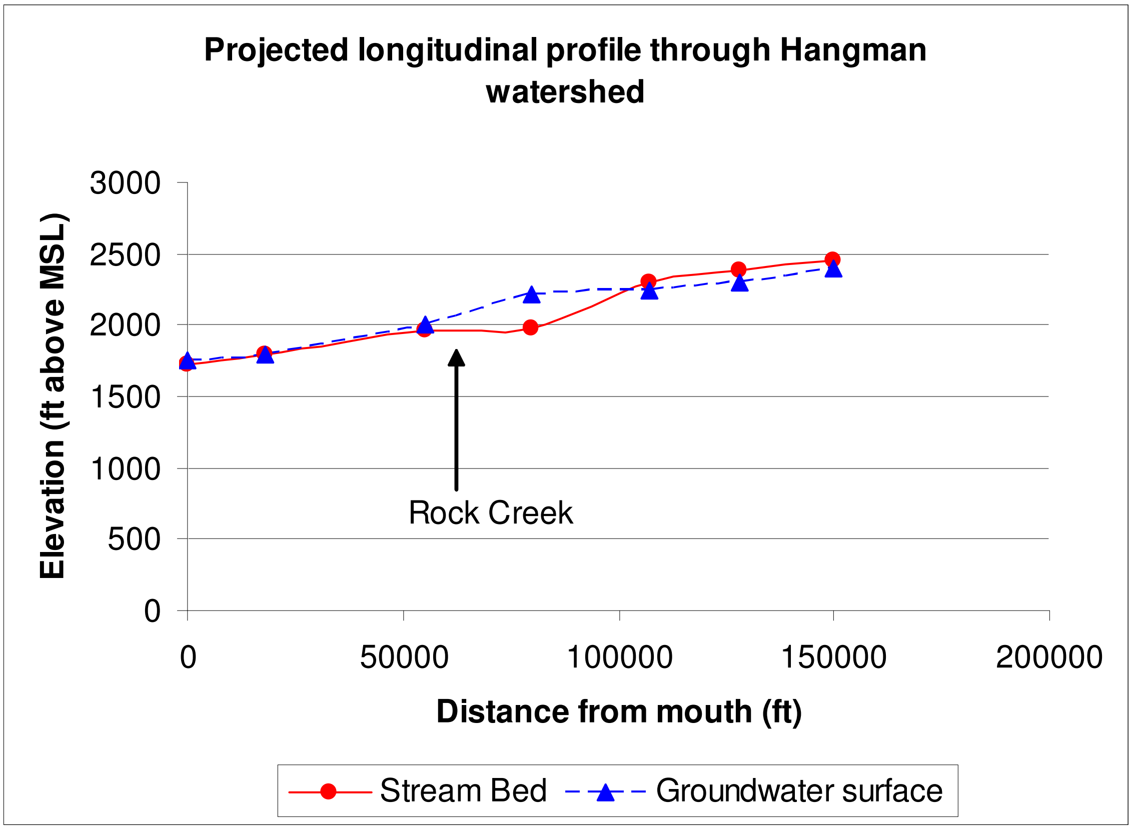

Figure 3. Projected longitudinal profile showing losing stream reach in the Upper Hangman sub-basin and the gaining reach below Rock Creek in the Lower Hangman sub-basin.

Precipitation and Evapotranspiration

Precipitation

The climate in WRIA 56 is generally very warm and dry in the summer and cool and moist during the winter. Because of the large range in elevation in the watershed significant variation in precipitation occurs, from less than 16 inches/year in the lower part of the basin that is sub-arid, to more than 40 inches/year in the upper part that is sub-humid. The "Hangman Creek Watershed Management Plan" (SCCD, 1994) includes a brief summary of the climate conditions in WRIA 56 and includes a basic isohyetal map.

Five meteorological stations exist in and around the periphery of WRIA 56. These are listed in the table that follows:

Summary of meteorological stations in and around WRIA 56

Name	Station ID	Period of Record
Spokane WSO Airport, Washington	457938	1/1/1890 to present
Rosalia, Washington	457180	6/1/1948 to present
Tekoa, Washington	458348	6/1/1948 to 9/30/1980
Plummer 3 WSW, Idaho	107188	2/1/1950 to 8/31/2000
Potlatch 3 NNE, Idaho	107301	3/1/1915 to present

Unfortunately, these stations are not spatially distributed in a meaningful manner, and their periods of record are somewhat incomplete, to provide comprehensive climate data in regards to a new analysis of the distribution of precipitation within the watershed.

Fortunately, the Spokane NRCS office has PRISM (Parameter-Elevation Regressions on Independent Slopes Model) coverage in GIS format for WRIA 56. This dataset uses point data and Digital Elevation Models (DEMs) to derive spatial variations in climatic parameters. The data sources include NOAA sites, SNOTEL sites and selected state sites. PRISM data is considered high quality data by most researchers.

In Figure 4, the PRISM data clearly show the gradient in precipitation that is influenced by topographic elevation in the watershed. Annual precipitation ranges from more than 40 inches per year in the upland areas in the southern portion of WRIA 56, to 16 inches or less in the lower elevation areas near Cheney. It is difficult to confirm the adequacy of the PRISM model for precipitation in WRIA 56 given the dearth of data from meteorological stations in the watershed. For purposes of this study, the PRISM data shown in Figure 4 is used to calculate the effective uniform depth (EUD) of precipitation by the isohyetal method (Fetter, 1990) in WRIA 56 and its sub-basins.

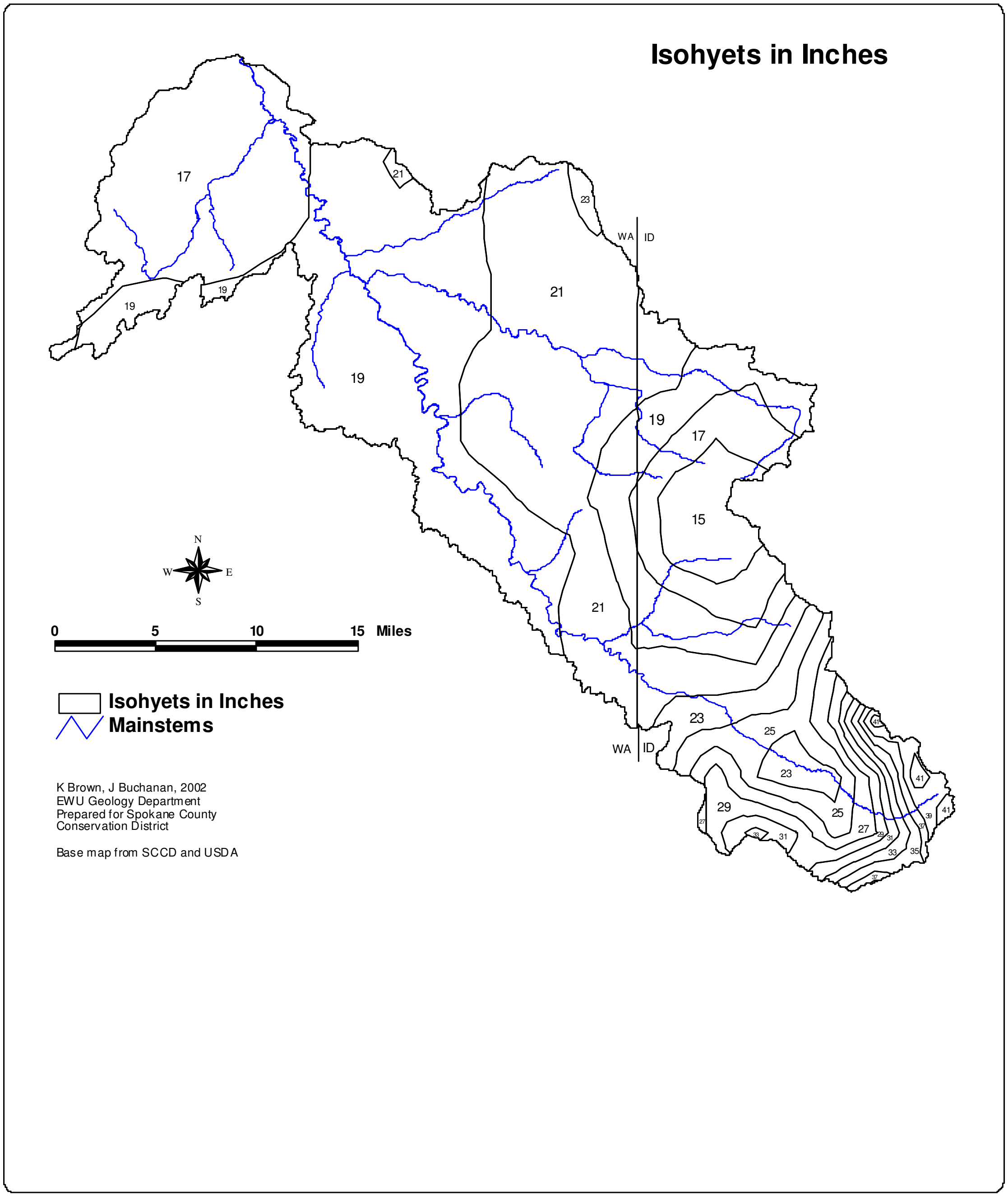

Figure 4. Isohyetal map of annual precipitation for WRIA 56 generated with PRISM data.

Evapotranspiration

Evapotranspiration (ET) is difficult to measure directly, and is similarly difficult to estimate on a basin-wide scale. Excellent evaporation data exists at Spokane Airport WSO where an evaporation pan shows an annual average evaporation of 47.02 inches.

Additional ET data for various types of common vegetation in the western U.S. that are also found in WRIA 56 has been gathered from Van der Leeden and others (1990). These data are listed in Table 2.

Table 2. Estimated evapotranspiration (ET) rates for types of vegetation in WRIA 56.

Land use code	Description	Average annual ET (inches)
Water		
11	open water	47
12	perennial ice/snow	na
Developed		
21	low intensity residential	20
22	high intensity residential	22
23	commercial/industrial	16
Barren		
31	rock/sand/clay	0
32	quarries	na
33	transitional	0
Forested Upland		
41	deciduous forest	23
42	evergreen forest	17
43	mixed forest	20
Shrubland		
51	shrubland	11
Non-Natural Woody		
61	orchards/vineyards	na
Herbaceous Upland		
71	grasslands	11
Herbaceous Planted		
81	pasture/hay	28
82	row crops	26
83	small grains	16
84	fallow	11
85	urban/recreational	na
Wetlands		
91	woody	40
92	emergent herbaceous	40

Notes:
Land use categories from National Land Cover Class Definitions
ET values from The Water Encyclopedia, 1990
na = not applicable in WRIA 56

In order to estimate an ET budget for WRIA 56 and its sub-basins, an additional GIS land use coverage map was acquired from the Spokane NRCS office (Figure 5) and the values in Table 2 applied in an area-weighted manner to the associated land coverages. The related spreadsheets for each sub-basin are provided in Appendix A of this report. The net result is an overall estimate of ET for the entire WRIA 56 basin and each of its sub-basins, very similar to the methodology employed in the Theissen weighted-polygon method of determining the effective uniform depth of precipitation (Fetter, 1990).

Table 3 provides a summary of climate data for WRIA 56, including the estimated effective uniform depth of precipitation (EUD) calculated by the isohyetal method from Figure 4 and the estimated evapotranspiration from Table 2 and Figure 5.

Table 3. Summary of estimated annual precipitation and evapotranspiration for sub-basins in WRIA 56.

	Estimated precipitation inches	Estimated evapotranspiration inches	Moisture surplus inches (acre-feet)
Upper Hangman	22.3	15.9	6.4 (114,338)
Rock Creek	19.6	15.4	4.2 (40,106)
California Creek	19.9	15.8	4.1 (5,447)
Lower Hangman	17.8	15.2	2.6 (9,955)
Marshall/Minnie Creek	17.4	16.2	1.2 (4,036)

Table 3 shows that there is, on average, an annual moisture surplus in WRIA 56. Note that the moisture surplus is greatest in those sub-basins that extend to the upland areas that receive more annual precipitation than those that are found in the lower semi-arid portions of the watershed. This surplus moisture is free to either run off into surface streams, or to infiltrate into the ground to recharge shallow and/or deep aquifer systems. In sum, based on the numbers in Table 3, the average annual moisture surplus in WRIA 56 is about 173,882 acre feet per year (af/yr).

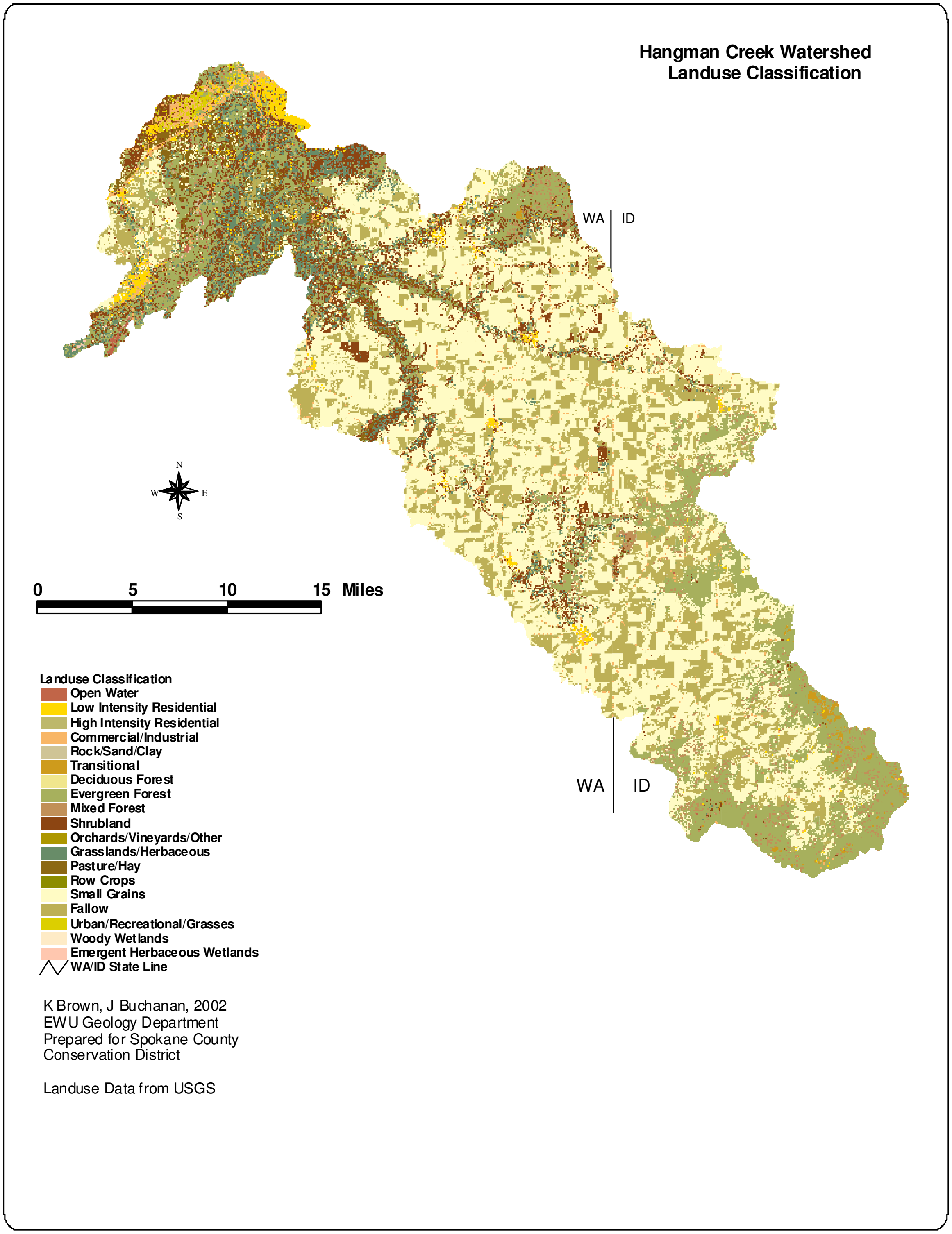

Figure 5. Land use coverage in WRIA 56 from Spokane NRCS office (1994 data).

Overall Water Balance

The discussion in the preceding section of this report indicates that there is a moisture surplus in WRIA 56 due to the difference in precipitation and evapotranspiration in the basin as shown in Table 3. During the average year the moisture surplus amounts to approximately 173,882 acre feet (af) for all sub-basins in WRIA 56 combined.

Note that in Table 3, the volume of water lost from precipitation by evapotranspiration (about 6.4 inches annually) from the Upper Hangman sub-basin is 71.3% of the precipitation total, leaving about 28.7% of the remaining moisture surplus available for runoff or infiltration to the ground. These numbers compare favorably with the earlier work by Ko and others (1974) in this specific part of the watershed despite an entirely independent study.

A technical study performed in the Idaho portion of the Hangman Creek drainage basin by Ko and others (1974) reports a simple mass balance for their limited study area. Their upper basin study showed that about 24.3% of precipitation flows from the basin as runoff, and about 74.2% returns to the atmosphere as evapotranspiration. They concluded that only about 1.5% of the moisture infiltrates as recharge to aquifer units in the area corresponding to the Upper Hangman sub-basin in this study.

Furthermore, recent work in the Colville watershed (WRIA 59) also yielded similar results (Kahle and others, 2002). Their study concluded that the "predominant fate of precipitation in the basin (83%) is evapotranspiration, a combination of evaporation from open bodies of water, evaporation from soil surfaces, and transpiration from the soil by plants." They go on to further infer that groundwater flow comprises only about 1% of precipitation in their overall water budget.

Therefore, it appears that the soil moisture surplus calculated for WRIA 56 is entirely consistent with these two previous studies in eastern Washington and northern Idaho. That is, the vast majority of precipitation falling in the basin is lost to evapotranspiration with a significant portion of the remaining surplus going to runoff. Both other studies (Ko and others, 1974; Kahle and others, 2002) concluded that only a minimal amount (1 to 1.5% of precipitation) goes to groundwater.

Another independent check on the water balance determined by this study can be made by examining the available gaging data for the mainstem of WRIA 56. The historical record at the gaging station, located very close to the basin mouth (Hangman Creek at Spokane, Washington, USGS number 12424000,) shows a long-term mean annual discharge from the basin of about 242.56 cubic feet per second (cfs) for the period of 1949-2000. This discharge rate converts to 175,608 af/yr and compares surprisingly well with the moisture surplus estimate made in the previous section of this report of 172,143 af/yr (agreement within 1.9%).

Table 4 is a summary of the comprehensive water balance for WRIA 56 that presents two different proportions of runoff and infiltration of the remaining moisture surplus: that is, either 99% of the moisture surplus goes to runoff leaving 1% to infiltrate (similar to Ko and others (1974) and Kahle and others (2002)) or 95% goes to runoff with 5% going to infiltration if one would prefer to accept a higher value for infiltration. Not surprisingly, it is the proportion of 99% runoff and 1% infiltration that yields the results closest to the two other similar studies. Additionally, the 99% runoff scenario results in a discharge volume that corresponds with the long-term average annual flow from the basin as measured at the U.S.G.S. gaging station at the mount of WRIA 56.

In summary, the overall water balance determined in this study for WRIA 56 appears reasonable, based on close agreement with the conclusions made in two other independent watershed studies in the region, and on the cross-check with long-term gaging data for WRIA 56 itself. About 172,143 af/yr of surface water runs off the entire basin, and only about 1,738 af/yr goes to infiltration.

Water Rights

Recorded Water Allocations

The WDOE tracks groundwater and surface water allocations and/or water rights information through their Water Right Tracking System (WRATS) system, and an abstracted version termed "WRTS-On-A-Bun." The latter database was utilized in this analysis of water allocation in WRIA 56, with the database current as of September 5, 2002.

The IDWR maintains an on-line database that is Web-accessible for similar access to water rights information for that portion of the Hangman watershed that exists in Idaho. The Coeur d'Alene Tribe had no meaningful records for groundwater or surface water allocation on their lands. In total, 2,928 records were found for WRIA 56 in the WDOE database, while 111 records were found for the Idaho portion of the watershed in the IDWR database.

Unfortunately, with all of these databases, the records are not necessarily complete and may contain omissions and/or errors made when transcribing paper records into a digital format. Also, they may not reflect the most up-to-date information at any moment in time. Most importantly, some water allocations may not be used at present, and some may have been abandoned entirely.

In this study, these databases were queried for the type of registration (claim, application, permit or certificate), the point of use or diversion, the purpose of use, and the allocation amount. For a thorough review of water rights registration and pertinent state laws and rules, the reader may want to visit related Web sites at WDOE and IDWR; such a discussion is beyond the scope of this report and is not included here.

During the analysis of the available data several assumptions had to be made, particularly if an allocation amount was not indicated in the records, in order to estimate an annual quantity of water use. In consultation with John Covert at WDOE in Spokane, water used by a single domestic unit is equivalent to 1 af/yr. Wells that fall under the domestic exemption, that is, use less than 5,000 gallons per day, were ignored and are not included in the registry.

Table 4. Summary of water balance for WRIA 56.

Sub-watershed	Basin Area acres (mi^2)	EUD Precipitation inches	Estimated ET inches	Moisture surplus inches (acre-feet)	Runoff acre-feet 99% 95%	Runoff feet 99% 95%	Infiltration acre-feet 1% 5%
Upper Hangman	214,383	22.3	15.9	6.4	113,194	0.53	1,143
	(334.9)			(114,338)	108,621	0.51	5,717
Rock Creek	114,589	19.6	15.4	4.2	39,705	0.35	401
	(179.0)			(40,106)	38,101	0.33	2,005
California Creek	15,942	19.9	15.8	4.1	5,392	0.34	54
	(24.9)			(5,447)	5,175	0.32	272
Lower Hangman	45,947	17.8	15.2	2.6	9,856	0.21	100
	(71.8)			(9,955)	9,457	0.21	498
Marshall/Minnie Creek	40,359	17.4	16.2	1.2	3,996	0.10	40
	(63.1)			(4,036)	3,834	0.10	202
Total	431,220	--	--	18.5	172,143	1.53	1,738
	(673.7)			(173,882)	165,188	1.47	8,694

EUD = effective uniform depth of precipitation calculated using the isohyetal method on PRISM data.
Estimated ET = evapotranspiration based on weighted values for various land uses within the watershed shown on GIS.
Runoff = water available for flow to streams and shallow (perched) aquifers.
Infiltration = water percolating to deep aquifers.

In order to calculate an annual allocation for a water well with a specified irrigation use, and where no amount was given in the water rights database, each acre under irrigation uses 3 af/yr and is 100% consumptive.

Table 5 presents an estimate of the total water right quantities for WRIA 56 and its sub-basins as recorded in the WDOE and IDWR databases, and using the assumptions listed above to calculate an annual water quantity that has been recorded for use.

Table 5. Water rights (claims/permits/certificates) in annual acre feet for WRIA 56.

	Groundwater	Surface	Springs	Totals
	ac-ft and %	**ac-ft and %**	**ac-ft and %**	**ac-ft**
Upper Hangman	3,659	1,353	234	5,246
	69.7%	25.8%	4.5%	
Rock Creek	3,430	14	9	3,453
	99.3%	0.4%	0.3%	
California Creek	539	5	151	695
	77.6%	0.7%	21.7%	
Marshall/Minnie Creek	10,805	1,756	487	13,048
	82.8%	13.5%	3.7%	
Lower Hangman	8,863	2,445	228	11,536
	76.8%	21.2%	2.0%	
Totals	27,296	5,573	1,109	33,978
	80.3%	16.4%	3.3%	(0.95 inches)
All data from WRATS/WOB and IDWR				

Furthermore, Figures 6, 7 and 8 show the spatial distribution of water right allocations in WRIA 56 for surface water, groundwater, and springs, respectively. Not surprisingly, surface water rights correspond to locations adjacent to the main stream channels, as shown in Figure 6. Groundwater rights, however, are distributed more widely, and are most prevalent in the Lower Hangman and Marshall/Minnie Creek sub-basins as shown on Figure 7. There are a few water right allocations on springs, and their locations can be seen in Figure 9.

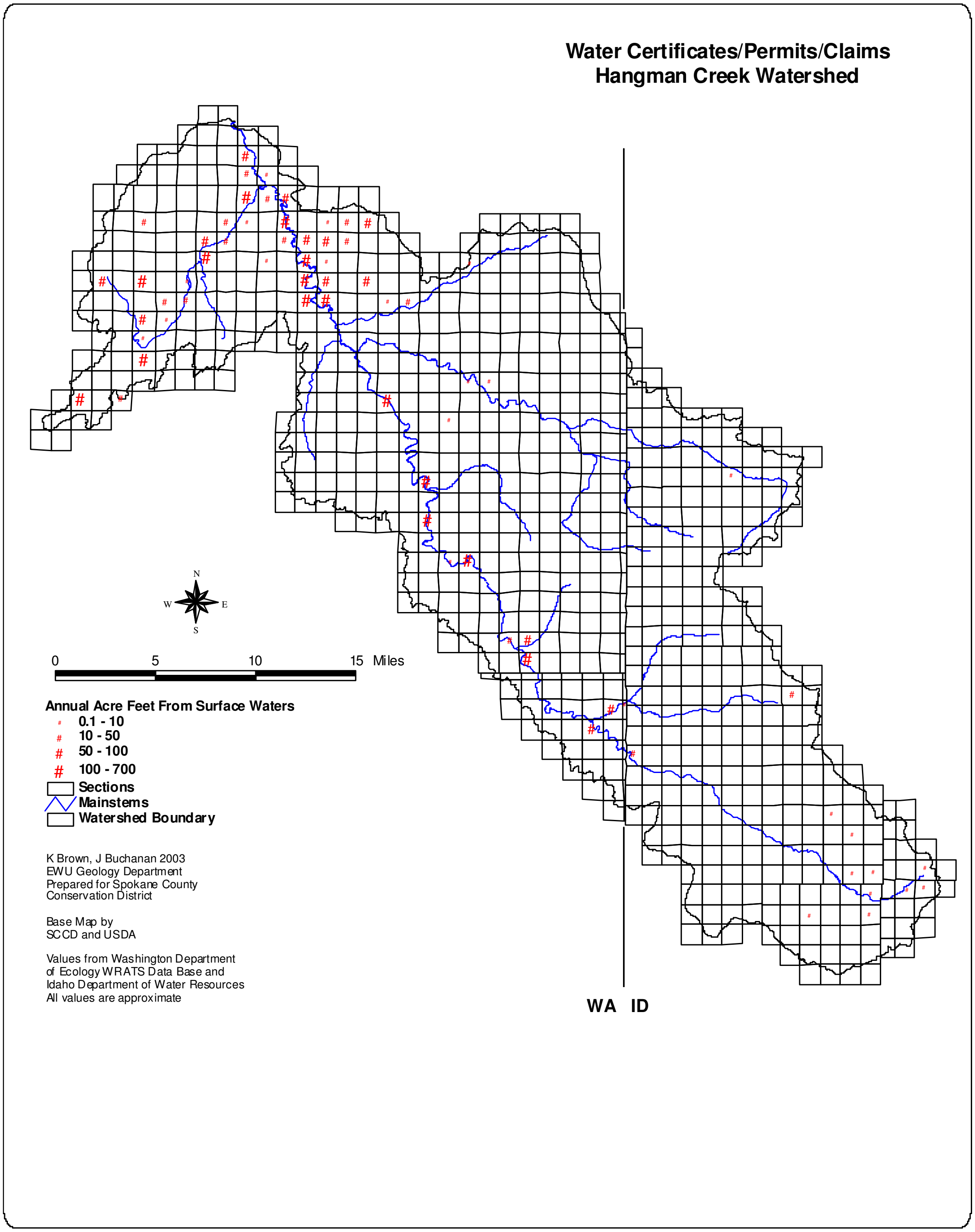

Figure 6. Summary of surface water rights in WRIA 56 from WDOE and IDWR records.

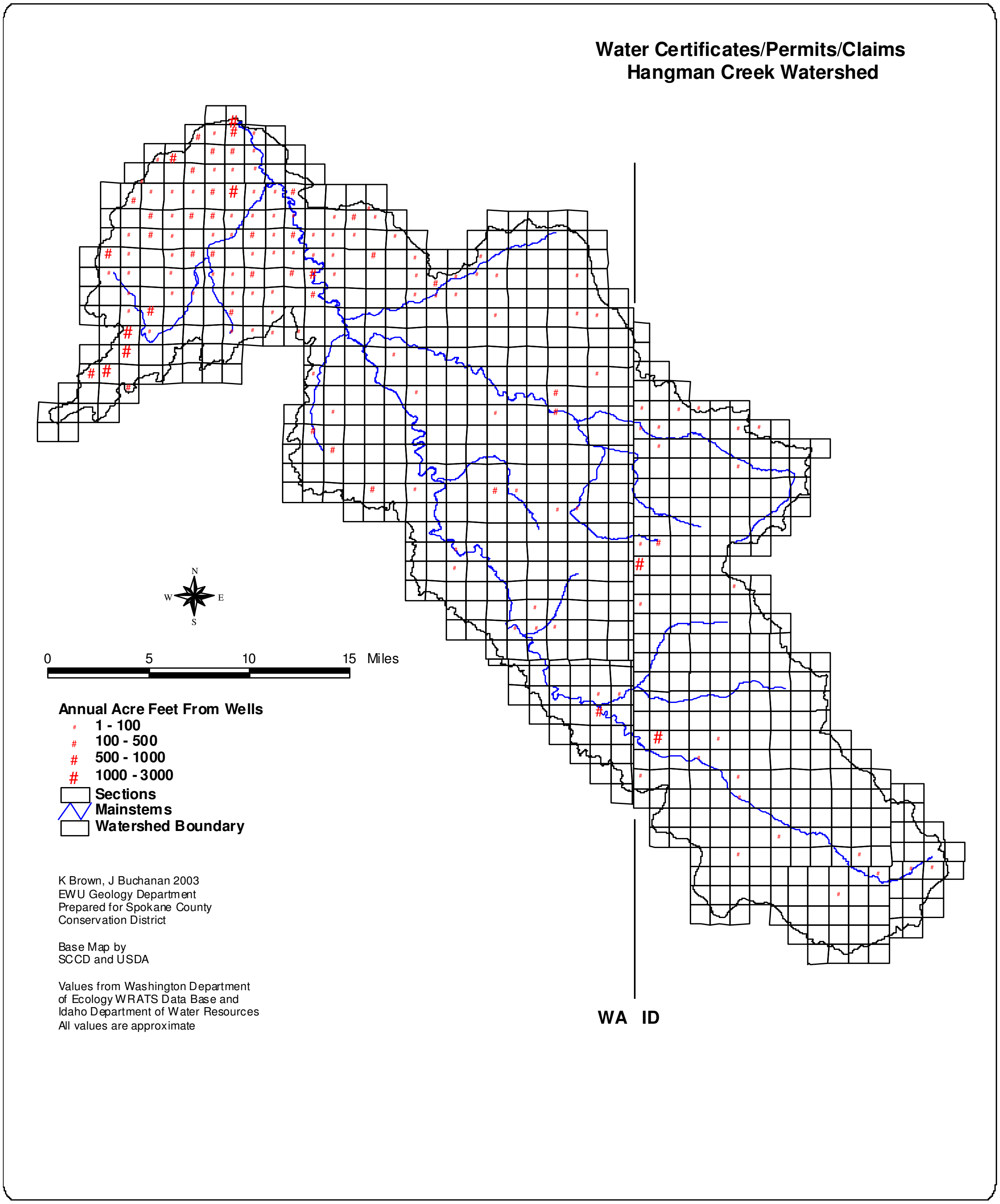

Figure 7. Summary of groundwater rights in WRIA 56 based on WDOE and IDWR records.

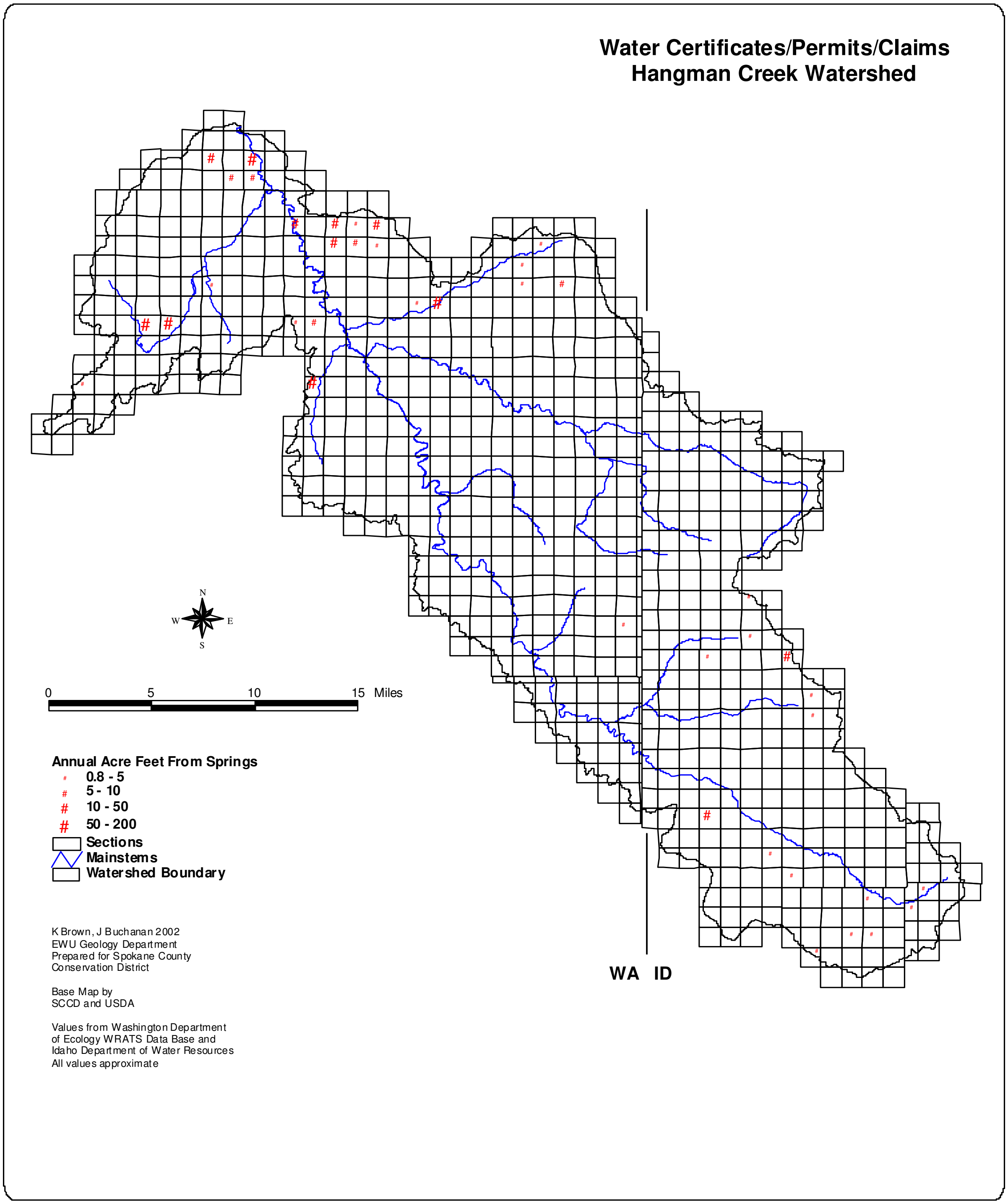

Figure 8. Summary of water rights from springs in WRIA 56 from WDOE and IDWR records.

Table 5 shows very clearly that groundwater allocations are the overwhelming source of water rights in WRIA 56, accounting for about 80% of all water use in the watershed. About 16% of water use is derived from water rights on surface water, and only 3% are associated with allocations on water flow from springs. In all, the total estimated volume of allocated water as recorded on "paper" is estimated to be about 33,978 acre feet annually in WRIA 56, the equivalent to 0.95 inches of precipitation across the entire watershed.

Estimated Actual Use

The actual water used by agricultural application is often quite different from the "paper" allocation, which almost always tends to be greater in quantity. Table 6 shows that the "paper" allocation for a specified irrigation use in WRIA 56 is 13,857 af based on the WRATS and IDWR databases.

GIS coverage for land use (Figure 5) was queried to assess the total amount of potential irrigated acreage in WRIA 56, and the results are listed in Table 6 by sub-basin. In total, 6,174 acres are potentially subject to irrigation in WRIA 56. No other better authoritative estimate of irrigated cropland was found, and no estimate is given in the Management Plan (SCCD, 1994). It is the opinion of the SCCD staff, however, that the estimate for irrigated land used here is probably high.

The crop irrigation requirement (CIR) is the amount of water actually used by a crop for growth, in addition to natural precipitation. This represents a theoretical maximum water use by plants, and it is entirely consumptive. In studies of WRIA 55 and 57, Golder Associates Inc. (2001) calculated the CIR to be 1.6 feet annually for the Little Spokane and Middle Spokane watersheds (for a mix of wheat, alfalfa/hay, and barley), and that number is used in this study.

The volume of water necessary for crop growth is the product of the CIR and the area of the irrigated land. For WRIA 56, the sum total of water actually used for watering the potentially irrigated land area within each sub-basin is 9,910 af/yr (Table 6,) a figure that is about 72% of the total "paper" rights listing irrigation as a specified use (13,857 af).

Evaluation of Water Rights Compared to Overall Water Balance

Total annual runoff as determined in the overall water balance is 172,143 af/yr (99% runoff scenario) to 165,188 af/yr (95% scenario) (Table 4). The total surface water allocation in WRIA 56 (both surface water and from springs) amounts to 6,682 af/yr (Table 5). Table 7 shows that surface water allocations are indeed a small proportion of the runoff volume for each sub-basin, and comprises nearly 4% of the total annual runoff from WRIA 56 as a whole.

Table 6. Summary of irrigation "paper" allocations and actual water use in WRIA 56.

Sub-watershed	Basin Area acres	Irrigated Area acres	CIR af/yr	All "Paper" Water Rights af/yr	"Paper" Rights for Irrigation af/yr	Non-Irrigation or Other Use af/yr
Upper Hangman	214,383	922	1,475	5,246	994	4,252
Rock Creek	114,589	419	670	3,453	130	3,323
California Creek	15,942	232	371	695	471	224
Lower Hangman	45,947	3,180	5,088	11,536	6,851	4,685
Marshall Creek	40,359	1,441	2,306	13,048	5,412	7,636
Totals	431,220	6,194	9,910	33,978	13,857	20,121

Notes:

Irrigated area by sub-basin from GIS database (NRCS, 1994)

All "Paper" water rights from WRATS/IDWR

"Paper" rights for irrigation is sum of water rights for specified irrigation use
CIR = estimate of actual irrigation based on crop irrigation requirement
(CIR) of 1.6 feet /acre/year (Golder, 2001)

Table 7. Surface water appropriations (surface water and springs) compared to annual runoff volume for WRIA 56.

SURFACE WATER APPROPRIATION (surface water + springs)

Sub-watershed	Basin Area acres	Irrigated Area acres	Annual SW rights acre-feet	Annual SW Rights in inches	Annual Runoff acre-feet 99% scenario 95% scenario	Annual SW Rights as % of runoff 99% scenario 95% scenario
Upper Hangman	214,383	922	1,587	0.0888	113,194 108,621	1.40 1.46
Rock Creek	114,589	419	23	0.0024	39,705 38,101	0.06 0.06
California Creek	15,942	232	156	0.1174	5,392 5,175	2.89 3.01
Lower Hangman	45,947	3,180	2,673	0.6981	9,856 9,457	27.12 28.26
Marshall Creek	40,359	1,441	2,243	0.6669	3,996 3,834	56.14 58.50
Totals	431,220	6,194	6,682	1.57	172,143 165,188	-- --

Notes:
Annual runoff (99% and 95% scenarios) from Table 4.
Irrigated area by sub-basin from GIS database (NRCS, 1994)

Table 8. Groundwater appropriations compared to annual infiltration volume for WRIA 56.

GROUNDWATER APPROPRIATION

Sub-watershed	Basin Area acres	Irrigated Area acres	Annual GW rights acre feet	Annual GW rights in inches	Annual infiltration acre-feet 1% scenario 5% scenario	Annual GW rights as % of infiltration 1% scenario 5% scenario
Upper Hangman	214,383	922	3,659	0.20	1,143 5,717	320 64
Rock Creek	114,589	419	3,430	0.36	401 2,005	855 171
California Creek	15,942	232	539	0.41	54 272	998 198
Lower Hangman	45,947	3,180	8,863	2.31	100 498	8,863 1,780
Marshall Creek	40,359	1,441	10,805	3.21	40 202	27,013 5,349
Totals	431,220	6,194	27,296	6.49	1,738 8,694	-- --

Notes:
Annual infiltration (1% and 5% scenarios) from Table 4.
Irrigated area by sub-basin from GIS database (NRCS, 1994)

However, in the Lower Hangman and the Marshall/Minnie Creek sub-basins, the allocations approach 27% and 56%, respectively, of the estimated runoff volumes from those basins (Table 7). This would suggest that water extraction via surface water rights in these two sub-basins has significant potential of affecting stream flows, particularly in the summer months when streams are low and the water use and irrigation season is peaking.

Table 5 shows very clearly that groundwater allocations are the overwhelming source of water rights in WRIA 56, accounting for about 80% of all water use in the watershed, or 27,296 af/yr. Recall that the volume of infiltration in the basin is between 1,738 af/yr (1% infiltration scenario) to 8,694 af/yr (5% scenario) (Table 4) based on the overall water balance determined by this study. It is clear that the amount of groundwater that is allocated for use is far greater than that volume of infiltrating moisture that potentially goes to aquifer recharge in the basin (Table 8).

Table 8 also shows that this trend is true for all of the sub-basins in WRIA 56, where each is potentially using groundwater at a rate that exceeds recharge. Such activity is likely to drive groundwater levels lower through time, in a condition sometimes known as "groundwater mining." This situation occurs when discharge of groundwater from an aquifer system exceeds the recharge amount to the system. This is especially true in the Marshall/Minnie Creek and Lower Hangman sub-basins, however, in the Rock Creek, California Creek and Upper Hangman sub-basins, this condition is not as significant.

Unfortunately there are no monitoring wells in WRIA 56 to assess long-term trends in groundwater levels, and no data is available from any identified source. However, wells developed in basalt aquifers in Lincoln County and in Medical Lake show declining trends in the elevation of the groundwater surface through time (Olson, T.M and J.J. Covert, 1994; Deobald and Buchanan, 1995). In addition, groundwater levels in the Pullman-Moscow basin (WRIA 34) have been declining for decades in an aquifer system similar to that in the Hangman watershed (Lum and others, 1990).

The center column in Table 8 (Annual GW Rights in inches) indicates a sense of the amount of annual groundwater decline, in each sub-basin, that may be expected into the future. The value in that column, when divided by the specific yield of the aquifer, results in the annual decline in the groundwater level to be expected in a well. For example, if one assumes a 25% specific yield for a basalt aquifer in the Marshall/Minnie Creek sub-basin, dividing 3.21 inches by 0.25 equals about one foot of groundwater decline, an amount that matches closely the amount of head loss in wells in the Medical Lake area adjacent to that sub-basin.

In sum, surface water appropriations in WRIA 56 have the potential to impact stream flows during the summer months, especially in the Lower Hangman and Marshall/Minnie Creek sub-basins. Groundwater mining is certainly a high potential, particularly in the Lower Hangman and Marshall/Minnie Creek sub-basins where water right allocations from groundwater greatly exceed the recharge rate. Allocated surface water rights are 3.9% of the total annual average stream flow in WRIA 56, while allocated surface water and groundwater rights are 19.7% of the average annual stream flow.

Evaluation of Potential for Numerical Modeling

Software exists today that enables scientists and land managers to simulate the hydrologic cycle, and its component parts, within an entire watershed. A well implemented watershed model can be used to identify the important data needs within a basin and guide future research, as well as serve as a predictive tool to anticipate potential impacts in the basin under various land use scenarios.

Watershed modeling software exists in the public domain (free) and is available from the U.S. Geological Survey, the Environmental Protection Agency, or the U.S. Army Corps of Engineers, or it is commercially available for a licensing fee. All modeling software requires comprehensive datasets representing information for each component of the hydrologic and physical system, at the appropriate resolution, in the proper format, and usually as a time series to enable transient simulations. Table 9 lists a subset of fundamental model data requirements, but it is not an exhaustive list.

Numerical modeling is typically very expensive and highly time consuming. Commercial software tends to cost several thousand dollars to license, and that fee does not include the added costs for training personnel to use the software, the time devoted to data entry, and the time for model calibration/verification and subsequent execution.

The latter aspect of modeling is typically underappreciated. All numerical models have to be calibrated and verified against field data to demonstrate their accuracy, prior to using the model as a tool to predict various scenarios and outcomes. In order to achieve this important goal, datasets have to span years of time (typically a minimum of 3 to 10 years) so that the model can be calibrated using one subset of the temporal data, and then verified against a second (separate) interval of time.

It is important that before any attempt is made to construct a watershed model of WRIA 56 there should be a consensus among all those involved in the planning process to clearly and specifically identify the primary purpose and objectives of the undertaking. The selection of the actual modeling code or software will depend on the expectations established by the planning process.

Numerous public domain codes exist for simple runoff and infiltration modeling. A brief review of some of these is provided in Appendix B. The models described there are not to be applied to an entire watershed, but rather to determine field values of runoff or infiltration on a local scale given the proper inputs. These models are free, are somewhat simple to operate, and can be instructive in understanding the hydrologic processes at work in various parts of a watershed.

However, more robust applications are required for full numerical modeling of a watershed system. The tool of choice being utilized for WRIA 55 and 57 is MIKE SHE, a very comprehensive code that can simulate all components of the hydrologic cycle (Golder Associates Inc., 2001). It appears the implementation for those basins will be achieved given

Table 9. Basic data requirements for watershed modeling (from Golder, 2001).

Watershed Geometry

- Boundaries of the watershed and all stream segments in a coordinate system
- Digital elevation model (DEM) of the watershed
- Specific site locations of all data, for example, locations of stream gages, water wells, stream withdrawals, etc.

Groundwater

- Aquifer/aquitard properties – hydraulic conductivity, storativity, specific yield, etc
- Locations of groundwater withdrawal or recharge
- Locations of water wells or monitoring wells

Soils

- Soil characteristics – profile information from land surface to groundwater surface
- Distribution of soil types
- Physical properties of soils – water content, saturated hydraulic conductivity, etc.

Runoff and Overland Flow

- Land use coverage
- DEM data for slope/length information
- Meteorologic data – station data or PRISM data
- Storage sites on surface
- Runoff coefficients
- Flood maps

Channel Flow

- Surveyed river transects
- Manning's n – channel roughness coefficient
- Specific locations for gaining/losing reaches – interaction with groundwater
- Specific locations for control structures, water input or abstraction, etc.

Snowmelt

- Climate data
- Temperature data
- Degree-day coefficients

Evapotranspiration

- Pan evaporation data
- Land use and vegetation cover – usually imported from GIS coverage

the outstanding set of spatially and temporally distributed data that is available for model input, and the availability of qualified consultants to design and implement the working model. However, for WRIA 56, using that code would not necessarily yield equally reliable results, especially given the limited quantity of data that exists for the Hangman Creek watershed.

Modeling could ultimately be helpful in future water resource management in WRIA 56. A model development project would take at least a year or more in time to formulate the model framework and to calibrate against field data, provided that a comprehensive dataset already exists. The first objective of such a project would be to build the model to represent the hydrologic system as it exists today in the watershed. Once constructed, calibrated and validated, the model may be applied to helping choose among different management schemes as a solution to a particular problem.

For example, a working watershed model could explore the potential of gradually increasing groundwater pumping in the select parts of the basin, and to predict whether it may eventually have an impact on stream flows. Similarly, a well constructed model could aid in further refinement of the water balance of the watershed, and provide insight to WDOE as it processes water right applications for WRIA 56 into the future. The model may also be used as a guide to further research, for example, in understanding the coupling of various stream reaches with the underlying groundwater system. Short-term and long-term climatic cycles could also be simulated as more information becomes available in the Pacific Northwest region, with simulated stream hydrographs as the model output. Lastly, historical conditions in the watershed could be simulated in the model, prior to major land use modifications, in order to contrast the present day hydrology with that of the past.

No attempts have been made at modeling WRIA 56 to this date, and such an attempt may have to wait at least several more years so that additional field data can be gathered. Recommendations for additional studies, most of which would assist in model development, are presented in the next section of this report.

Future Data Needs

This study has identified the following as primary data needs in order to better understand the hydrologic system in WRIA 56. In addition, these would be prerequisite to any reasonable attempt at constructing a numerical model of the watershed system.

First, there is no groundwater assessment or monitoring system in place at all in WRIA 56. Groundwater monitoring wells in select locations, in select aquifer units, should be installed, and coupled to a long-term monitoring program. Autonomous data-loggers are available at modest cost that can record water levels, temperature, and water chemistry parameters. Some select existing wells may be utilized in the near term to begin to gather data on groundwater level fluctuations through time.

Second, a special subset of groundwater monitoring wells should be installed close to the stream in the Upper Hangman sub-basin in order to better understand the relationship there between surface and groundwater. Influent reaches of the stream should be identified in this area, with two or more monitoring wells installed in an array perpendicular to the stream course. Additional wells should be installed at different depths to better understand the vertical gradients in the groundwater system immediately adjacent to the stream.

Third, similar groundwater monitoring of water levels and river stage in the alluvial aquifer adjacent to Hangman Creek below the confluence of Rock Creek should also occur. An accurate survey of the elevation of the wellheads should be made in this area as the hydraulic gradients are likely to be very small.

Fourth, the SCCD has established five stream gages in the basin and three years of data have been gathered to date. These gages should be maintained long-term, and data gathering efforts continued as long as funding permits. Additional seepage runs on the mainstem of Hangman Creek and select tributaries should be continued in successive years to augment the existing data set.

Fifth, a very important field survey to identify and verify the specific locations of all irrigators in WRIA 56 should be undertaken. Both surface water and groundwater diversions should be investigated, and the amounts of withdrawal and the acreage under irrigation should be gathered. The existing water rights databases are often incomplete and may contain erroneous data.

Sixth, water use is likely occurring on Tribal Lands in the upper watershed. However, as best as this study could determine, much of this use is entirely undocumented. Watershed planners and managers should encourage better record keeping by the Coeur d'Alene Tribe.

Summary and Conclusions

Water resources inventory area (WRIA) 56 encompasses the Hangman (Latah) Creek watershed in Washington, with headwaters in Idaho. The basin covers 431,220 acres and contains approximately 222 miles of perennial streams. The headwaters in Idaho lie at an elevation of about 3,600 feet above mean sea level, and at its confluence with the Spokane River the elevation is 1,720 feet above mean sea level.

The geology varies considerably within the basin. The primary geological units include, from oldest to youngest: 1) crystalline basement rocks of meta-sedimentary and igneous plutonic origin that underlie the entire region and occur in the higher peaks, 2) widespread horizontally-bedded volcanic rocks consisting of basalt flows separated by laterally discontinuous sedimentary interbeds, and 3) unconsolidated surficial deposits consisting primarily of flood-deposited sand and gravel and the wind-deposited silts that comprise the rolling hills characteristic of the Palouse.

An unconfined aquifer exists in the sand and gravel deposits in the lower portion of WRIA 56, below the confluence of Rock and California Creek. The water table in this aquifer unit is strongly connected to, and is influenced by, the stage of flow in Hangman Creek. Groundwater discharge from the Hangman valley aquifer and into the lower Spokane aquifer is almost 13 cubic feet per second. However, the most prolific and important aquifer in WRIA 56 is contained within the Columbia River Basalts where multiply stacked confined or semi-confined aquifers are accessible through deep wells. Due to its limited recharge potential within WRIA 56, the basalt aquifer system may be impacted by increasing groundwater withdrawals into the future.

The climate in WRIA 56 is generally very warm and dry in the summer and cool and moist during the winter. Because of the large range in elevation in the watershed significant variation in precipitation occurs, from less than 16 inches/year in the lower part of the basin that is sub-arid, to more than 40 inches/year in the upper part that is sub-humid. Area-weighted calculations of evapotranspiration in the watershed, when compared to the areal distribution of precipitation, show that there is a moisture surplus of 173,882 acre feet per year. This excess water is free to either run off into surface streams, or to infiltrate into the ground to recharge shallow and/or deep aquifer systems.

Surface water appropriations in WRIA 56 have the potential to impact stream flows during the summer months, especially in the Lower Hangman and Marshall/Minnie Creek sub-basins. Groundwater mining is certainly a high potential, particularly in the Lower Hangman and Marshall/Minnie Creek sub-basins where water right allocations from groundwater greatly exceed the recharge rate. Allocated surface water rights are 3.9% of the total annual average stream flow in WRIA 56, while allocated surface water and groundwater rights are 19.7% of the average annual stream flow.

Numerical modeling could ultimately be helpful in future water resource management in WRIA 56. A model development project would take at least two years or more in time to formulate the model framework and to calibrate against field data, provided that a comprehensive dataset already exists. The first objective of such a project would be to build the model to represent the hydrologic system as it exists today in the watershed. Once constructed, calibrated and validated, the model may be applied to helping choose among different management schemes as a solution to a particular problem.

For example, a working watershed model could explore the potential of gradually increasing groundwater pumping in the select parts of the basin, and to predict whether it may eventually have an impact on stream flows. Similarly, a well constructed model could aid in further refinement of the water balance of the watershed, and provide insight to WDOE as it processes water right applications for WRIA 56 into the future. The model may also be used as a guide to further research, for example, in understanding the coupling of various stream reaches with the underlying groundwater system. Short-term and long-term climatic cycles could also be simulated as more information becomes available in the Pacific Northwest region, with simulated stream hydrographs as the model output. Lastly, historical conditions in the watershed could be simulated in the model, prior to major land use modifications, in order to contrast the present day hydrology with that of the past.

No attempts have been made at modeling WRIA 56 to this date, and such an attempt may have to wait at least several more years so that additional field data can be gathered.

This study has identified the following as primary data needs in order to better understand the hydrologic system in WRIA 56. Groundwater monitoring wells in select locations, in select aquifer units, spatially distributed around the basin should be installed, and coupled to a long-term monitoring program. Additional groundwater monitoring wells should be installed close to the stream in the Upper Hangman sub-basin in order to better understand the relationship there between surface and groundwater, which is fundamentally influent (losing). Similar groundwater monitoring of water levels and river stage in the alluvial aquifer adjacent to Hangman Creek below the confluence of Rock Creek should also occur in this reach that is dominantly effluent (gaining).

Additional stream gages should be established at the mouths of the major sub-basins identified in this study to better understand their hydrologic behavior, particularly if numerical modeling is going to be seriously considered. Additional seepage runs on the mainstem of Hangman Creek and select tributaries should be continued in successive years to augment the existing data set already gathered by SCCD and other consultants.

Examination of the water right databases in Washington and Idaho showed that many records are incomplete or may contain erroneous data on water use in the basin. It is very important that a detailed field survey be performed in order to identify and verify the specific locations of all irrigators in WRIA 56. Both surface water and groundwater diversions should be investigated, and the amounts of withdrawal and the acreage under irrigation should be gathered.

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APPENDICES

Appendix A. Land use by sub-basin spreadsheets

Appendix B. Review of runoff and infiltration models

Appendix A. Land use spreadsheets for each sub-basin

Marshall/Minnie Creek Sub-basin: land use (acreage and percent) by precipitation range (inches)						
Precipitation (isohyet zone)	17	19		Precipitation	17	19
Land use category (see Table 2)				Land use %		
11	315.15	406.22		11	0.95	5.72
21	1129.11	311.57		21	3.39	4.39
22	13.65	10.06		22	0.04	0.14
23	663.06	208.78		23	1.99	2.94
31	226.46	30.69		31	0.68	0.43
33	36.66	46.71		33	0.11	0.66
41	91.70	29.21		41	0.28	0.41
42	10253.76	3180.46		42	30.83	44.80
43	367.59	111.95		43	1.11	1.58
51	4777.29	1347.68		51	14.36	18.98
71	4043.45	1192.85		71	12.16	16.80
81	1686.06	83.17		81	5.07	1.17
82	2.64	0.96		82	0.01	0.01
83	4750.49	52.01		83	14.28	0.73
84	4745.02	32.31		84	14.27	0.46
85	0.96	4.07		85	0.00	0.06
91	26.41	27.32		91	0.08	0.38
92	132.60	23.73		92	0.40	0.33
Total acres	33262.04	7099.73	40361.77		100	100

Appendix A. Land use spreadsheets for each sub-basin (continued)

Lower Hangman Sub-basin: land use (acreage and percent) by precipitation range (inches)								
Precipitation (isohyet zone)	17	19	21		Precipitation	17	19	21
Land use category (see Table 2)					Land use %			
11	76.47	43.61	0.24		11.00	0.27	0.27	0.03
21	3000.45	180.23	0.24		21.00	10.56	1.10	0.03
23	2361.65	126.27	0.96		23.00	8.31	0.77	0.12
31	15.58	13.35	0.00		31.00	0.05	0.08	0.00
33	74.75	0.15	0.00		33.00	0.26	0.00	0.00
41	87.85	4.08	0.00		41.00	0.31	0.02	0.00
42	5413.73	2110.10	306.30		42.00	19.05	12.83	39.39
43	148.85	81.26	36.00		43.00	0.52	0.49	4.63
51	5424.84	4261.34	100.06		51.00	19.09	25.92	12.87
71	4062.83	3080.22	97.60		71.00	14.30	18.74	12.55
81	3178.92	428.88	0.00		81.00	11.19	2.61	0.00
82	18.45	6.75	0.00		82.00	0.06	0.04	0.00
83	1454.39	4701.69	227.04		83.00	5.12	28.60	29.20
84	1822.79	1399.20	8.38		84.00	6.41	8.51	1.08
91	1220.10	1.68	0.72		91.00	4.29	0.01	0.09
92	58.97	1.65	0.00		92.00	0.21	0.01	0.00
Total acres	28420.61	16440.43	777.54	45638.58	Total	100.00	100.00	100.00

Appendix A. Land use spreadsheets for each sub-basin (continued)

California Creek Sub-basin: land use (acreage and percent) by precipitation range (inches)								
Precipitation (isohyet zone)	19	21	23		Precipitation	19	21	23
Land use category (see Table 2)					Land use %			
11	10.54	7.43	0.96		11	0.12	0.11	0.23
21	194.50	37.38	0.00		21	2.17	0.57	0.00
23	94.19	20.74	0.01		23	1.05	0.32	0.00
31	0.96	1.20	0.00		31	0.01	0.02	0.00
33	0.00	1.28	0.98		33	0.00	0.02	0.24
41	0.48	0.24	0.00		41	0.01	0.00	0.00
42	502.53	2340.32	327.01		42	5.61	35.62	79.84
43	25.40	317.29	58.33		43	0.28	4.83	14.24
51	1479.13	593.18	21.49		51	16.50	9.03	5.25
71	620.54	205.90	0.78		71	6.92	3.13	0.19
81	2.64	0.01	0.00		81	0.03	0.00	0.00
83	4159.51	2257.84	0.00		83	46.41	34.36	0.00
84	1870.10	780.18	0.00		84	20.87	11.87	0.00
91	1.94	3.84	0.00		91	0.02	0.06	0.00
92	0.00	4.07	0.00		92	0.00	0.06	0.00
Total acres	8962.45	6570.89	409.56	15942.90		100.00	100.00	100.00

Appendix A. Land use spreadsheets for each sub-basin (continued)

Rock Creek Sub-Basin: land use (acreage and percent) by precipitation range (inches)												
Precipitation (isohyet zone)	15	17	19	21	23		Precipitation	15	17	19	21	23
Land use category (see Table 2)							Land use %					
11	3.84	5.27	19.71	26.77	0.00		11	0.05	0.04	0.06	0.05	0.00
21	2.30	119.29	35.64	253.45	9.38		21	0.03	0.88	0.10	0.44	0.61
23	53.15	108.39	293.11	672.35	0.80		23	0.76	0.80	0.85	1.16	0.05
31	0.24	0.00	1.92	2.16	0.00		31	0.00	0.00	0.01	0.00	0.00
33	0.00	0.00	0.00	110.11	21.72		33	0.00	0.00	0.00	0.19	1.42
41	0.48	1.92	3.36	10.37	0.00		41	0.01	0.01	0.01	0.02	0.00
42	2135.15	2013.48	1799.10	2455.45	951.26		42	30.56	14.81	5.24	4.22	62.32
43	407.62	313.78	321.82	614.37	202.15		43	5.83	2.31	0.94	1.06	13.24
51	14.65	77.10	2449.40	3798.54	226.50		51	0.21	0.57	7.14	6.53	14.84
71	0.62	33.67	675.61	1081.66	81.59		71	0.01	0.25	1.97	1.86	5.35
81	0.00	0.00	209.36	11.26	3.84		81	0.00	0.00	0.61	0.02	0.25
82	0.00	0.00	0.00	0.00	0.00		82	0.00	0.00	0.00	0.00	0.00
83	2879.64	7002.95	20276.39	36763.09	29.07		83	41.22	51.50	59.08	63.21	1.90
84	1489.07	3921.27	8229.58	12350.16	0.00		84	21.31	28.84	23.98	21.23	0.00
91	0.00	0.00	6.71	11.27	0.00		91	0.00	0.00	0.02	0.02	0.00
92	0.00	0.00	0.00	0.24	0.00		92	0.00	0.00	0.00	0.00	0.00
Total	6986.75	13597.12	34321.70	58161.24	1526.29	114593.10	Total	100.00	100.00	100.00	100.00	100.00

Upper Hangman Sub-Basin: land use (acreage and percent) by precipitation range (inches)															
Precipitation (isohyet zone)	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43
Land use (see Table 2)															
11	12.47	6.23	56.21	6.59	6.47	6.23	6.64	7.98	5.75	0.96	5.27	1.68	4.79	0.72	0.00
21	29.37	14.16	296.58	372.95	17.33	76.29	30.33	27.05	17.03	19.99	12.74	8.77	0.17	0.00	0.00
23	128.46	72.61	833.12	588.80	91.54	92.30	32.89	14.43	4.19	6.67	4.38	8.56	7.67	0.00	0.00
31	8.87	20.37	3.92	2.88	0.24	0.72	0.24	0.96	0.48	0.00	0.00	0.00	0.00	0.00	0.00
33	0.00	0.00	0.00	0.00	0.00	38.22	12.27	61.55	120.53	112.68	231.64	194.14	257.94	123.19	0.00
41	0.72	0.00	12.23	11.98	2.16	1.79	3.25	7.64	3.14	0.96	1.87	0.91	0.81	0.48	0.00
42	2416.55	3275.29	2820.13	1583.02	2068.75	3524.85	3730.46	6013.01	4079.50	2489.87	2909.67	2103.22	3000.03	1125.03	1.02
43	443.03	498.61	209.04	328.85	324.62	528.63	531.97	714.30	306.54	197.19	274.29	210.89	335.98	99.86	0.00
51	22.44	134.12	7025.02	1689.77	11.51	11.45	26.35	18.91	46.16	3.81	5.90	0.34	0.96	0.00	0.00
71	3.22	81.75	3008.96	635.10	0.00	0.00	0.72	3.21	14.76	0.24	2.16	0.00	0.00	0.00	0.00
81	0.00	0.00	768.61	0.00	0.00	0.00	1.92	5.96	6.08	0.00	4.07	0.00	0.96	0.00	0.00
82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
83	3303.89	3700.53	44208.64	27028.02	8861.58	8056.74	4238.72	2430.45	851.14	505.01	248.55	104.19	44.31	0.00	0.00
84	2758.10	1979.14	18982.50	13253.99	3787.75	3601.62	1365.43	485.04	354.38	227.57	54.49	77.16	4.51	0.00	0.00
91	0.00	0.00	10.05	0.00	0.00	0.48	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	0.24	0.00	2.16	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	9127.34	9782.81	78237.15	45502.18	15171.94	15939.32	9981.17	9790.48	5809.68	3564.94	3755.04	2709.85	3658.13	1349.27	1.02

Precipitation (isohyet zone)	15	17	19	21	23	25	27	29	31	33	35	37	39	41	43
Land use %															
11	0.14	0.06	0.07	0.01	0.04	0.04	0.07	0.08	0.10	0.03	0.14	0.06	0.13	0.05	0.00
21	0.32	0.14	0.38	0.82	0.11	0.48	0.30	0.28	0.29	0.56	0.34	0.32	0.00	0.00	0.00
23	1.41	0.74	1.06	1.29	0.60	0.58	0.33	0.15	0.07	0.19	0.12	0.32	0.21	0.00	0.00
31	0.10	0.21	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
33	0.00	0.00	0.00	0.00	0.00	0.24	0.12	0.63	2.07	3.16	6.17	7.16	7.05	9.13	0.00
41	0.01	0.00	0.02	0.03	0.01	0.01	0.03	0.08	0.05	0.03	0.05	0.03	0.02	0.04	0.00
42	26.48	33.48	3.60	3.48	13.64	22.11	37.38	61.42	70.22	69.84	77.49	77.61	82.01	83.38	100.00
43	4.85	5.10	0.27	0.72	2.14	3.32	5.33	7.30	5.28	5.53	7.30	7.78	9.18	7.40	0.00
51	0.25	1.37	8.98	3.71	0.08	0.07	0.26	0.19	0.79	0.11	0.16	0.01	0.03	0.00	0.00
71	0.04	0.84	3.85	1.40	0.00	0.00	0.01	0.03	0.25	0.01	0.06	0.00	0.00	0.00	0.00
81	0.00	0.00	0.98	0.00	0.00	0.00	0.02	0.06	0.10	0.00	0.11	0.00	0.03	0.00	0.00
82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
83	36.20	37.83	56.51	59.40	58.41	50.55	42.47	24.82	14.65	14.17	6.62	3.84	1.21	0.00	0.00
84	30.22	20.23	24.26	29.13	24.97	22.60	13.68	4.95	6.10	6.38	1.45	2.85	0.12	0.00	0.00
91	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
92	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Appendix B. Review of runoff and infiltration models

Basic Runoff Model Summary

Runoff models differ mainly in the methods used to generate runoff and to route it through a basin. They also differ in the control options available, data handling, and user interface, but these differences generally have little or no effect on how the model computes runoff (Zarriello, 1998). The most utilized models (Table 10) calculate runoff (excess precipitation) by one of the following:

(1) SCS (Soil Conservation District) curve number,
(2) Horton's equation, or
(3) continuous soil moisture accounting.

The SCS curve number is the most widely used method because of its relative simplicity; it defines the watershed storage and is determined for a watershed or sub-watershed predominantly from the types of soils, vegetative cover, and land-use characteristics (Soil Conservation Service, 1986). Horton's equation assumes that the soil infiltration rate decreases exponentially as a function of time since the storm began. Some models account for soil-moisture storage and infiltration using either the Green-Ampt or Phillips equation (see separate summary of infiltration models), or a variation thereof. The PSRM model uses the SCS curve number for determining soil infiltration, but uses soil moisture accounting to determine available storage. These models are either continuous or quasi-continuous (soil-moisture accounting is continuous, but routing is only performed only for a specified storm period). Continuous meteorologic data must be available for best results rather than estimating initial starting conditions for each storm event. Soil moisture accounting and infiltration procedures generally are more data-intensive than the SCS curve and Horton methods, and require a number of parameters corresponding to physical soil-water storage and infiltration characteristics.

Once excess precipitation is determined, surface runoff is calculated for overland flow and channel flow by one of the following methods:

(1) unit hydrograph,
(2) SCS triangular unit hydrograph, or
(3) by solving equations for flow.

The unit-hydrograph procedure derives a hydrograph by assuming a specific shape that represents land-use, soil, and geometric characteristics of the watershed, and techniques are available to derive the unit hydrograph from observed rainfall-runoff data. The SCS triangular unit hydrograph is an approximation of a nonlinear runoff distribution that is assumed to be constant in a unit hydrograph method. A number of methods exist for solving equations for flow. The Muskingum method is used for channel routing by determination of a wedge-shaped channel storage in relation to inflow and outflow channel volume. Overland flow and channel routing is performed in some models by kinematic wave to solve the continuity equation for flow or by diffusive wave, which includes an additional pressure-

Table 10. Comparison of runoff models.

Model Name	Authors	Simulation Type	Runoff Generation	Overland Flow	Channel Flow
CASC2D Cascade 2-D	Julian and Saghafian, 1991	event	soil moisture accounting	cascade	diffusive wave
CUHP Colorado Unit Hydrograph Procedure	Urban Drainage Flood Control District, 1984	event	Horton	unit hydrograph	unit hydrograph
DR3M Distributed Rainfall Routing Runoff Model	Alley and Smith, 1982	quasi-continuous	soil moisture accounting	kinematic wave	kinematic wave
HEC-1 Hydrologic Engineering Ctr.	Hydrologic Engineering Center, 1990	event	SCS curve number	unit hydrograph	Muskingum
HSPF Hydrologic Simulation Program Fortran	Bicknell and others, 1993	continuous	soil moisture accounting	kinematic wave	kinematic wave
PRSM Penn State Runoff Model	Aron and others, 1996	quasi-continuous	SCS curve number	cascade	kinematic wave
SWMM Storm Water Management	Model Huber and Dickenson, 1988	event	Horton	kinematic wave	kinematic wave
TR20 Technical Release No. 20	Soil Conservation Service, 1983	event	SCS curve number	SCS unit hydrograph	SCS unit hydrograph

differential term (Miller, 1984). The cascade method is a two-dimensional kinematic wave approximation for routing overland flow (Julien and others, 1995). Models that use the kinematic or diffusive wave routing differ by how overland flow and channel characteristics are specified.

In an uncalibrated test application for a watershed in Colorado, models based on the SCS curve number (HEC-1 and TR20) for generating runoff generally had the poorest fit. HEC-1 simulations substantially overpredicted peak flows, and TR20 simulations substantially underpredicted peak flows; this may indicate the sensitivity of the simulations to user judgment of the SCS curve number (Zarriello, 1998). A comparison of runoff simulation techniques in west-central Florida indicated a somewhat less, but comparable error, in simulated peak-flows and storm volumes for TR20 and HEC-1 simulations (Trommer and others, 1996). In that study, average uncalibrated-model peak-flow and storm-volume error averaged 45 and 43 percent, respectively, for TR20 simulations and 105 and 27 percent, respectively, for HEC-1 simulations.

Basic Infiltration Model Summary

The Environmental Protection Agency presents information on six infiltration models for which they provide the model code in MathCad. A comprehensive web site is available at the following URL: http://www.epa.gov/ada/csmos/ninflmod.html. Brief descriptions of each are provided below.

Description of the SCS (Soil Conservation Service) Model

The SCS Model is an empirically developed approach to the water infiltration process. It has been developed by first finding a mathematical function whose shape as a function of time matches the observed features of the infiltration rate. In semi-empirical models, most physical processes are represented by commonly accepted and simplistic conceptual methods rather than by equations derived from fundamental physical principles. The commonly used semi-empirical infiltration model in the fields of soil physics and hydrology is the SCS Model.

Description of the Philip's Two-Term Model

The Philip's Two-Term model (PHILIP2T) is a truncated power series solution developed by Philips (1957). During the initial stages of infiltration, i.e., when t (time) is very small, the first term of the model/equation dominates the process. In this stage, the vertical infiltration proceeds at almost the same rate as absorption, or horizontal infiltration. In this stage of infiltration the gravity component, represented by the second term of the model/equation, is negligible. As infiltration continues, the second term becomes progressively more important until it dominates the infiltration process. Philips (1957) suggested the use of the two-term model in applied hydrology when t is not too large.

Description of the Layered Green-Ampt Model

The Green-Ampt Model has been modified in this application to calculate water infiltration into non-uniform soils by several researchers (Bouwer, 1969; Fok, 1970; Moore, 1981; Ahuja and Ross, 1983). The implementation for layered systems (GALAYER) was developed by Flerchinger et al. (1989). Specifically, the model could be utilized for the determination of water infiltration over time in vertically heterogeneous soils.

Description of the Explicit Green-Ampt Model

The initial Green-Ampt model was the first physically-based model/equation describing the infiltration of water into soil. It has been the subject of considerable developments in soil physics and hydrology owing to its simplicity and satisfactory performance for a great variety of water infiltration problems. This model yields cumulative infiltration and the infiltration rate as an implicit function of time (i.e., given a value of time (t), values of the cumulative infiltration (I) and the infiltration rate (q) can be directly obtained. The Explicit Green-Ampt model was developed by Salvucci and Entekhabi (1994), which provides a straightforward and accurate estimation of infiltration for any given time. This formulation supposedly yields an error of less than 2% at all times when compared to the exact values resulting from the Implicit Green-Ampt Model.

Description of the Constant Flux Green-Ampt Model

For the constant flux Green-Ampt model, two formulations are required, one for the condition that the application rate (r) is less than the saturated hydraulic conductivity (Ks), and one for the condition that the application rate is greater than the saturated hydraulic conductivity. When r<Ks, the infiltration rate (q) is always equal to the surface application rate (r), and the surface never becomes saturated. When r>Ks , the surface becomes saturated at the time of the initial application (t0).

Description of the Infiltration/Exfiltration Model

The vertical movement of water in the soil profile from the surface to water table is a dynamic condition, and can be conceptualized as being composed of basically two predominant processes: 1) infiltration and 2) exfiltration. Exfiltration can be envisioned as the processes dominating during drying periods, and water released during this period can be thought of as being released through evaporation to the atmosphere. The model (INFEXF) selected for this project is a formulation of the Philips model developed by Eagleson (1978) to account for water infiltration during the wetting season and exfiltration during the drying season. Infiltration and exfiltration as described in this application assumes the soil medium to be effectively semi-infinite and the internal soil water content at the beginning of each storm event and inter-storm period is assumed to be uniform at its' long-term and space-time average. The exfiltration equation is modified for the presence of natural vegetation through the approximate introduction of a distributed sink representing the moisture extraction by plant roots. Two scenarios are presented in the accompanying worksheet applications: 1) demonstrates water infiltration during the rainy season and 2) exfiltration during the drying season.

HELP Model Summary

In addition, a simple model that is also in the public domain and provided by the U.S. Army Corp of Engineers is the Hydrologic Evaluation of Landfill Performance (HELP) Model. This model can be used to evaluate infiltration and runoff from small parcels of land, and is not necessarily strictly limited to landfill evaluation. Their web site provides access to the free model code at: http://www.wes.army.mil/el/elmodels/helpinfo.html.

Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The program facilitates rapid estimation of the daily, monthly, annual, and average annual amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may result from the operation of a wide variety of landfill designs.

The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model is sufficiently sophisticated to consider all of the principal design parameters including vegetation, soil types, geosynthetic materials, initial moisture conditions, thicknesses, slopes, and drain spacing as well as climate effects. Local consultants in the Spokane area have used this model to predict runoff and groundwater levels due to storm events and the routing of storm water runoff into grassy swales.

Version 3 of the Hydrologic Evaluation of Landfill Performance (HELP) model is a user-friendly computer program that computes estimates of water balances for municipal landfills. The model accepts weather and soil data and uses solution techniques that account for the effects of surface storage, snowmelt, frozen soil, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners.

Climate data requirements: General evapotranspiration data and daily values of precipitation, temperature, and solar radiation. The HELP model has a default evapotranspiration database for 183 U.S. cities, containing data for latitude, evaporative zone depths, leaf area indices, growing season, average wind speed, and average quarterly relative humidities. A default precipitation database is included, containing 5 years of daily values for 102 cities throughout the United States. The model also has a synthetic weather generator with coefficients for 139 cities for daily precipitation data generation and for 183 cities for daily temperature and solar radiation data generation. The user interface also contains a number of utility routines to import weather data from other databases.

Soil data requirements: Porosity, field capacity, wilting point, initial moisture content, and saturated hydraulic conductivity of up to 20 layers of materials. The model contains a default soil database of characteristics for 42 types of materials (soils, waste, and geosynthetics). Design data requirements include the AMC-II runoff curve number for the site, a description of the vegetation, a description of the function of each layer of material, the thickness of each layer, the slope at the base of each drainage layer, the spacing between drainage collectors in each drain system, a description of leakage potential of each geomembrane liner, and a description of the leachate recirculation, if used. As evident by the data requirements, the model permits an evaluation of detailed designs and a sensitivity analysis of design components and climatological variables.