A RECESSION ANALYSIS OF SPRINGS AND STREAMS IN THE MOSCOW-PULLMAN BASIN

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AUTHORIZATION TO SUBMIT

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ABSTRACT

Declining water levels in the Moscow-Pullman basin have caused growing concern over future supplies of ground water in the region. In the past, the major streams and rivers in Whitman County including Union Flat Creek, the South Fork of the Palouse River, and the Snake River have been considered the major ground water discharge areas for the Moscow-Pullman basin. Tributary flow into these streams is derived from multiple springs discharging from the valley walls. Recharge mechanisms have generally been considered to either be a combination of areally distributed infiltration of precipitation through the loess and infiltration of water through the Sediments of Bovill or at the contact of the crystalline rock and the basalt. In order to estimate the available ground water supply, a better understanding of the mechanisms affecting natural discharge and recharge to the system must first be established. The purpose of the research was to investigate implications of the locations of springs on ground water discharge and recharge in the Moscow-Pullman basin.

Weekly discharge measurements were taken at seventeen spring-fed sites during a period when streamflow in southeastern Washington consisted solely of baseflow. Each measurement site was located just downstream from a spring and in some cases, multiple springs. Fifteen of the hydrographs showed a characteristic increase in discharge during the month of August in the absence of precipitation, the remaining two hydrographs showed neither an increase nor a decrease in discharge during the same period. Winter wheat transpiration was tested as a potential mechanism for creating this characteristically shaped curve. A combination of the measured discharge and the winter wheat transpiration successfully fit the widely used exponential decay model for baseflow recession for all seventeen spring hydrographs. Values for recession constant ranged from 0.004 to 0.020 for the summer of 2000.

Data suggest the sources of the springs along Union Flat Creek and the South Fork of the Palouse River are from perched water tables within the loess or at the loess-basalt contact rather than from within the basalts. Recession analyses on Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek using historical discharge data from USGS gaging stations suggest that the majority of the discharge in the streams is, however, derived from the basalts as opposed to the loess derived discharge of the springs. These recession analyses provide evidence for shallow flow systems, which feed the springs along the major streams of the study area, and intermediate flow systems, which appear to discharge directly into the streams.

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CHAPTER 1

INTRODUCTION

Statement of the Problem

Since the cities of Moscow and Pullman first began pumping ground water in the 1890's, water levels in the producing aquifers have been declining. The first wells in the area were flowing artesian wells, but by the turn of the twentieth century those wells were no longer flowing at the surface (Russell, 1897; Stevens, 1960). By 1960, water levels in the shallow, Wanapum aquifer had declined to 120 feet below land surface. During the 1960's, pumping shifted from the Wanapum aquifer, to the deeper Grande Ronde basalt aquifer due to problems with high concentrations of iron and moderate hardness (Jones and Ross, 1972; Kopp, 1994). Currently, the water levels in the Grande Ronde aquifer are declining by approximately one to two feet per year (McKenna, 2001).

The declining water levels in the Moscow-Pullman basin have caused growing concern over exactly how much water will be available for future water supplies. In order to understand how much water will be available, accurate estimates of recharge, and knowledge of the mechanisms controlling natural ground water discharge are of particular importance. Past researchers have estimated recharge (Stevens, 1960; Foxworthy and Washburn, 1963; Crosby and Chatters, 1965; Barker, 1979; Bauer and Vaccaro, 1990; Johnson, 1991; Muniz, 1991; O'Brien et al, 1996); however, the accuracy of their results is unclear. Natural discharge from the basaltic aquifers was believed to occur along the major streams in Whitman County, and along the Snake River (Lum et al, 1990; Heinemann, 1994; Barker, 1979). Various mathematical models have used some of these estimates as input (Barker, 1979; Lum et al, 1990); however, these models were unable to predict future water level declines and may have incorporated inaccurate hydrologic conditions in order to duplicate the water levels at the time.

Purpose and Objectives

The purpose of this research is to investigate the mechanisms of ground water discharge and recharge in the Moscow-Pullman basin using recession analysis techniques, and available soil and geologic data. Recent work conducted by Heinemann (1994) pointed toward Union Flat Creek and possibly the South Fork of the Palouse River as streams receiving significant contributions of baseflow from the basalt aquifers. Geochemical data, however, suggest that baseflow in these streams is not derived from the deep flow systems in the Grande Ronde basalts (Kirk, 2000). The hypothesis to be tested is that the springs along Union Flat Creek and South Fork of the Palouse River drain shallow ground water flow systems within the Palouse Formation.

Specific objectives of the study are to:

(1) locate and measure discharge from springs along Union Flat Creek and South Fork of the Palouse River;

(2) evaluate the recession characteristic of the springs and streams in the study area;

(3) delineate the factors that control the locations of the springs along Union Flat Creek and South Fork of the Palouse River;

(4) use measured discharge data, available soil and geologic data, and a knowledge of flow systems to investigate the mechanisms potentially affecting recharge and natural discharge in the Moscow-Pullman basin.

Hydrogeologic Setting

Climate

Precipitation amounts decrease from east to west within the Moscow-Pullman basin, corresponding to land surface elevation changes. Annual precipitation averaged over approximately the past 100 years is 23.50 inches in Moscow, Idaho and 19.70 inches in Colfax, Washington. Averaged from 1940 through 2000, the annual precipitation for Pullman, Washington is 21.52 inches (Western Regional Climate Center, 2001). Most of the precipitation occurs during fall, winter, and spring (October to May) with very little precipitation occurring during the summer months.

Geology and Geohydrology

The Moscow-Pullman basin is located on the eastern edge of the Columbia Plateau physiographic province, which includes southeastern Washington and northwestern Idaho (Jones and Ross, 1972). The basin boundaries are Moscow Mountain to the north, Paradise Ridge to the south, Tomer Butte and surrounding highlands to the east, and the Snake River to the west (Figure 1). There is, however, debate over the location of the western boundary of the basin. Three hydrogeologic regimes exist in the Moscow-Pullman area that can be distinguished by their differing geologic compositions, 1) the crystalline basement rock, 2) the aquifers within the Columbia River Basalts, and 3) the water table aquifers in the Palouse Formation. The aquifers within the basalts are the most productive aquifers in the region.

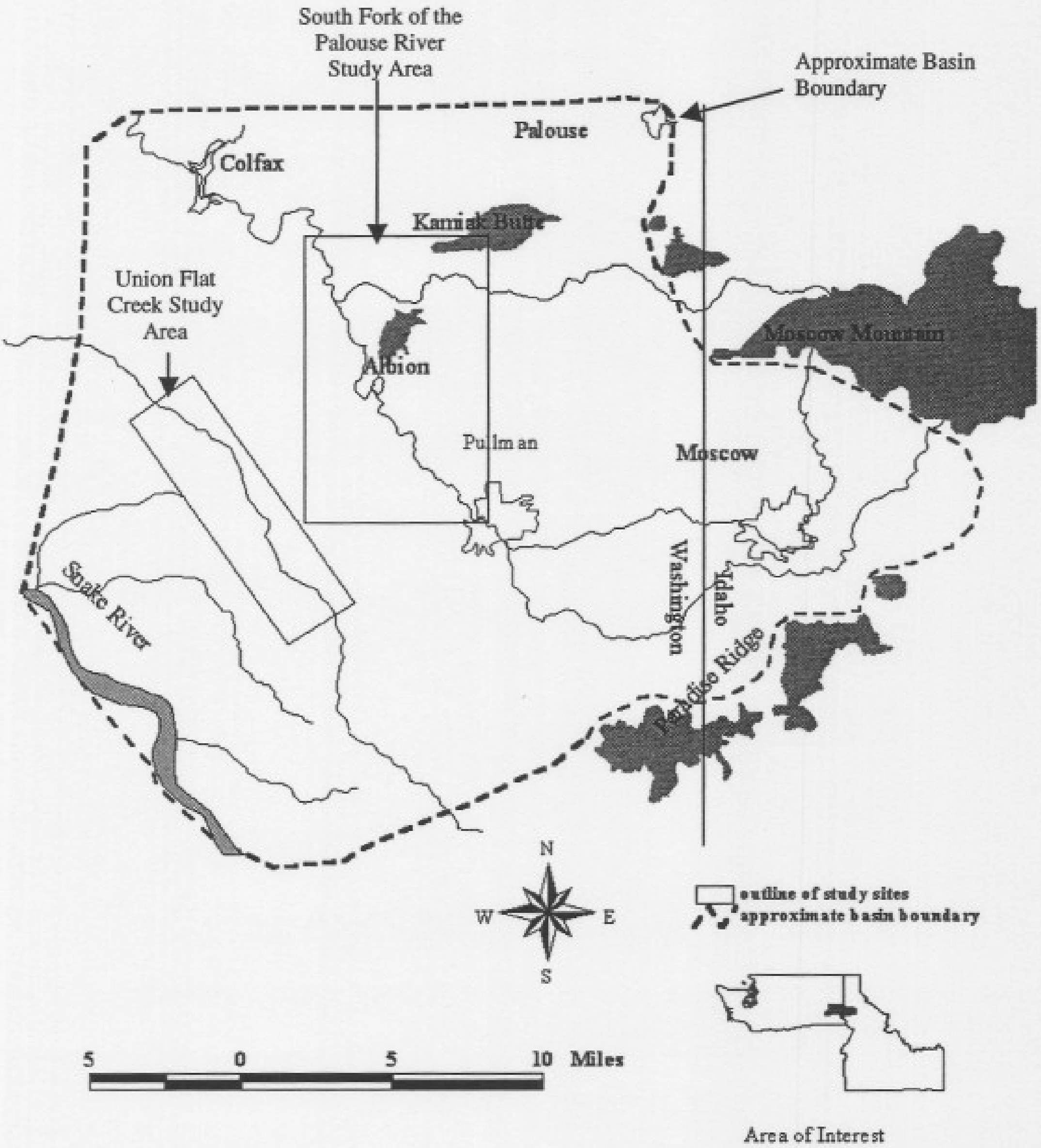


Figure 1. Location map of the Moscow-Pullman basin.

Crystalline Rocks

The crystalline rocks consist of Precambrian quartzite, schist, and gneiss, which were intruded during the Cretaceous by granitoid plutonic rocks of the Idaho Batholith (Pierce, 1998). These metamorphic and intrusive crystalline rocks form Moscow Mountain, Tomer Butte and the surrounding highlands, Paradise Ridge, and the basement rock in the vicinity of Moscow and Pullman. The crystalline rocks are considered to be relatively impermeable and therefore form the northern, eastern, and southern boundaries of the ground water basin. Local yields of up to 20 gallons per minute can be obtained from wells within the crystalline rocks. These wells provide water for stock and domestic use. Well yields in the crystalline rocks are not large enough relative to the basalts to be considered as a productive part of the Moscow-Pullman basin (Lum et al, 1990).

Columbia River Basalts

After a period of mountain building and erosion following the intrusion of the Idaho Batholith, massive flood basalts erupted from fissures in what is now northeastern Oregon, southeastern Washington and adjacent parts of Idaho approximately 17 million years ago. These flood basalts are known as the Columbia River Basalts and continued to erupt intermittently over an 11 million year period during the Miocene Epoch (Pierce, 1998).

The Grande Ronde Formation, which consists of multiple basalt flows that erupted between 15.6 and 17.0 million years ago, forms the lower productive zones and contains deep flow systems in the Moscow-Pullman basin (Figure 2).

	GEOLOGIC UNIT		THICKNESS (FT)	AGE
	PALOUSE FORMATION		0-300	2 Million Years Ago - Present
	SEDIMENTS OF BOVILL (Latah Formation)		0-200	-
COLUMBIA RIVER BASALTS	SADDLE MOUNTAINS BASALT	Asotin Member	0-100?	13 - 14.5 Million Years Ago
		Wilbur Creek Member		
		Umatilla Member		
	WANAPUM BASALT with Latah Formation Interbeds	Priest Rapids Member	0-250	14.5 - 15.6 Million Years Ago
		Roza Member		
	VANTAGE MEMBER (Latah Formation)		0-400	-
	GRANDE RONDE BASALT with Latah Formation Interbeds		0-3500	15.6 - 17 Million Years Ago
	IDAHO BATHOLITH AND BELT SERIES SUPERGROUP		-	PreCambrian Metamorphics and Cretaceous Plutonics

Figure 2. Generalized stratigraphic column showing the geologic units present in the Moscow-Pullman basin.

The Wanapum Formation is 14.5 to 15.6 million years old and lies stratigraphically above the Grande Ronde Formation, but is separated from the Grande Ronde by sedimentary interbeds near Moscow (Pierce, 1998). The members of the Wanapum Formation, which are present in the Moscow-Pullman area, from youngest to oldest, are the Priest Rapids and the Roza. Locally, the Priest Rapids consists of one to three flows while the Roza Member consists of a single flow with its eastern terminus between Pullman and Colfax (Heinneman, 1994). The Saddle Mountain Formation is the youngest Columbia River Basalt formation in the Moscow-Pullman basin and lies stratigraphically above the Wanapum Formation in places. The Saddle Mountain Formation locally includes the Umatilla Member, the Asotin Member, and the Wilbur Creek Member, which are only found just to the east and west of the Union Flat Creek drainage in the basin (Swanson et al., 1980).

The total thickness of the basalt flows increases to the west-northwest. The basalt thickness increases from zero at the edges of the basin to approximately 1300 feet thick in Moscow and 2000 feet thick in Pullman (Smoot, 1987). This thickening to the west is a result of the ancient topography of the crystalline rock consisting of deeply incised paleo channels, which drained to the west prior to the deposition of the Columbia River Basalts.

The productive zones in the basalts are typically at and between the contacts of individual basalt flows. The heterogeneous nature of individual basalt flows results from varying cooling rates during emplacement. As a result, the vesicular zones at the tops and bottoms of the flows and the platy zones at the bottom typically form the primary aquifers. In the centers of the flows, the entablature and colonnade impede vertical movement and form confining layers.

The Columbia River Basalt aquifers are the primary source of water within the Moscow-Pullman basin. The City of Moscow, the City of Pullman, Washington State University, and the University of Idaho pump all of their water supplies from aquifers within the basalts. Over 90 percent of the water is derived from the Grande Ronde aquifers (McKenna, 2001). Water levels in the Grande Ronde aquifers generally reflect cones of depression formed by the pumping centers of Moscow, Pullman, Palouse and Colfax and do not imply a natural flow direction. Approximately 2000 feet of Grande Ronde Formation is exposed along the Snake River about 11 miles southwest of Pullman. The Snake River is at an elevation of 638 feet above mean sea level (pool elevation) below Lower Granite Dam. The question of whether Grande Ronde aquifers are in direct hydraulic connection with the Snake River remains unanswered.

Sedimentary Interbeds and the Sediments of Bovill

All of the sedimentary deposits within the Moscow-Pullman region, with the exception of the Palouse Formation, are derived from the surrounding crystalline highlands. Numerous interbeds exist between the basalt flows of the Wanapum and Grande Ronde Formations and are generally referred to as the Latah Formation. These interbeds, which are thickest in the vicinity of Moscow and thin to the west, are thought to be lacustrine deposits resulting from the damming of streams by basalt flows during the Miocene Epoch (Lin, 1967). The thick sedimentary interbed between the Wanapum Formation and the Grande Ronde Formation is considered to be equivalent to the

Vantage Member of the Ellensburg Formation in central Washington. This interbed, consisting of clay, silt, sand, and gravel, ranges from a few hundred feet thick in Moscow to less than 20 feet thick near Pullman and is nonexistent further west in the basin (Provant, 1995; Kopp, 1994).

The Sediments of Bovill are differentiated from the other sediments because they do not exist as interbeds, but rather overlie the basalts and therefore were deposited after the last basalt flow. Both Provant (1995) and Pierce (1998) describe these sediments as composed of clay, silt, sand and gravel. The Sediments of Bovill are somewhat difficult to distinguish in driller's logs from the overlying Palouse Formation, but are generally identified by the first appearance of yellow and white clay and/or the presence of a considerable sand unit.

Other sedimentary deposits that are important to mention, are the clay deposits derived from the basalts. These clay deposits are found stratigraphically above the Columbia River Basalts in various areas in Latah County, Idaho and Spokane County, Washington. Clay deposits up to 10 feet thick can be found in the Palouse hills area and up to 80 feet thick in other areas (Hosterman et al, 1960).

The heterogeneous nature of these sedimentary deposits affects the ground water flow to various degrees. The Latah Formation interbeds and the Vantage equivalent can form aquitards when they consist of finer sediments like clay and silt, or aquifers when consisting of sands and gravels. The coarser grained deposits of the Sediments of Bovill are considered to be potential routes for recharge into the basalts (Provant, 1995; Pierce, 1998). Unfortunately, little is known of the actual hydraulic conductivity distributions of the sedimentary deposits in the Latah Formation, the Vantage equivalent, and the

Sediments of Bovill. Similarly, little is known as to the effect of the basalt-derived clays on ground water flow in the Moscow-Pullman basin, but the clay may effectively seal surface fractures and form a perching layer on the top of the uppermost basalts.

The Palouse Formation

The Palouse Formation is the youngest formation in the area. This formation consists of the thick soil layer that covers a large portion of southeastern Washington and northwestern Idaho and is manifested as dune like topography, which is characteristic of the “Palouse”. These rolling hills formed on top of relatively flat Columbia River Basalt flows (Figure 3). The source of materials for this formation has been investigated since European settlers first came to this region in the mid-1800’s. The first documented speculation of the source of this Palouse soil was that the soil was derived from the underlying basalts (Russell, 1897). Since then, however, the prevailing view has shifted focus to eolian processes. More recently, researchers found that the Palouse loess was deposited over the past 2 million years by wind from southwest Washington in the Walla Walla area, Yakima valley, and Pasco and Quincy basins. The sediments were derived from slackwater deposits from multiple episodes of cataclysmic flooding during the Quaternary Period (Busacca, 1994). Busacca (1994) believed that periods of rapid deposition of loess followed each flooding episode and created thick layers of undeveloped soils, but after the source had been substantially depleted, the paleosols were then able to develop. At least eight and up to 21 episodes of loess deposition occurred in the Palouse with each episode separated by an ancient soil, a paleosol (Krapf, 1978; Reuter, 1995). Both the thickness and the grain sizes of the loess decrease from

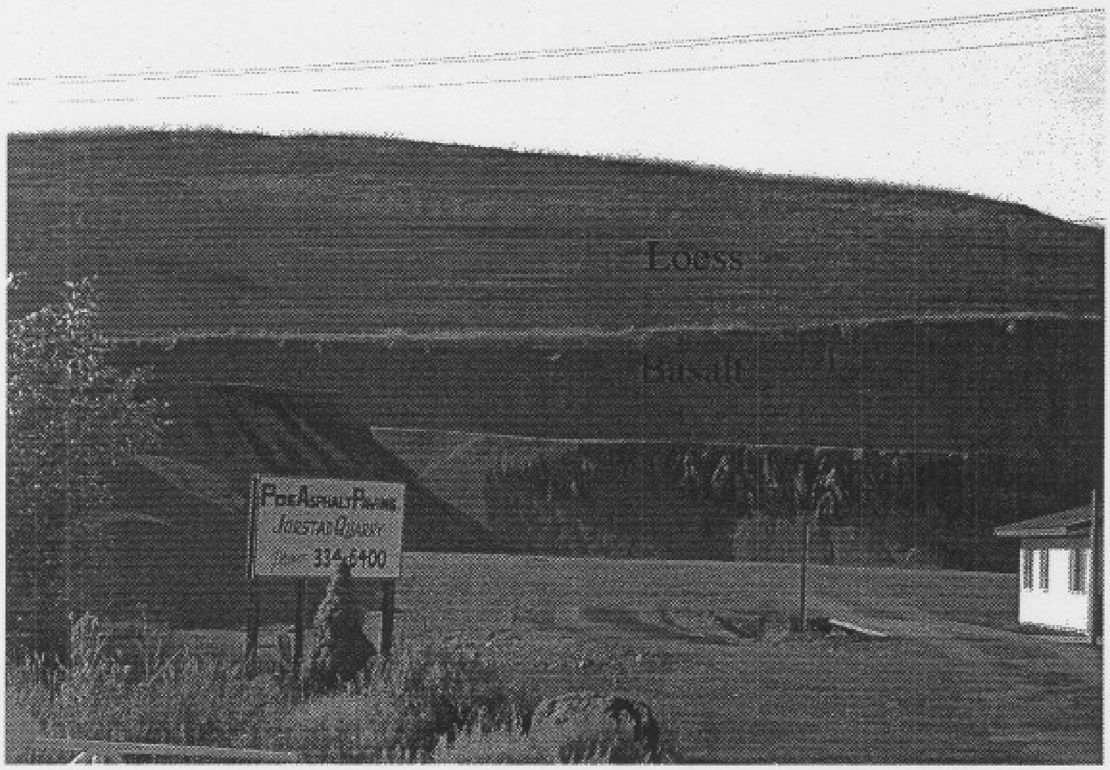


Figure 3. Photograph showing the Palouse Formation overlying the relatively flat surface of a Priest Rapids basalt flow.

southwest to northeast in the direction of the prevailing wind (Ringe, 1970; Busacca, 1994).

Water wells completed in the loess can produce up to 30 gallons per minute (gpm), enough only for domestic supply and local stock (Lum et al., 1990). Various researchers have considered springs of less than 30 gpm to discharge from the contact between the loess and the basalt along stream channels (Lum et al, 1990; Nassar and Walters, 1975). Other researchers, however, have considered these springs to originate from the Wanapum aquifer (Heinemann, 1994).

Thickness of the Palouse Formation plays an important role when considering recharge into the Moscow-Pullman basin. Many researchers have considered recharge to be areally distributed across the basin, which would mean that the precipitation would have to infiltrate through the overlying Palouse loess in order to recharge the deeper basalt aquifers. The more developed paleosols within the loess hills typically contain a clay-rich horizon, which has been shown to create perched conditions and thus impact recharge in the eastern part of the Palouse (Reuter, 1995; Gabehart, 1996; Rockefeller, 1997; Young, 1998). Over fifty percent of the soils mapped in Latah County contain restrictive horizons, which could result in perched water conditions (Barker, 1981). Little work, though, has been conducted to investigate potentially restrictive layers in the western part of the Palouse, in Whitman County.

Ground Water-Surface Water Interactions

Natural discharge from the Moscow-Pullman basin has been referred to in previous work. Lum et al. (1990) referred to seepage faces along the Snake River canyon as apparent ground water discharge points for the Moscow-Pullman basin. Heinemann (1994) concluded that significant ground water discharge from the Wanapum aquifer occurs along the central portion of Union Flat Creek and the upper reach of the North Fork of the Palouse River, and that seepage along the Snake River is less than previously thought. Heinemann's research was based on temperature and discharge data for the streams, and water levels in the surrounding domestic wells; however, he did not investigate the multiple springs contributing flow to the streams.

Pardo (1993) investigated the relationship between ground water and surface water at the University of Idaho Groundwater Research Site in Moscow, Idaho. She found that Paradise Creek was in direct hydraulic connection with the shallow soil and underlying shallow basalt aquifers, but did not appear to be connected with the slightly deeper basalt aquifer. She concluded that the shallow aquifers were receiving recharge from the stream and precipitation, while the deeper aquifer appeared to receive recharge from elsewhere.

Overall, the ground water and surface water interactions within the basin are not well understood. It is impossible to estimate how much water the Snake River may be gaining or losing to the basin because it has been dammed making discharge measurements out of the question. The only existing USGS gaging stations within the basin that are in use currently are on the North Fork of the Palouse River at Colfax, which receives some of its discharge from waste water treatment plants upstream, and on Paradise Creek near Moscow. So far, no one has measured directly the naturally occurring discharge from the Moscow-Pullman basin.

Recharge

Many recharge processes in the Moscow-Pullman basin have been proposed. These processes generally fall within the following three types: (1) the recharge is areally distributed and infiltrates through the Palouse Formation covering the basin; (2) recharge occurs along the margins of the basin, at the Basalt-Crystalline bedrock contacts; (3) losing streams are recharging the basalt aquifers, particularly via percolation through the Sediments of Bovill in the eastern part of the basin. These processes refer to the recharge of the basalt aquifers as a whole. It has been suggested also that the mechanisms for recharge are different for the Wanapum aquifers and the Grande Ronde aquifers.

Most of the ground water studies in the Moscow-Pullman basin have supported the concept of areally distributed recharge to the basalt aquifers via infiltration of precipitation, and percolation through the Palouse Formation and/or Sediments of Bovill. Foxworthy and Washburn (1963) conducted one of the first ground water studies in the Pullman area and concluded that recharge occurs through a combination of all of the afore mentioned processes, but they considered infiltration of precipitation and percolation through the Palouse loess to be the dominant recharge mechanism. Sokol (1966) also concluded that recharge to the local ground water basin is dominated by areally distributed infiltration and percolation of stream water through the Palouse Formation. Based on Carbon-14 dating, Crosby and Chatters (1965) concluded that the deeper basalt aquifer had received virtually no recharge since the period of Pleistocene glaciations. They also found that the shallow basalt aquifer in Pullman receives recharge through basalt outcrops and by the percolation of water through the loess. Larson et al. (2000) also came to the same finding as Crosby and Chatters by analyzing stable isotopes in the ground water. They found that recharge to the shallow basalt aquifers in Moscow occurs areally. Williams and Allman (1969) found the occurrence of tubular openings of unknown origin in some of the Palouse Formation sediments, making the loess more susceptible to vertical percolation of recharge. Several other researchers also considered infiltration of precipitation and percolation through the Palouse Formation to be the dominant mechanism of recharge to the Wanapum aquifer in the Moscow-Pullman basin (Barker, 1979; Smoot and Ralston, 1987; Lum et al, 1990; Kopp, 1994; Bauer and Vaccaro, 1990; Provant, 1995; Johnson, 1991; O'Brien et al, 1996; Muniz, 1991).

Recharge mechanisms involving infiltration of precipitation at the basalt-granite contacts and percolation of water through the Sediments of Bovill have also been proposed; however, these mechanisms are not supported by data. An early study by Stevens (1960) concluded that recharge to the artesian aquifers in the Moscow-Pullman basin was occurring through a conduit at the basalt-granite contact. Lin (1967) concluded that recharge entered the basin through paleo channels (scour features) on the surface of the crystalline rock. Consideration of the Sediments of Bovill as a dominant factor controlling recharge to the basin was suggested more recently. Both Provant (1995) and Pierce (1998) considered the possibility of percolation through the coarser grained sediments of the Sediments of Bovill, especially from losing streams in the eastern part of the basin.

The mechanisms and amounts of recharge to the Moscow-Pullman basin are necessary factors to be considered when investigating how much ground water will be available for future generations. Recharge may be a combination of all of the afore mentioned mechanisms rather than one single mechanism. More work must be done before the recharge mechanisms in the Moscow-Pullman basin can be sufficiently understood.

Baseflow

Streamflow is made up of three, primary hydrologic components: surface runoff, interflow, and baseflow. Baseflow is the ground water contribution to a stream and accounts for a majority of the flow during periods of no precipitation, usually during the summer months. Baseflow can either enter a stream directly from the aquifer or it can contribute to the stream via spring discharge. A majority of past research has examined baseflow recession characteristics from streamflow measurements rather than discharge measurements directly from springs, but the techniques for analysis are virtually identical.

The focus of research involving baseflow typically deals with baseflow separation, calculating recharge, or recession analysis. The early work with baseflow mostly consisted of developing techniques for separating baseflow from stream hydrographs. Kunkle (1962) used baseflow-duration curves to aid in separating baseflow from bank storage. Shirmohammadi et al. (1987) partitioned out precipitation from the hydrograph with the aid of threshold rainfall values. Since then, automated techniques for separating baseflow from stream hydrographs have become more popular (Arnold et al., 1995). Researchers, though, have so far been unable to derive an objective technique that can be used to consistently separate baseflow from stream hydrographs (Halford and Mayer, 2000).

Calculations of recharge to ground water flow systems discharging to streams or springs are another important focus of research involving baseflow. Meyboom (1961) estimated recharge as the difference between the remaining potential ground water discharge at the end of one recession and the total potential ground water discharge at the beginning of the next recession. Rorabaugh (1964) presented a recession curve displacement method to estimate recharge during a single runoff season. Later, similar methods were used by Korkmaz (1990) to calculate the recharge to the ground water that contributed to a particular spring in Turkey. Automated techniques of calculating ground water recharge based on baseflow recession became the focus of more recent papers (Rutledge and Daniel, 1994; Perez, 1997).

Most papers dealing with baseflow have been dedicated toward recession analysis. Recession analysis is based on the principle that some type of mathematical equation can quantitatively describe a baseflow recession curve. The equations that describe these curves are derived from both linear and non-linear solutions to differential equations, which were presented by Boussinesq (1877; 1904). The linear solutions used for this analysis are discussed in detail in the Materials and Methods section of this thesis.

The slope of the recession curve is related to the geologic and geomorphologic characteristics of the basin. As early as 1963, geologic influences were compared to baseflow recession characteristics (Knisel, 1963; Farvolden, 1963). More recently, researchers found the major factors controlling the recession constants for karst springs in northern Israel to be aquifer lithology and the geometry of the water conduits (Amit et al., 2002). More quantitative relationships based on solutions of Boussinesq's equation directly relate the recession constant to hydraulic conductivity of the aquifer and indirectly relate it to the specific yield and width of the aquifer (Moore, 1992; Angelini and Dragoni, 1997; Baedke and Krothe, 2001). A similar relationship was also presented which relates the recession constant to the transmissivity and specific yield of the aquifer (Rorabaugh, 1964; Atkinson, 1977). Relationships between baseflow recession and geomorphologic properties of the drainage basin such as land slope and drainage density were also suggested (Zecharias and Brutsaert, 1988; Vogel and Kroll, 1992).

Though evapotranspiration does not affect the actual recession constant of a ground water flow system, it tends to increase the slope of the recession curve during the summer as the growing season progresses. Several researchers have mentioned the effect of evapotranspiration on recession curves; however, only limited work has been dedicated towards its better understanding and quantification. Most investigations dealing with evapotranspiration withdrawals from stream flows have dealt with riparian vegetation. Croft estimated that one third of the stream discharge of Farmington Creek in northern Utah was lost to transpiration by riparian vegetation during the summer (1948). Tschinkel (1963) and Reigner (1966) attempted to estimate stream losses due to riparian zone evapotranspiration from stream discharge measurements. Federer (1973) showed that stream discharge increased dramatically after the cutting of trees in a forested watershed in central New Hampshire. Weisman (1977) also found relationships between slopes of recession curves and evaporation rates. Little work, though, has dealt with crop evapotranspiration effects on recession curves.

Numerous investigations including those conducted by Kunkle (1962), Meyboom (1961), and Hall (1968) have been dedicated toward the better understanding of baseflow recession by looking at baseflow separation, recharge estimates, or recession analysis.

Recession analysis includes techniques used to derive valuable information about the aquifer producing the baseflow. During the months when baseflow makes up the entire flow of the stream, evapotranspiration from plants and the soil surface must be considered in a recession analysis. Baseflow recession characteristics reflect both hydrologic and geologic factors of the system. Information about these characteristics is important relative to increasing our current understanding of the Moscow-Pullman basin recharge-discharge relationships.

CHAPTER 2

MATERIALS AND METHODS

Recession Analysis

Recession analysis is based on the principal that some type of mathematical equation can quantitatively describe a baseflow recession curve. A simplified linear solution to the Boussinesq (1904) equation,

$$Q = Q_0 e^{-\alpha t}, \qquad (1)$$

describes baseflow as exponentially decaying over time. In Equation 1, Q is discharge at time t, Q_0 is the initial discharge at time t=0, α is the recession constant which is related to properties of the aquifer, and t is elapsed time. Maillet (1905) was the first to apply Equation 1 to field data. This equation has been used successfully for purposes of recession analysis by many researchers over the past 100 years (Kunkle, 1962; Hall, 1968; Nutbrown and Downing, 1976; Anderson and Burt, 1980; Baedke and Krothe, 2001; Amit et al., 2002). Recently, research has focused more on deriving techniques by which recession curves can be analyzed using non-linear methods; however, for the purposes of application, this thesis will analyze the recession curves with the widely used linear Equation 1 (Brutsaert and Nieber, 1977; Tallaksen, 1995).

Equation 1, which describes baseflow as exponentially decaying over time, can also be derived, along with the relationship between the recession constant and the hydrogeologic characteristics of the aquifer, using a mass-balance approach,

$$M_{in} = M_{out} + \Delta M \,, \qquad (2)$$

Where M_{in} is the mass entering the system, M_{out} is the mass leaving the system, and ΔM is the change in mass storage. Assuming that all of the water in the system is in place at t=0, the inflow is then equal to zero, the outflow is the discharge from the spring and the change in storage is equal to the change in the volume within the aquifer, resulting in the equation

$$Q\rho_w(\Delta t) = -\Delta V \rho_w \,, \qquad (3)$$

where Q is the discharge from the spring, ρ_w is the density of water, Δt is the time since the start of baseflow recession, and ΔV is the change in volume in the simplified aquifer. Assuming that the ground water flow can be described using Darcy's law, and as the change in time approaches zero, the equation becomes

$$\frac{dV}{dt} = -\frac{KA}{L}(H - H_0) \qquad (4)$$

where K is the hydraulic conductivity of the media in the aquifer, A is the cross-sectional area of the aquifer, L is the distance to the sub-basin divide, H is the water level at time t, and H_o is the water level as time approaches infinity. By substituting storativity (S), expressed as into equation 4 and simplifying, the equation becomes

$$\frac{dH}{dt} = -\frac{K}{SL}(H - H_0) \qquad (6).$$

where at t=0, the head (H) is equal to the initial head (H_i) or water level in the aquifer. By integrating Equation 6 and setting the datum at H_0, we get

$$H = H_i e^{-\frac{K}{SL}t} \qquad (7),$$

which describes the head in an aquifer as exponentially decaying over time. Assuming that head in an aquifer (H) is proportional to discharge from a spring (Q), and substituting Darcy's law into Equation 7 for H, the equation becomes

$$Q = Q_0 e^{-\frac{K}{SL}t} \qquad (8).$$

Equation 8 is identical to Equation 1 when

$$\alpha = \frac{K}{SL} \qquad (9).$$

The recession constant as described by Equation 9 is consistent with the formula used by Schoeller (1962) and Fairley (2001) when describing spring discharge from a simplified aquifer. Specific yield (S_y) can be substituted for storativity (S) in Equation 9 for unconfined systems (Atkinson, 1977). The discharge (Q) from the spring, which is described by Equations 1 and 8, assumes no evapotranspiration effects; therefore, the amount of water, which is transpired or evaporated from the system, is included in the value of discharge (Q) in the exponential decay equation.

The parameters used for the recession analyses for both the springs and the streams were either estimated or obtained from hydrogeologic texts and soil surveys. The distance from the measurement point to the sub-basin divide (L) was estimated from a topographic map (DRGs) using the Xtool extension in Arcview. The distances from the gaging stations to the nearest topographical sub-basin divide were measured and the range was used for deriving the values of hydraulic conductivity using Equation 9.

Spring Discharge Measurements

Small tributaries, which were believed to originate from springs, were identified and their point discharges were measured at convenient locations. Also, the actual sources of the springs were later located, either on foot or with the aid of aerial photography, to relate the locations to the geology and soils based on available maps. Initially, six spring measurement sites were selected along the South Fork of the Palouse River and its tributary of Fourmile Creek, and nineteen sites were selected along Union

Flat Creek. Only six measurement sites were selected along the South Fork of the Palouse River because fewer springs could be found contributing to the flow of the South Fork of the Palouse River as compared to Union Flat Creek. By the end of the summer some springs were no longer flowing or were inaccessible. Thus the number of measurement sites was reduced to five along the South Fork of the Palouse River, which includes two along Fourmile Creek, and twelve along Union Flat Creek. Data for these seventeen spring fed sites are the basis of the analysis of this research. Later exploratory trips uncovered more springs discharging into both the South Fork of the Palouse River and Union Flat Creek, but these springs were not included in the analysis process. The measurement sites and spring source locations along Union Flat Creek and the South Fork of the Palouse River are shown in Figures 4 and 5, respectively. Spring discharge measurements were taken weekly during the summer of 2000 at the seventeen spring-fed sites. Measurement sites were chosen near the road for easy access; discharge was measured using a small 60° V-notch trapezoidal flume, or with a bucket and stop-watch when a culvert pipe was available. Discharge measurements were taken every week from the end of May or mid-June through August.

Many exploratory trips were made to completely evaluate the hydrogeologic settings of the seventeen springs. It was also necessary to document the crop type and the existence of basalt outcrops surrounding the sources of the springs.

Stream Discharge Measurements and Precipitation

The USGS currently does not maintain gaging stations for the streams in the study area; therefore, historical discharge measurements were used for the stream

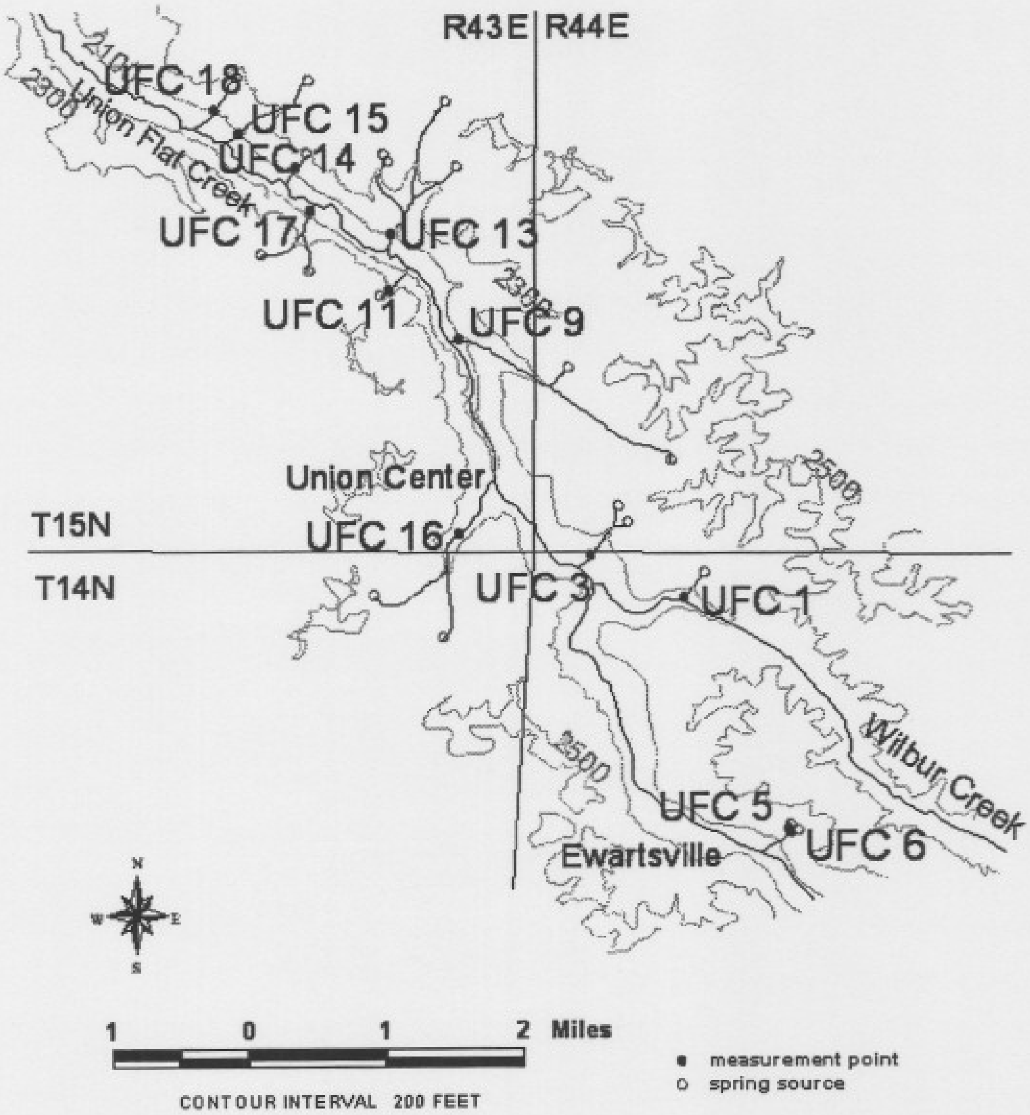


Figure 4. Union Flat Creek study area with the locations of the measurement points and sources of the springs.

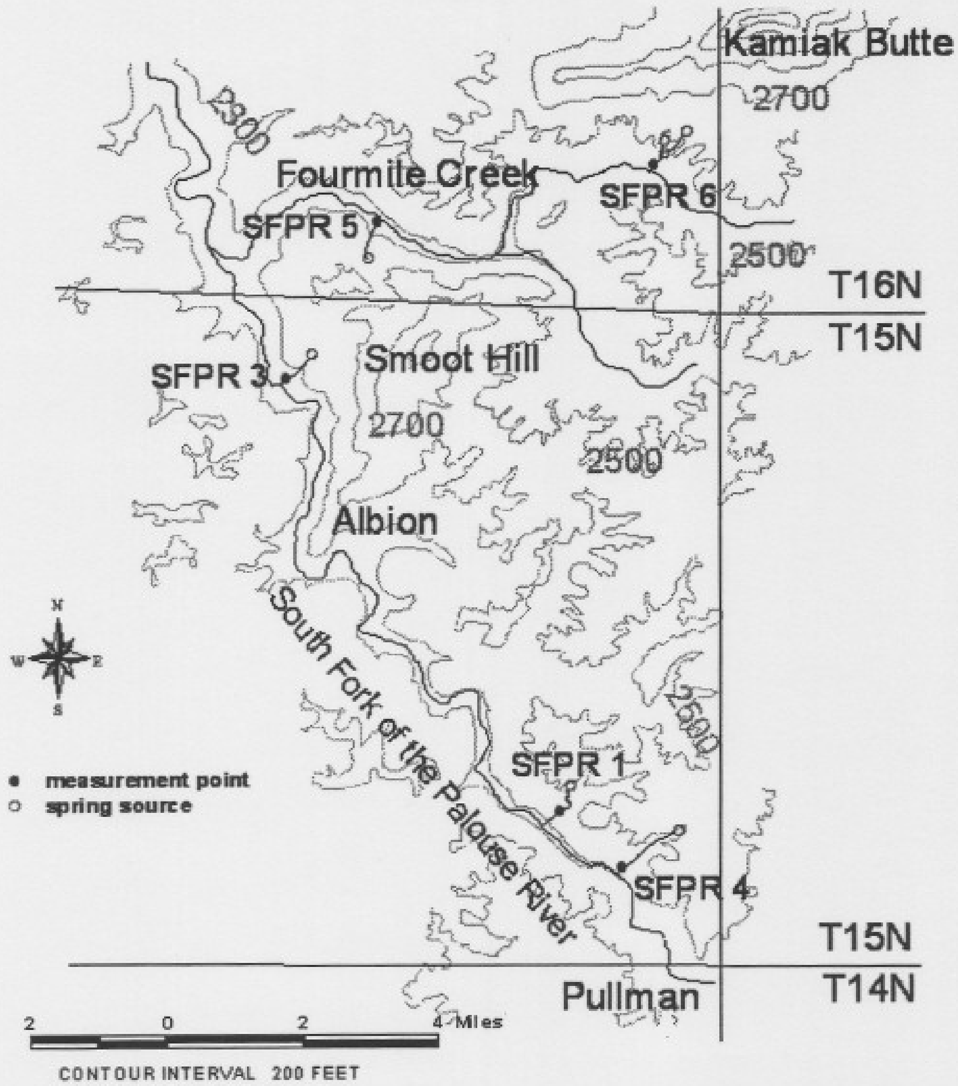


Figure 5. The South Fork of the Palouse River study area with the locations of the measurement points and sources of the springs.

recession analyses for Fourmile Creek, the South Fork of the Palouse River, and Union Flat Creek. These discharge measurements were obtained from the USGS web site. Selection of the time periods for analysis was based on available stream discharge data, precipitation data, and the existence of a significant period of time without precipitation. Discharge measurements from July through August were used because they were taken after the rainy season and after snowmelt could be a major contributor to streamflow. Only the discharge measurements taken at least five days after any precipitation event were used for the actual recession analyses. Historical and current precipitation data were obtained from the National Climate Data Center (NCDC) web site.

Discharge measurements also were taken for three major streams, which are the only known direct discharges from the Moscow-Pullman basin to the Snake River. The South Fork of the Palouse River and Union Flat Creek also discharge into the Snake River, but these confluences are not within the region considered the Moscow-Pullman basin. The streams, which discharge to the Snake River within this region, are Almota Creek, Little Almota Creek, and Wawawai Creek. The discharge measurements for these streams were taken on January 10, 2001 when no significant precipitation was recorded for at least one week prior to the measurement and the flow was considered to consist of baseflow only. The velocity-area method was used to calculate the average discharge for each of the streams. The velocity of the stream at a depth of 0.6 of the total stream depth was obtained with a current meter. Velocity and depth measurements were taken 0.9 feet apart in Almota Creek and 0.6 feet apart in Little Almota Creek and Wawawai Creek. Incremental discharge for each measurement was then calculated as

$$q_i = v_i\left(\frac{b_{i+1} - b_{i-1}}{2}\right)d_i \tag{15}$$

where q_i is the incremental discharge, v_i is the velocity measured at 0.6 of the stream depth which is assumed to be the mean velocity in cross-section centered around vertical i , b_{i+1} is the distance from the bank to the next vertical, b_{i-1} is the distance from the bank for the preceding vertical or zero for the bank itself, and d_i is the depth from the water surface to the stream bed at vertical i (Figure 6). The total discharge for the stream was obtained by summing the incremental discharges, q_i. Transects of the three streams are shown in Figure 7.

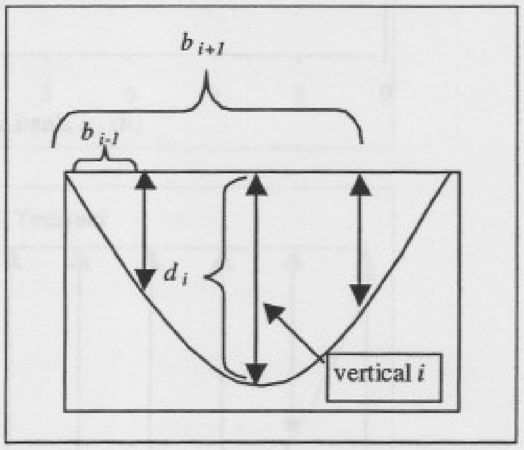


Figure 6. Hypothetical stream cross-section showing the parameters used in the velocity-area method for calculating discharge of a stream using depth at vertical i (d_i) and the distance from the bank of the next and last vertical (b_{i+1} and b_{i-1})

Water samples from Union Flat Creek and streams discharging into the Snake River within the bounds of the Moscow-Pullman basin were also sampled for purposes of Oxygen-18 analysis. These samples were collected with Alex Kirk (Washington State University graduate student) on October 14, 2002 and were analyzed to compare ratios of ^{18}O to ^{16}O to evaluate whether the streams in the western portion of the basin represent significant discharge areas for the deeper flow systems in the Grande Ronde basalts. Multiple samples were collected along Union Flat Creek. Two samples were taken at springs along Union Flat Creek (UFC 3 and UFC 11). Samples were also taken from

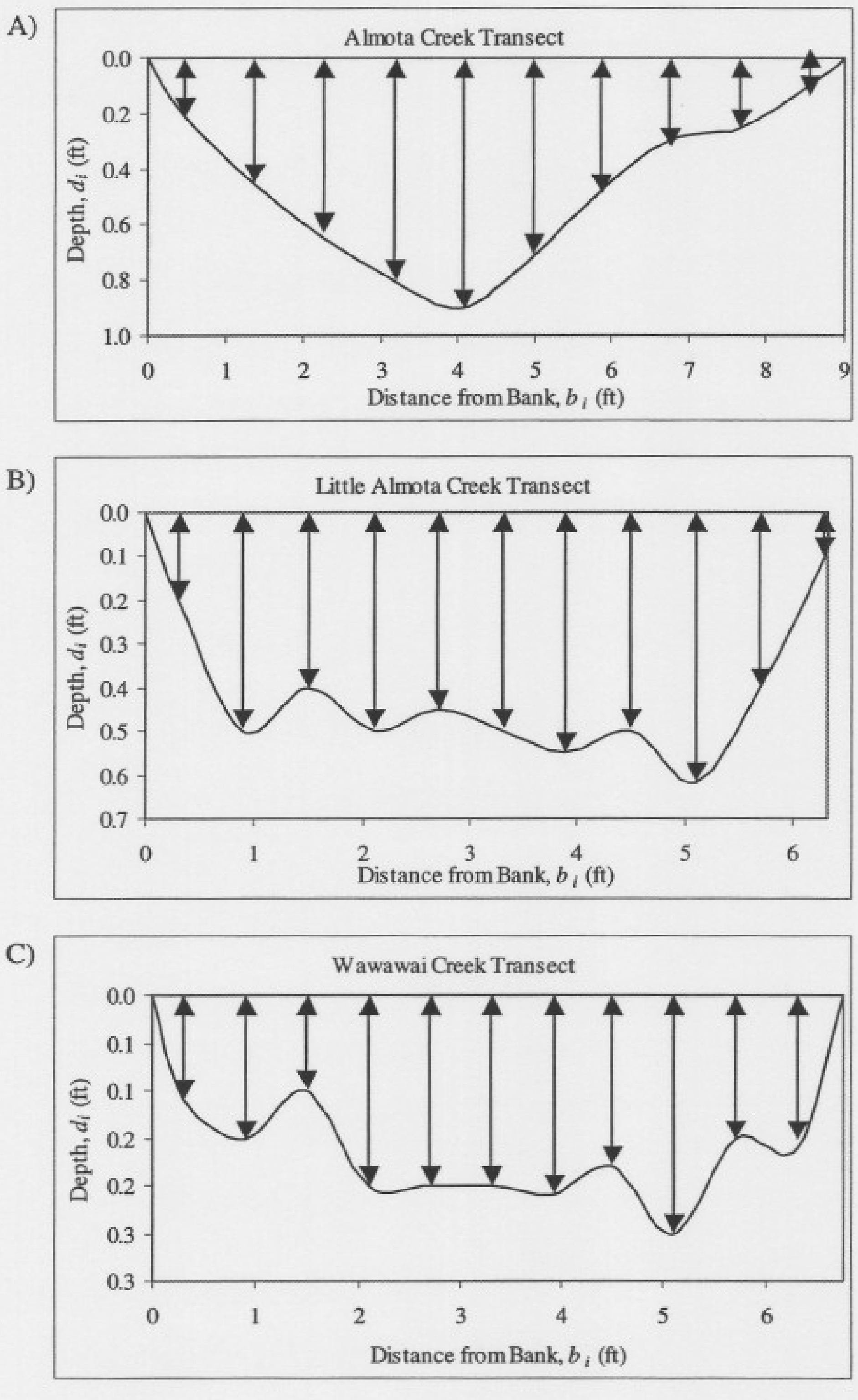


Figure 7. Delineation of a cross-section for measurement of discharge by the velocity-area method for A) Almota Creek, B) Little Almota Creek, and C) Wawawai Creek.

Goose Creek, Almota Creek, Little Almota Creek, Wawawai Creek, Steptoe Canyon, and two small tributaries of the Snake River (Figure 8).

Calculation of Winter Wheat Evapotranspiration

During the months when baseflow makes up the entire flow of the stream, evapotranspiration from plants must be considered in a recession analysis. Spring discharge measurements were taken during the spring and summer months when evapotranspiration is the highest, therefore, it was necessary to calculate evapotranspiration for the crops growing near the source of the springs in the study area. The effects of evapotranspiration potentially have a considerable influence on the shape of recession curves. Therefore, the effects must be quantified to allow detailed analysis of the recession characteristics of the springs.

In the absence of additional weather data, crop evapotranspiration was estimated using the equation recommended by the Food and Agricultural Organization of the United Nations (Allen et al., 1998). First, the reference evapotranspiration was estimated using the method of Hargreaves (1985),

$$ET_0 = 0.0023(T_{mean} + 17.8)(T_{\max} - T_{\min})^{0.5} R_a \quad (10)$$

ET_0 is the reference evapotranspiration in mm/day, T_{mean} is the mean daily temperature in degrees Celsius, T_{max} is maximum daily temperature in degrees Celsius, T_{min} is the minimum daily temperature in degrees Celsius, R_a is the extraterrestrial radiation [MJ/m^{2}d^2] and is calculated based on Julian day and latitude, and 0.0023 and 17.8 are

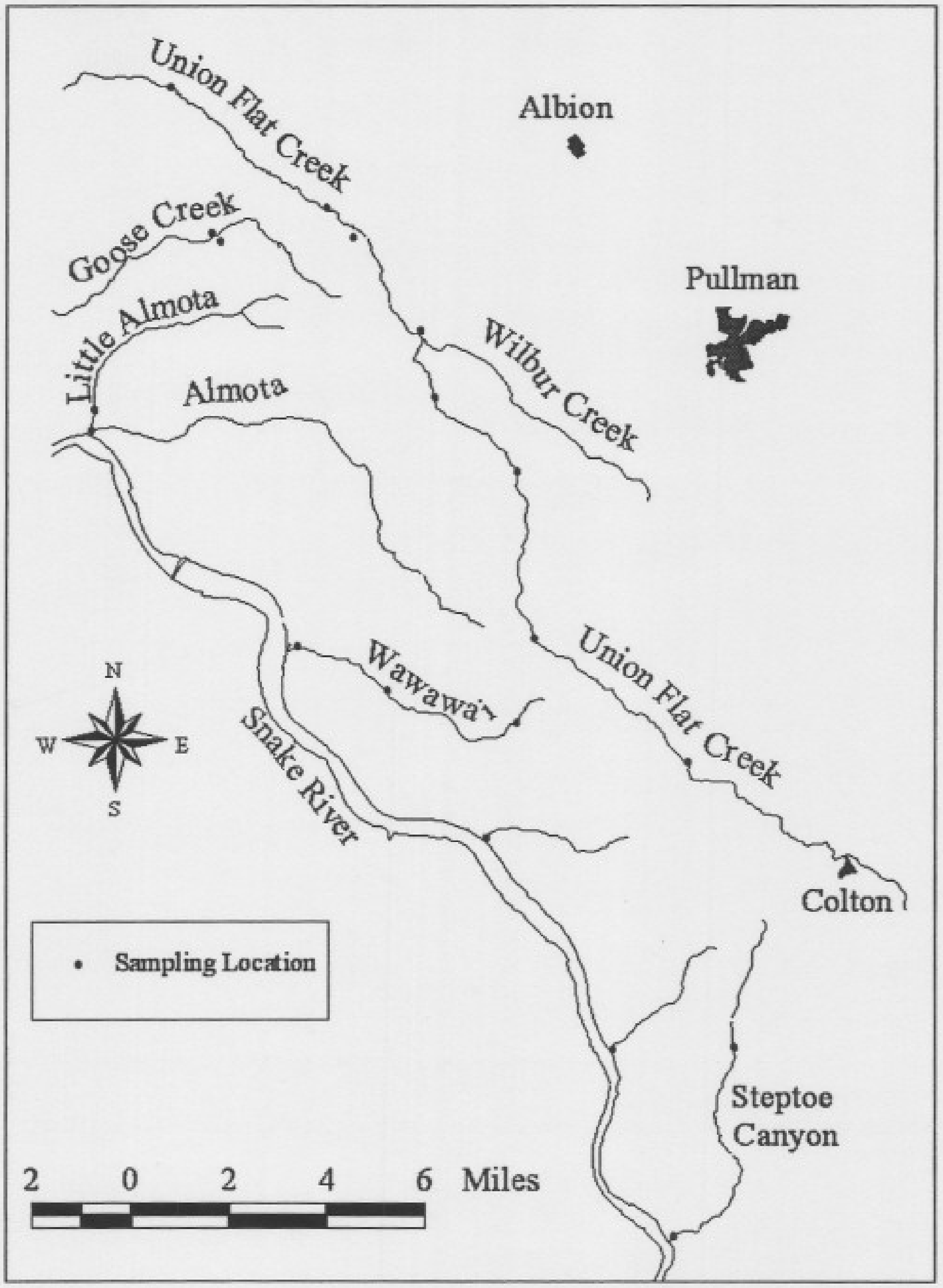


Figure 8. Map of sampling locations for geochemical analysis.

empirical coefficients resulting from calibrations based on eight years of grassland, lysimeter, evapotranspiration data from Davis, California (Hargreaves, 1985). Reference evapotranspiration refers to the evapotranspiration rate from a surface of a hypothetical reference crop of grass, not short of water. A hypothetical grass reference is a reference used for comparison purposes independent of crop characteristics or soil factors.

Most of the crops in the study area are winter wheat; therefore, the crop coefficients were chosen based on winter wheat crop development stages. To get the crop evapotranspiration (ET_c), the crop coefficient for winter wheat (K_c) was multiplied by the reference evapotranspiration from Equation 10,

$$ET_c = ET_0 \times K_c \tag{11}$$

The crop evapotranspiration represents the amount of water taken up by the roots of the winter wheat and then transpired from the plant's leaves, in addition to the amount of water evaporated from the soil surface.

According to Allen et al. (1998), winter wheat in Idaho and eastern Washington is typically planted some time in October. October 1 was used for the purposes of this analysis. There are four growth stages: initial, development, middle, and late. The durations of these growth stages are given in Appendix 2 totaling 335 days, putting the harvest some time during the month of August. Evapotranspiration does not start to become significant until some time during the development stage, from mid-March through May.

Winter wheat evapotranspiration estimates were multiplied by the area of the evapotranspiration-effected zone to obtain units of discharge. This zone should encompass the area extending from the spring to an elevation uphill equal to the projected elevation of the winter wheat roots, assumed to be approximately 5 feet above the source of the spring. Since a topographic map with a contour interval of 5 feet was unavailable, the highest resolution topographic map in the study area, with a contour interval of 20 feet, was used instead. To estimate the area of the perched water table affected by evapotranspiration, polygons were delineated from the source of the spring upslope to the next higher elevation contour on a digital raster graphic (DRG) using the Xtool extension in Arcview (Figure 9). This total discharge was then added to the collected spring discharge and then compared to Equation 1, which describes baseflow recession as exponentially decaying over time.

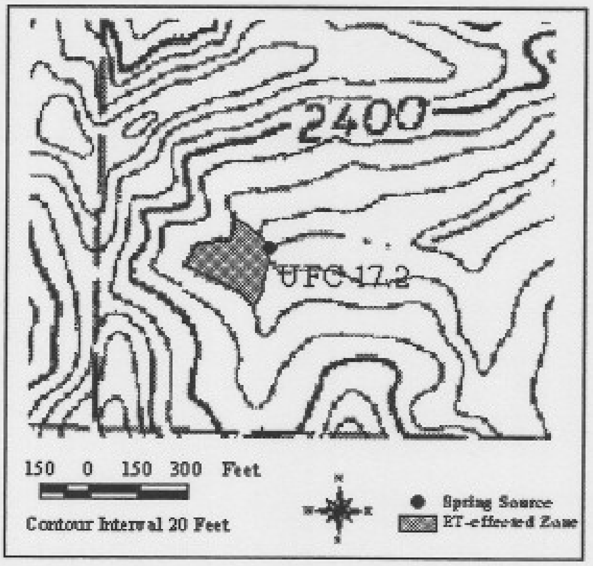


Figure 9. Evapotranspiration-effected area delineated for one of the sources to site UFC 17.

Assessment of the Palouse Formation

Knowledge of whether the Palouse Formation is the source of the springs could significantly affect the understanding of the flow systems in the Moscow-Pullman basin. The existence of separate flow systems in the Palouse Formation implies the Palouse

Formation is intercepting some of the potential recharge to the productive aquifers within the basalts.

If the Palouse Formation is the source of the springs, it would need to be extensive and thick enough to provide adequate storage capacity for perennial, perched water tables. In addition, the springs would have to be discharging from the top of a hydraulically restrictive layer within the loess and/or at loess-basalt contacts. To assess the Palouse Formation as a possible source of the springs along Union Flat Creek and the South Fork of the Palouse River, the thickness of the loess, the soil type at and above the spring sources, and the locations of the springs relative to the basalts were evaluated. Thickness of the Palouse Formation was estimated from all available well logs in the Moscow-Pullman area and contour maps of thickness were developed. Soil survey maps were used to estimate the hydrologic characteristics of the soils at and above the sources of the springs. Maps showing the tops of the exposed basalts and the sources of the springs also were produced. The locations of the tops of the basalts were estimated based on the 1:100,000 geologic map compiled by Gulick (1994), and by personal, field observations. These observed outcrops were then plotted on a map, and correlated based on elevations and on the conclusions of Ringe (1970) that the tops of the basalts below the Palouse Formation are relatively flat and dipping gently to the northwest.

Installation and Location of Piezometers

To test the hypothesis that the springs are discharging from the Palouse Formation, piezometers A through H were installed above what was thought to be the source of the spring contributing to site UFC 11 on Union Flat Creek (Figures 10 and 11).

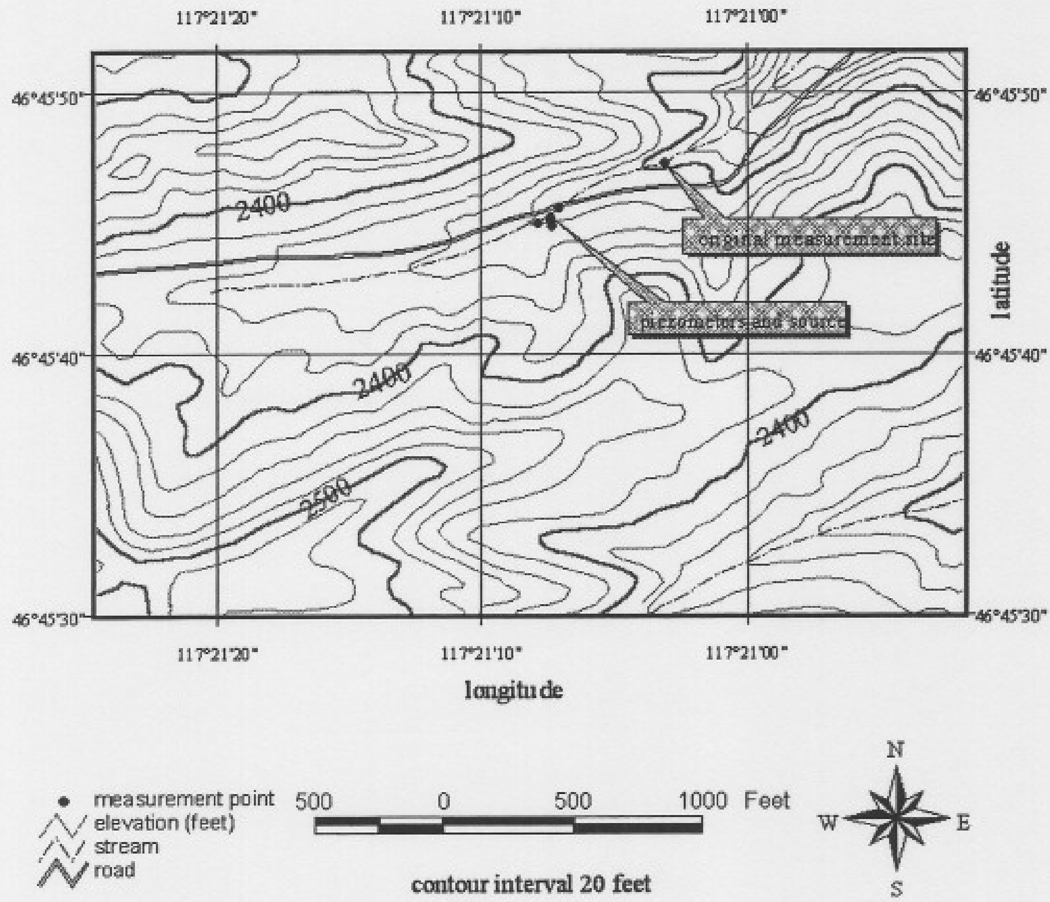


Figure 10. Map showing the local topography near site UFC 11 on Union Flat Creek and the piezometers installed above the apparent source.

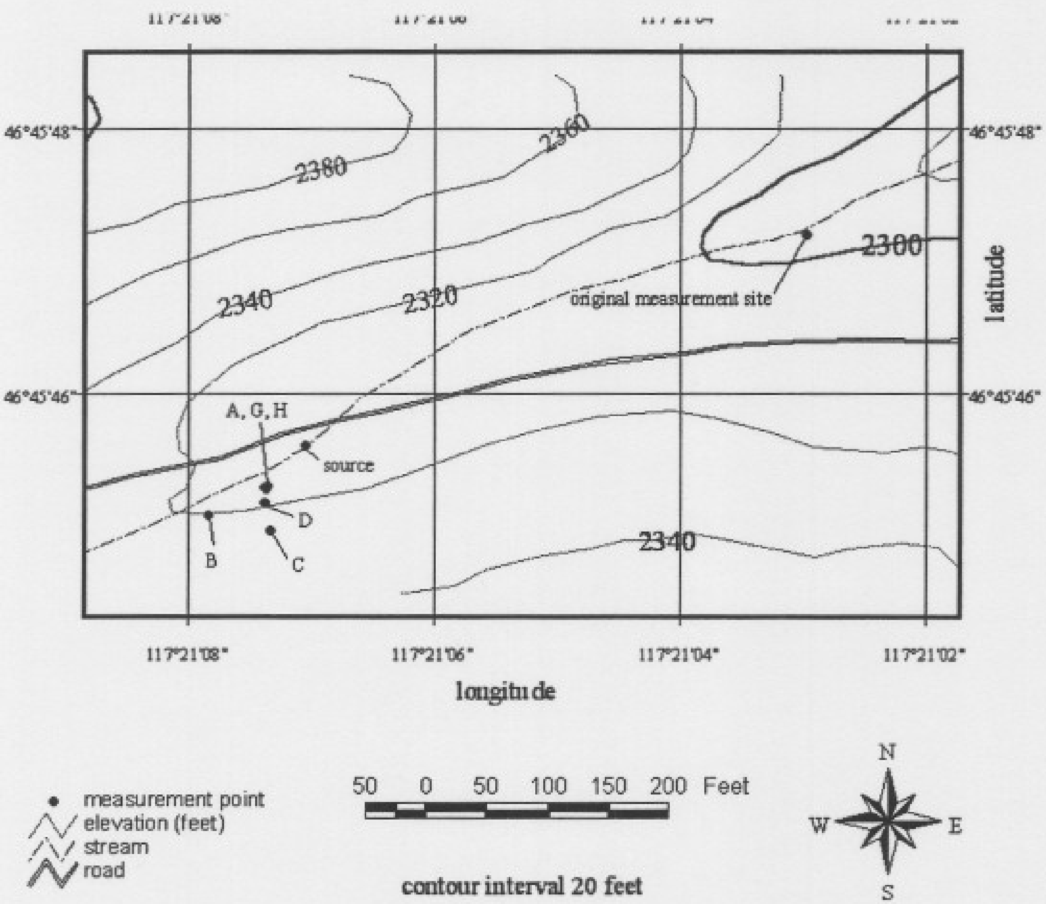


Figure 11. Site locations for the piezometers installed above the source of the spring at Union Flat Creek, site UFC 11.

The piezometers were installed with the expectation that they would intersect the perched water table from which the spring was discharging. It is expected that if the Palouse Formation is the source of the springs, then the recession constant for the springs should be the same as the recession constant derived from the change in head in the piezometers. For this comparison to be successful, though, the piezometers must be installed in the perched water table from which the spring is derived.

Eight holes were originally augered (A thorough H), most of which did not readily fill back with water, consequently only six of those holes were chosen for piezometer installation. Three of the piezometers were placed within one foot of each other at different elevations to study the vertical ground water flow characteristics. A two-inch diameter hole was augered for each piezometer and a 3/4-inch diameter PVC pipe, with slots in the bottom six inches, was installed to the bottom of each augered hole. The bottom of the borehole annulus was filled with approximately two feet of sand followed by 0.5 feet of hydrated bentonite chips. The rest of the hole was filled with the loess, auger cuttings. Logs for all of the piezometers are shown in Appendix 9.

The spring, which feeds site UFC 11 along Union Flat Creek, was chosen because it is one of the few springs that does not originate from a tile drain. A Leica™ GPS unit was used to determine the latitude, longitude, and elevation of all of the piezometers, the apparent source of the spring, and the original measurement site for UFC 11. Water level measurements for the piezometers, and discharge measurements for the apparent source and the original measurement site were taken on a weekly basis from June 13 to August 14, 2001. A less rigorous recession analysis based on Equation 7 was performed on the water levels measured in Piezometers A, B, C, D, and H.

CHAPTER 3

RESULTS AND DISCUSSION

Recession Analysis of the Springs

The discharge measurements for the springs discharging into Union Flat Creek and the South Fork of the Palouse River were plotted against time to produce hydrographs. Fifteen of the spring hydrographs showed decreases in discharge until the end of July, then increases in discharge through August (Figures 12 and 13). The discharges for UFC 11 and UFC 14 remained constant from the end of July through August. No significant precipitation events occurred for the entire summer of 2000, therefore, a recharge event to the water table due to percolation of rainwater can be ruled out as an explanation for the deviation of the hydrographs from the expected exponential decay in spring discharge.

Evapotranspiration from riparian vegetation is typically thought to explain the steepening of recession curves; however, Croft (1948) attributed some of the increase in discharge of a creek in northern Utah in early fall to a decrease in transpiration resulting from the killing of leaves by frost. Most of the local farmers in the study area, however, have removed the riparian vegetation from the stream banks where springs are located. Decreased transpiration by riparian vegetation, therefore, probably is not the cause for the increases in spring discharges at the end of July. Winter wheat, however, is consistently grown in the study area. Rather than growing on the banks of the stream, this crop is grown upgradient of the springs; however, the effects are similar. It was assumed that the areas where the root zones of the winter wheat intersected the capillary fringes and/or

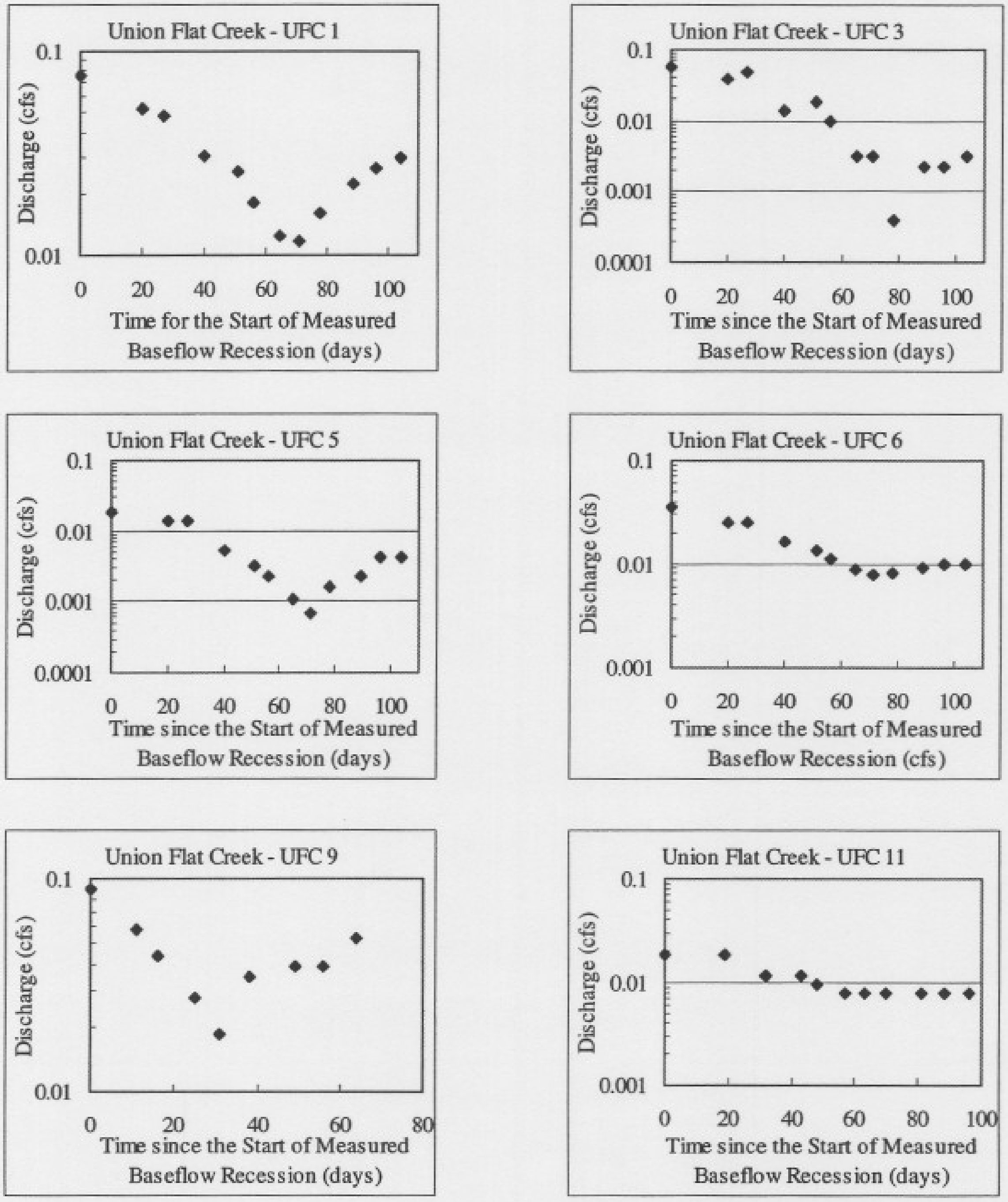


Figure 12. Semilogarithmic plots of spring discharge versus time for the Union Flat Creek sites (continued on the next page).

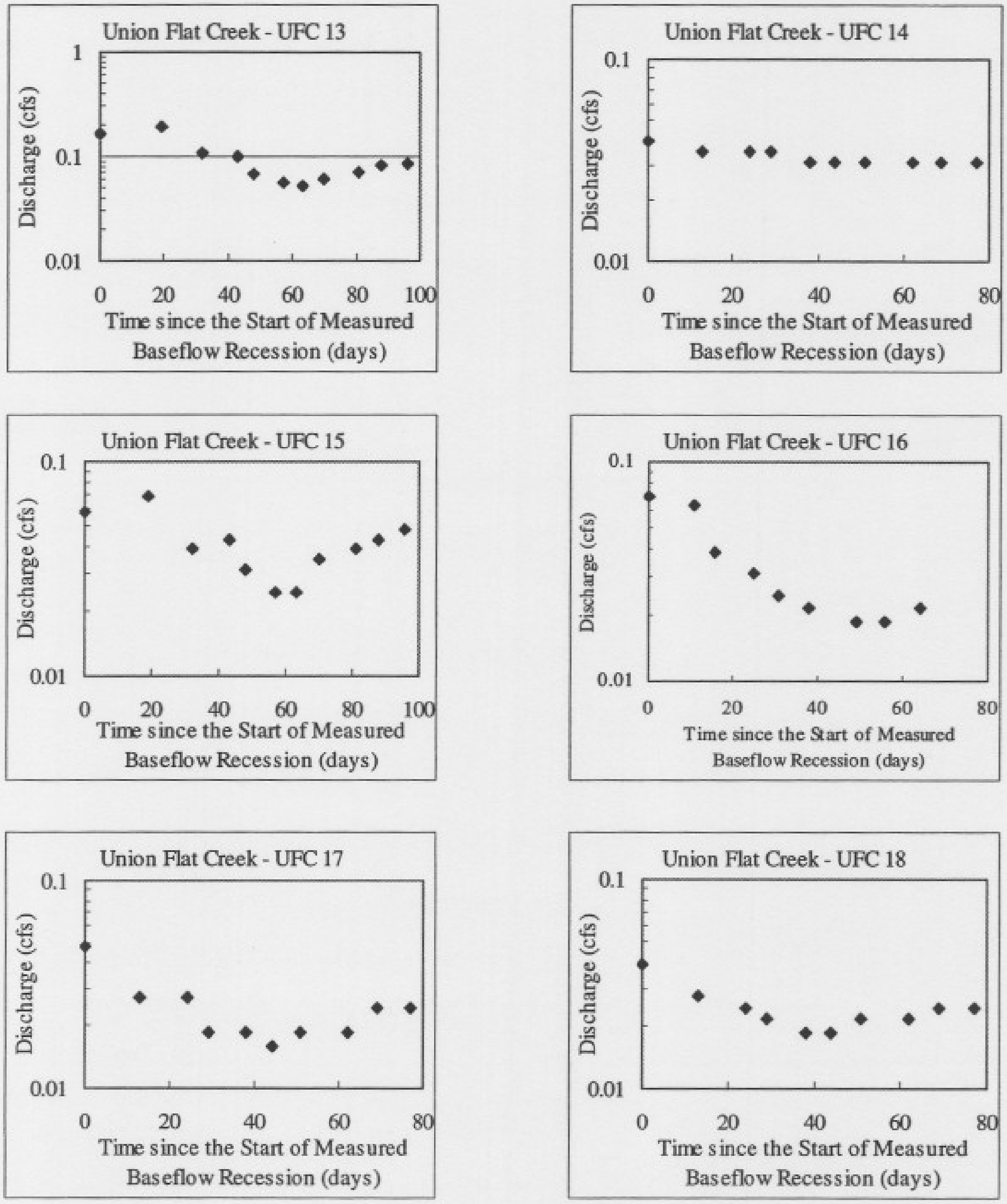


Figure 12. Semilogarithmic plots of spring discharge versus time for the Union Flat Creek sites (continued from previous page).

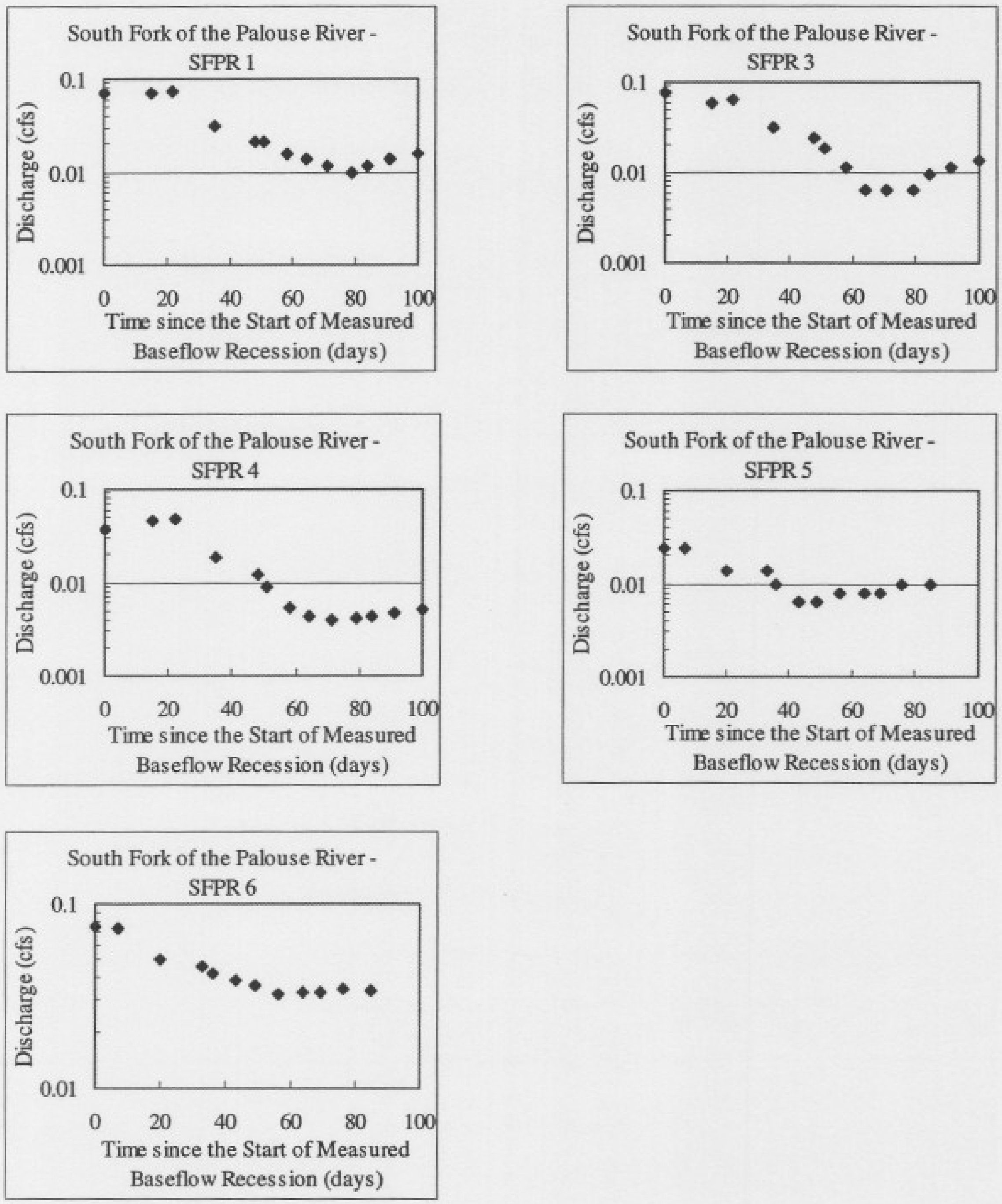


Figure 13. Semilogarithmic plots of spring discharge versus time for the South Fork of the Palouse River sites.

perched water tables in the loess, evapotranspiration affected the amount of discharge emanating from the springs (Figure 14).

Wheat is not generally considered to be a phreatophyte. Various studies, however, have been conducted which have found that some types of wheat use a mechanism known as hydraulic lift (Caldwell et al., 1998; Breazeale, 1930). Hydraulic lift is the process by which water is transported through the plant roots from deeper, moist soil layers or ground water to upper, drier soil layers (Horton, 1998). Sinh (1996) also found that an upward water flux from a shallow water table was produced by wheat crops in India.

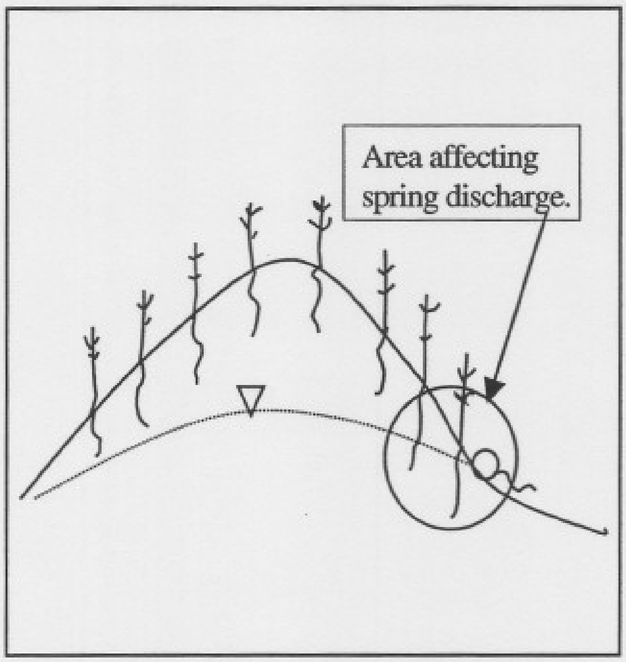


Figure 14. Schematic of the area where winter wheat evapotranspiration is affecting the spring discharge.

As the transpiration of the winter wheat increases, more water is taken from the perched water tables in the loess. This withdrawal of water from the perched water table in the soil also decreases the amount of water available to feed the springs, therefore, decreasing the discharge emanating from the springs. Without this loss of water, the natural exponential decay of discharge over time would result in a steeper slope of the recession curve. Near the end of the growing season, decreasing rates of transpiration affects the hydrograph in the opposite manner. As transpiration decreases, less water is removed from the perched water tables, providing more water to feed the springs. The effect that this decreased loss of water has on the hydrographs is an increased discharge during the times of decreased evapotranspiration. This explanation and the fact that tile lines feed many of the springs support the hypothesis that the springs are discharging from the Palouse Formation and not from the deeper, productive aquifers of the Columbia River Basalts.

Winter wheat transpiration estimates, calculated using the Hargreaves (1985) method, increased from the time the wheat was planted until the end of July, when transpiration began to decrease. Figure 15 shows the evapotranspiration estimates over the entire growing season. The graph demonstrates an inverse relationship to the flow rates for the spring hydrographs (Figures 12 and 13). The volumes per unit time of water estimated to have been lost due to evapotranspiration were added to the measured spring discharges to develop modified hydrographs. Figures 16 and 17 show semi-logarithmic plots of the resultant hydrographs for the measurement sites along Union Flat Creek and the South Fork of the Palouse River. These hydrographs were fit with the accepted model (Equation 1) for spring discharge over time (i.e., a straight line on semi-logarithmic graph paper). The equations for each fit and the coefficients of determination, showing the closeness of the fit, are noted on each hydrograph. All 17 hydrographs show good fits to this model after the addition of the winter wheat evapotranspiration estimates, with the coefficients of determination ranging from 0.66 to 0.98 (Table 1). Based on this analysis, winter wheat evapotranspiration appears to be responsible for the characteristic steepening of the recession curves during the growing season until the end of July.

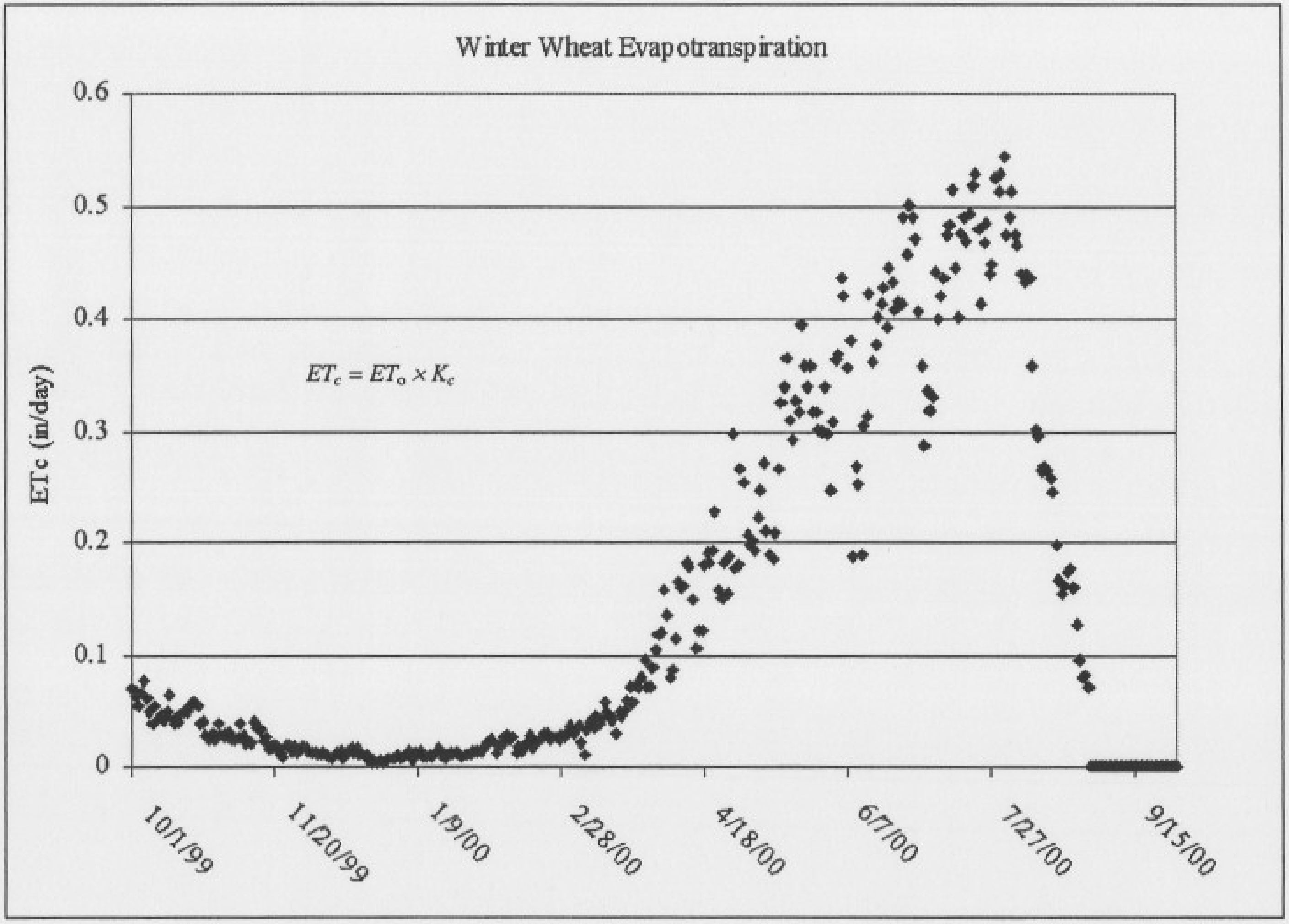


Figure 15. Winter wheat evapotranspiration for the 1999-2000 growing season estimated by the Hargreaves method and FAO's single crop coefficent method. The K_c values and the length of the development stages needed to calculate winter wheat evapotranspiration are shown in Appendix 2.

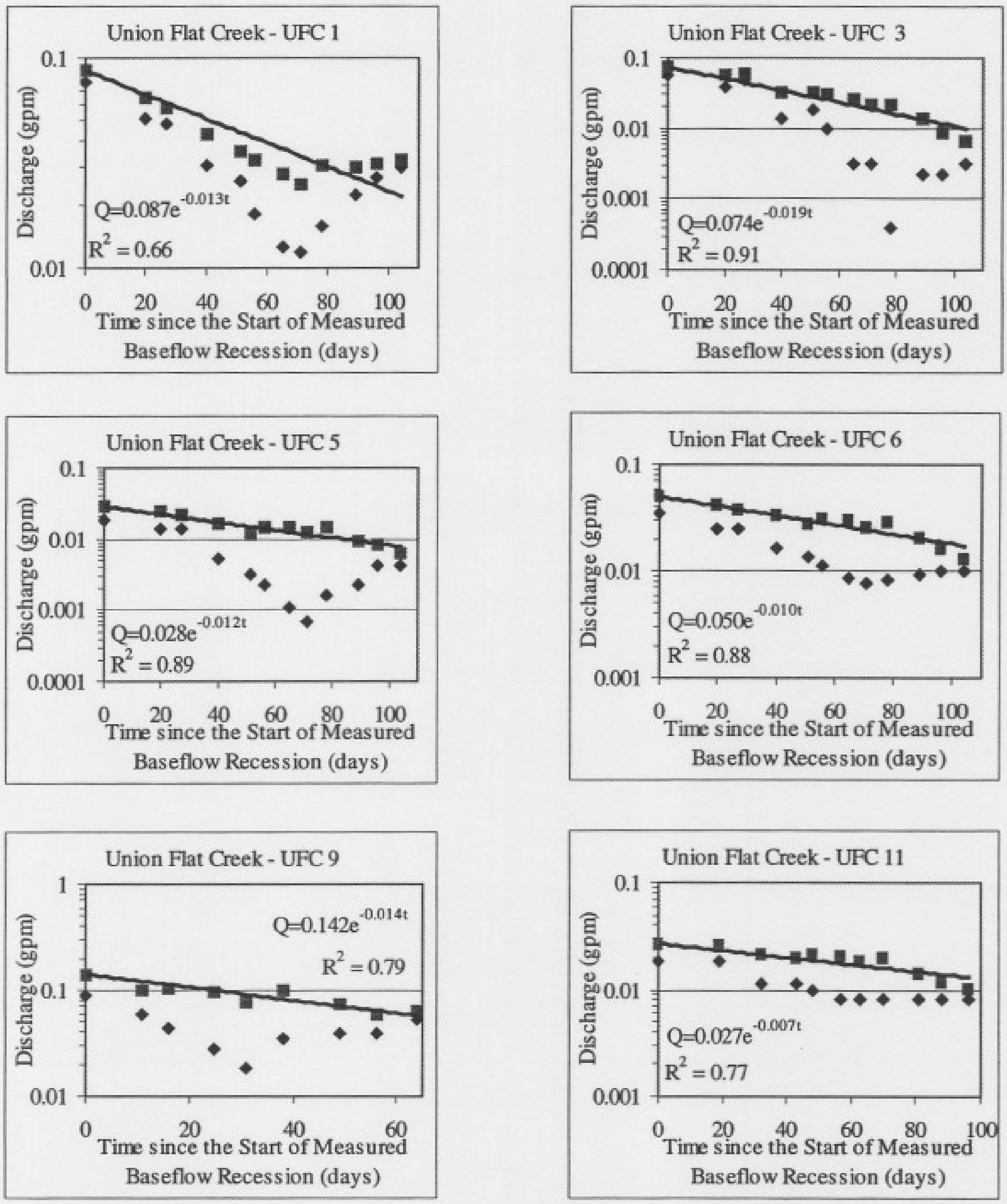


Figure 16. Semi-logarithmic plots of the resultant hydrographs (squares) for measurement sites on Union Flat Creek and, for comparison, the original discharge hydrographs (diamonds).

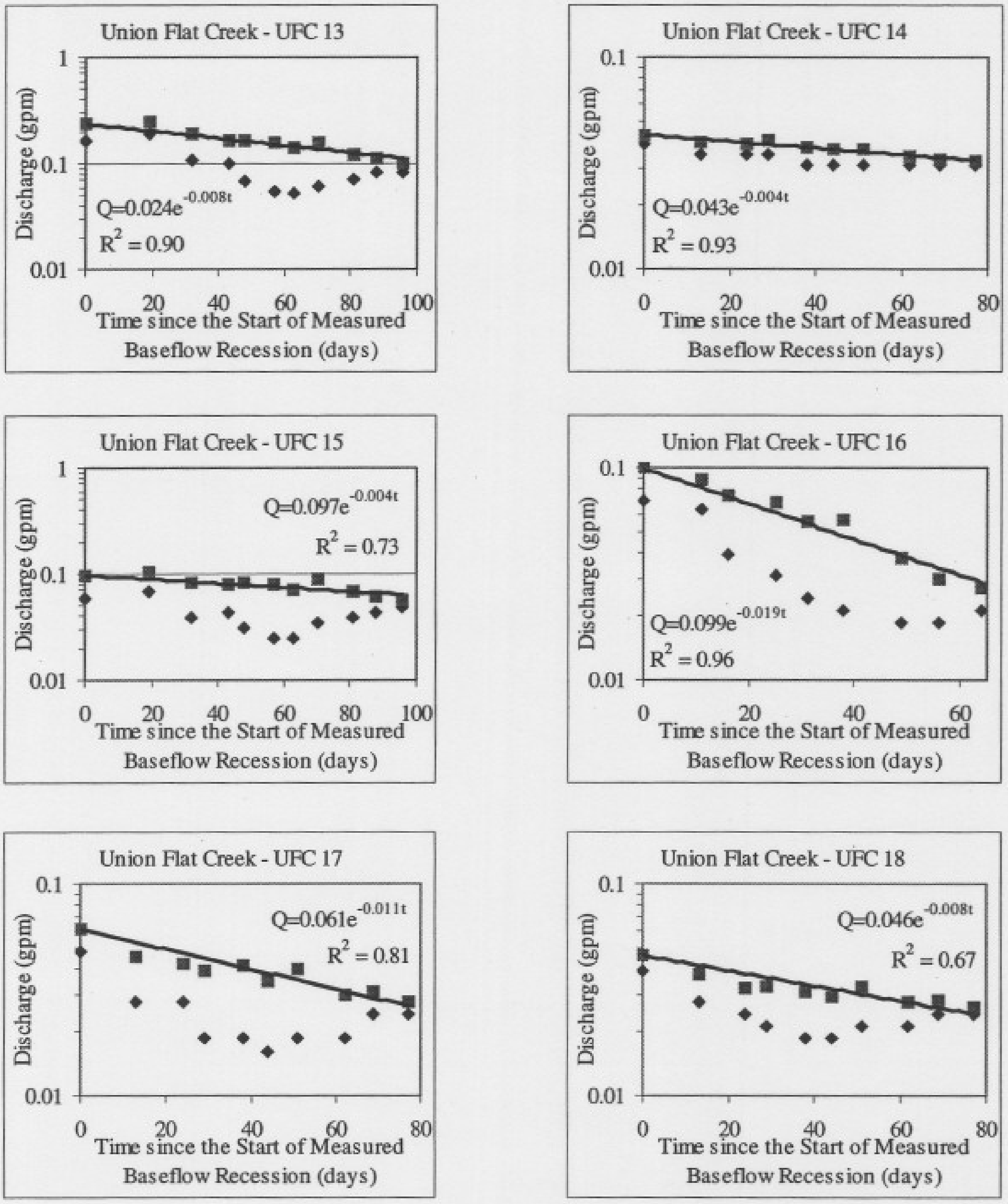


Figure 16. Semi-logarithmic plots of the resultant hydrographs (squares) for measurement sites on Union Flat Creek and, for comparison, the original discharge hydrographs (diamonds) (continued from previous page).

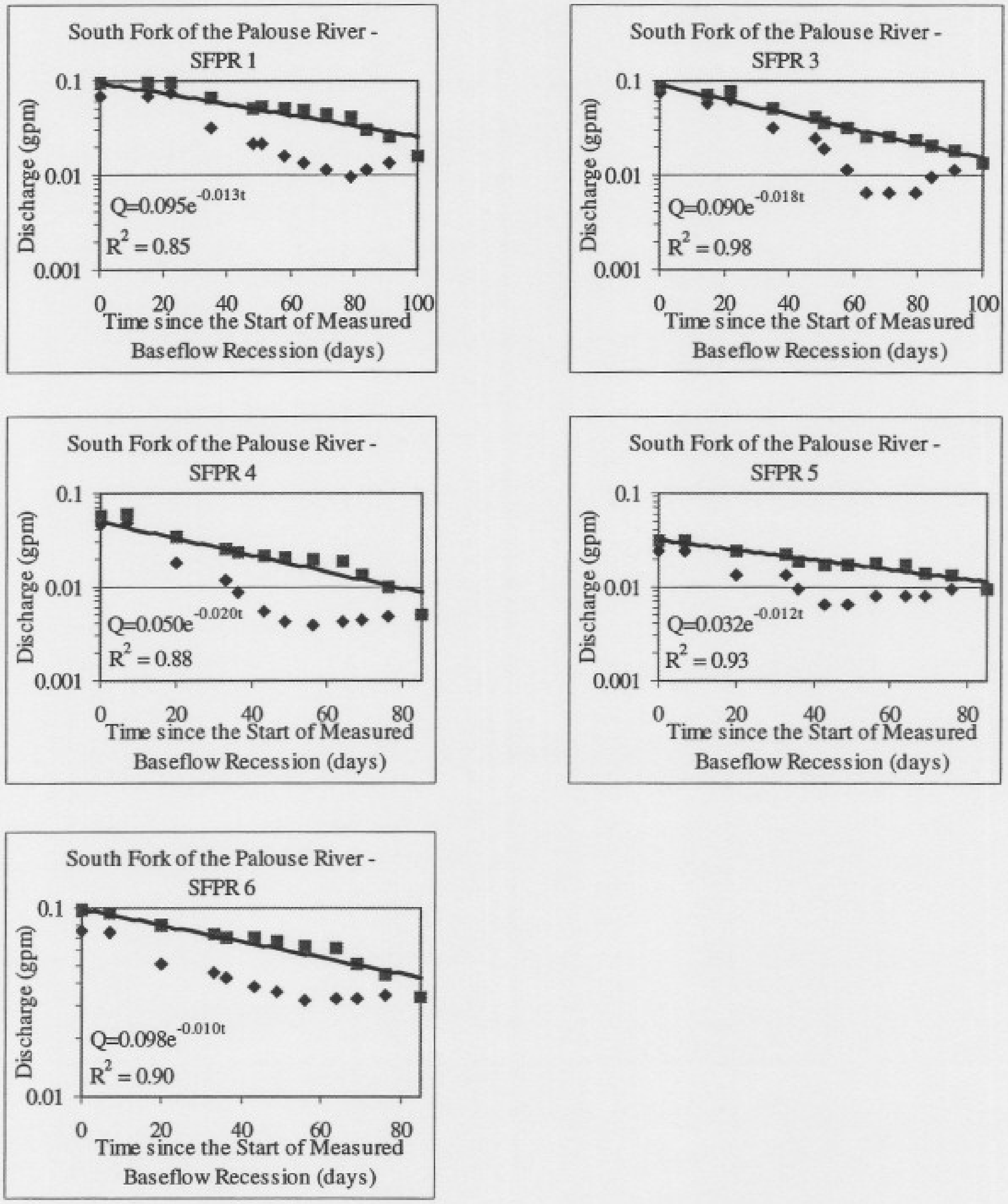


Figure 17. Semi-logarithmic plots of the resultant hydrographs (squares) for measurement sites on the South Fork of the Palouse River and, for comparison, the original spring discharge hydrographs (diamonds).

The close fits of this recession analysis also support the baseflow recession model used to describe the spring flow recessions for this study area.

Hydrogeologic characteristics of the ground water flow systems can also be interpreted from the subsequent recession constants. Table 1 lists the recession constants and areas estimated to be affected by evapotranspiration for the 17 springs in the study area. Various relationships based on solutions to Boussinesq's equation relate the recession constant directly to hydraulic conductivity of the aquifer and indirectly to the specific yield of the aquifer (Moore, 1992; Angelini and Dragoni, 1997; Baedke and Krothe, 2001). The order of magnitude range of 0.004-0.020 for the recession constants implies that these springs may have similar characteristics, but the lengths of the flow systems may vary significantly.

Union Flat Creek				South Fork of the Palouse River			
Site	Recession Constant (day^{-1})	ET affected area (ft^2)	R^2	Site	Recession Constant (day^{-1})	ET affected area (ft^2)	R^2
UFC 1	0.013	30921	0.66	SFPR 1	0.013	73297	0.85
UFC 3	0.019	44307	0.91	SFPR 3	0.018	41416	0.98
UFC 5	0.012	26748	0.89	SFPR 4	0.020	34183	0.88
UFC 6	0.010	73394	0.88	SFPR 5	0.012	22676	0.93
UFC 9	0.014	133940	0.79	SFPR 6	0.010	65697	0.90
UFC 11	0.007	25637	0.77				
UFC 13	0.008	205954	0.90				
UFC 14	0.004	12401	0.93				
UFC 15	0.004	111565	0.73				
UFC 16	0.019	74980	0.96				
UFC 17	0.011	44420	0.81				
UFC 18	0.008	24649	0.67				

Table 1. Table of recession constants and the size of the area affected by winter wheat evapotranspiration of 17 measurement sites for springs along Union Flat Creek and South Fork of the Palouse River. The coefficient of determination (R^2) for the fit of the resultant hydrograph to the exponential decay model described by Equation 1 is also shown.

The mathematical relationship that relates the recession constant to hydraulic coefficients of the aquifer is described by Equation 9. This equation relates the recession constant (α) to the hydraulic conductivity (K) and storativity (S) of the aquifer and the distance to the sub-basin divide (L). For the springs, the specific yield of the loess was used in place of storativity since the material from which the springs are discharging appears to be unconfined loess. Estimates for specific yield, storativity, and the distance to the sub-basin divide, and calculated recession constants were plugged into Equation 9 to calculate values of hydraulic conductivity. The calculated values of hydraulic conductivity were then compared to estimates of hydraulic conductivity from the literature for the loess and for the basalt.

The calculated values fall in the low range of estimated values for hydraulic conductivity found in the literature for both the loess and the basalt. The results based on the hydrogeologic values for the loess produces a much smaller range of values, within an order of magnitude, as compared to the range of calculated hydraulic conductivity for the basalt, with a range of one to two orders of magnitude. In order to account for the varying size ranges for the calculated hydraulic conductivity values, the medians of the calculated values were also compared to the ranges of hydraulic conductivity found in the literature. Only three of the median values, compared to the estimates of hydraulic conductivity of the loess, did not fall within the accepted range (UFC, UFC 17, and SFPR 3). Six median values derived from the properties of the basalt, on the other hand, did not fall within the accepted range for hydraulic conductivity of the basalt (UFC 11, UFC 13, UFC 14, UFC 15, UFC 17, and UFC 18). The median values derived from the loess appear to fit slightly better to the accepted ranges for hydraulic conductivity using Equation 9, however, from this analysis, a definite geologic source for the springs could not be determined.

Measurement Site	Recession Constant from Hydrograph (day^{-1})	Specific Yield for Loess (%) [Boll, 2003]	Distance to Divide (ft)		Hydraulic Conductivity for Loess (in/hr) [Soil Survey]		Calculated Hydraulic Conductivity (in/hr) [Eq. 12]		
			min	max	min	max	min	max	median
UFC 1	0.013	4	1200	3600	0.6	2.0	0.3	0.9	0.8
UFC 3	0.019	4	700	2400	0.2	2.0	0.3	0.9	0.7
UFC 5	0.012	4	1600	2300	0.6	2.0	0.4	0.6	0.7
UFC 6	0.010	4	2000	3200	0.6	2.0	0.4	0.6	0.7
UFC 9	0.014	4	85	2200	0.2	2.0	0.02	0.6	0.3
UFC 11	0.007	4	600	2000	0.2	2.0	0.1	0.3	0.2
UFC 13	0.008	4	500	2300	0.2	2.0	0.1	0.4	0.3
UFC 14	0.004	4	700	3000	0.6	2.0	0.1	0.2	0.2
UFC 15	0.004	4	500	3000	<0.06	2.0	0.04	0.2	0.2
UFC 16	0.019	4	1300	3600	0.6	2.0	0.5	1.4	1.2
UFC 17	0.011	4	400	700	0.6	2.0	0.1	0.2	0.2
UFC 18	0.008	4	1400	1800	0.2	2.0	0.2	0.3	0.4
SFPR 1	0.013	4	1600	2100	0.6	2.0	0.4	0.5	0.7
SFPR 3	0.018	4	4200	5700	0.6	2.0	1.5	2.1	2.5
SFPR 4	0.020	4	1600	4800	<0.06	2.0	0.6	1.9	1.6
SFPR 5	0.012	4	1300	5200	<0.06	2.0	0.3	1.2	0.9
SFPR 6	0.010	4	3700	5000	0.2	2.0	0.7	1.0	1.2

Table 2. Table of hydraulic parameter values of the loess and the resultant values for hydraulic conductivity using Equations 9 for spring measurement sites.

Measurement Site	Recession Constant from Hydrograph (day-1)	Storativity for Basalt (-) [Lum et al., 1990]		Distance to Divide (ft)		Hydraulic Conductivity for Basalt (ft/day) [Vaccaro, 1999]		Calculated Hydraulic Conductivity (ft/day) [Eq. 12]		
		min	max	min	max	min	max	min	max	median
UFC 1	0.013	0.0005	0.006	1200	3600	0.0873	6.42	0.007	0.281	0.148
UFC 3	0.019	0.0005	0.006	700	2400	0.0873	6.42	0.006	0.274	0.143
UFC 5	0.012	0.0005	0.006	1600	2300	0.0873	6.42	0.009	0.166	0.092
UFC 6	0.010	0.0005	0.006	2000	3200	0.0873	6.42	0.009	0.192	0.105
UFC 9	0.014	0.0005	0.006	85	2200	0.0873	6.42	0.001	0.185	0.093
UFC 11	0.007	0.0005	0.006	600	2000	0.0873	6.42	0.002	0.084	0.044
UFC 13	0.008	0.0005	0.006	500	2300	0.0873	6.42	0.002	0.110	0.057
UFC 14	0.004	0.0005	0.006	700	3000	0.0873	6.42	0.001	0.072	0.037
UFC 15	0.004	0.0005	0.006	500	3000	0.0873	6.42	0.001	0.072	0.037
UFC 16	0.019	0.0005	0.006	1300	3600	0.0873	6.42	0.012	0.410	0.217
UFC 17	0.011	0.0005	0.006	400	700	0.0873	6.42	0.002	0.046	0.025
UFC 18	0.008	0.0005	0.006	1400	1800	0.0873	6.42	0.005	0.086	0.048
SFPR 1	0.013	0.0005	0.006	1600	2100	0.0873	6.42	0.010	0.164	0.092
SFPR 3	0.018	0.0005	0.006	4200	5700	0.0873	6.42	0.036	0.616	0.343
SFPR 4	0.020	0.0005	0.006	1600	4800	0.0873	6.42	0.015	0.576	0.303
SFPR 5	0.012	0.0005	0.006	1300	5200	0.0873	6.42	0.007	0.374	0.195
SFPR 6	0.010	0.0005	0.006	3700	5000	0.0873	6.42	0.017	0.300	0.167

Table 3. Table of hydraulic parameter values of the basalt and the resultant values for hydraulic conductivity using Equations 9 for the spring measurement sites.

Recession Analysis of the Streams

The historical discharge measurements for USGS gaging stations on Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek were plotted against time to produce hydrographs. Figures 18, 19, and 20 show the precipitation and discharge over a period of one month to two months during the summer for various years. The stream discharge measurements for these periods of time appear to correlate well with the precipitation events and show little effects of waste water treatment plant contributions. Waste water treatment plant discharge, therefore, was assumed to be constant. Contributions from bank storage and interflow were assumed to be zero and withdrawals from evapotranspiration from riparian vegetation, evaporation from the water surface, and water supply withdrawals were assumed to be insignificant.

Recession analyses were performed for Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek using Equation 1, which describes the discharge as exponentially decaying over time. Figures 21, 22, and 23 show the discharge data for the hydrographs in Figures 18, 19, and 20 and the fits of Equation 1 to these data. Fourmile Creek dried up during July of 1937, 1938, and 1939 making a recession analyses for 1938 and 1939 impossible. A recession analysis was performed for 1937, but it was only based on five days worth of data and the recession constant may be affected by bank storage rather than baseflow. Table 4 lists the resultant recession constants and coefficients of determination. Based on the coefficients of determination, ranging from 0.60 to 0.99, most of these discharge data appear to fit the proposed exponential decay model described by Equation 1. The recession constants determined for the streams are one to two orders of magnitude larger than those determined for the springs.

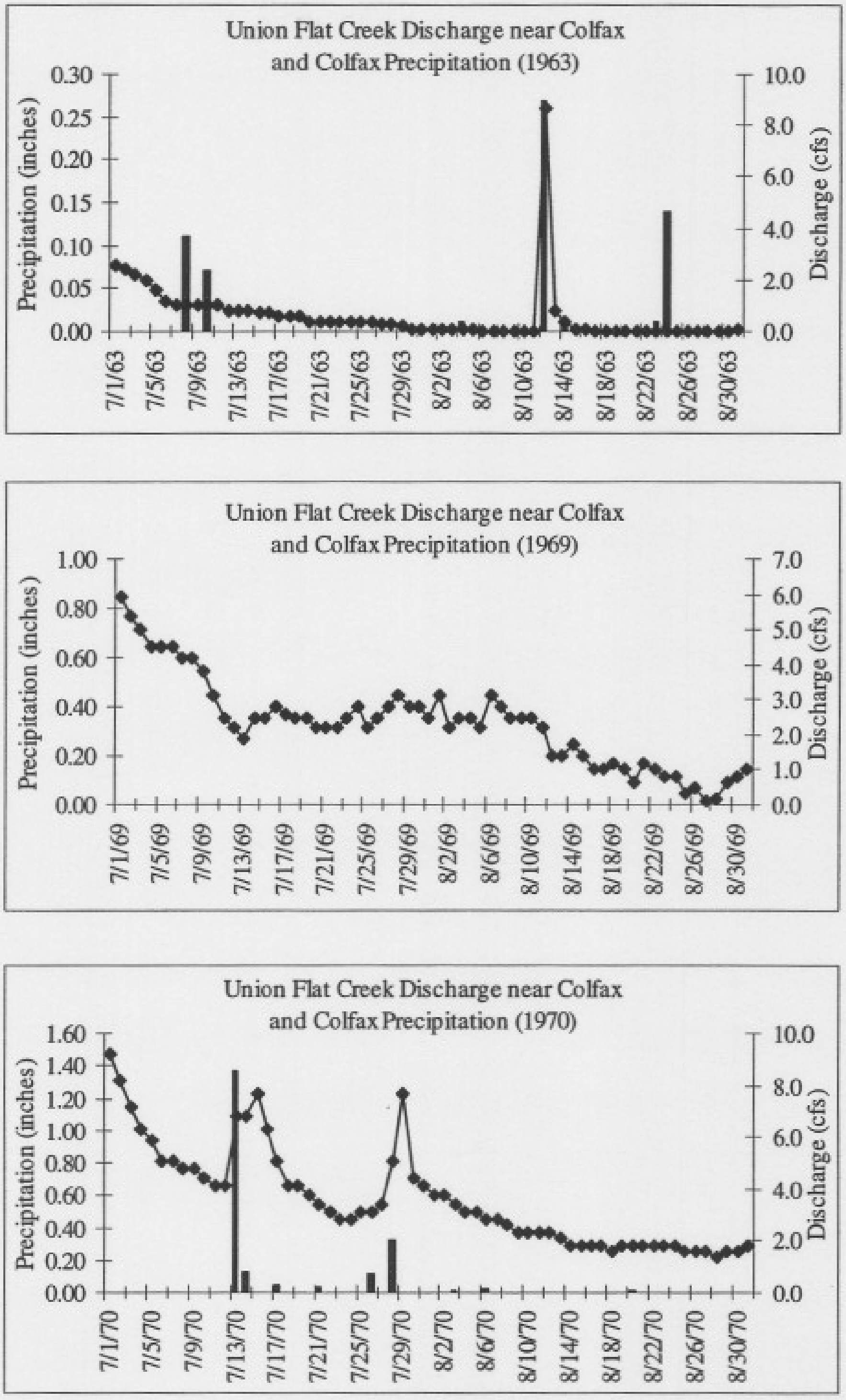
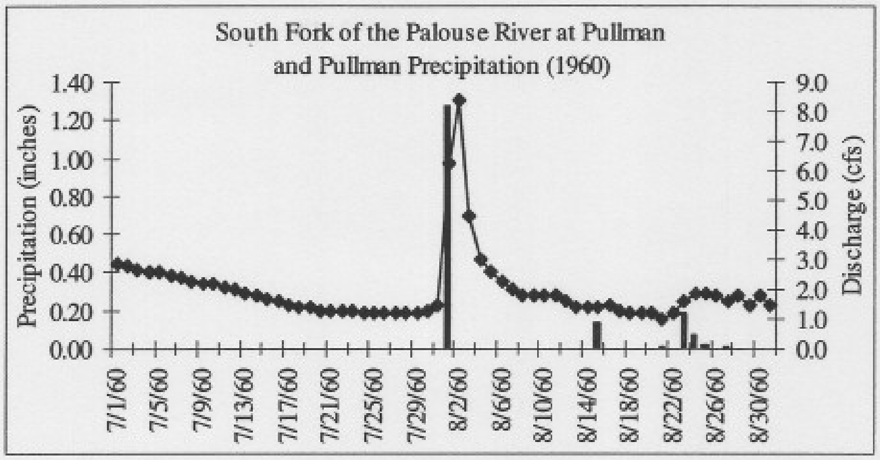
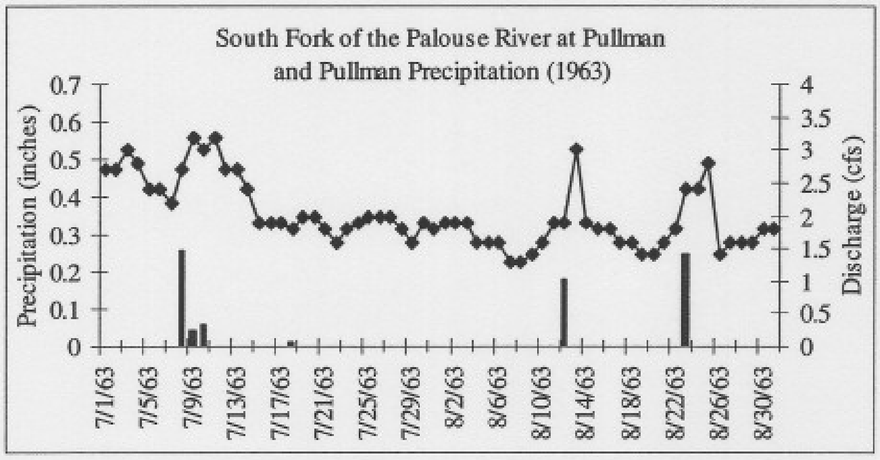


Figure 18. Plots of the hydrographs of Union Flat Creek taken at the USGS gaging station near Colfax, WA (diamonds) and the precipitation in Colfax, WA taken for the same time period (bar chart).





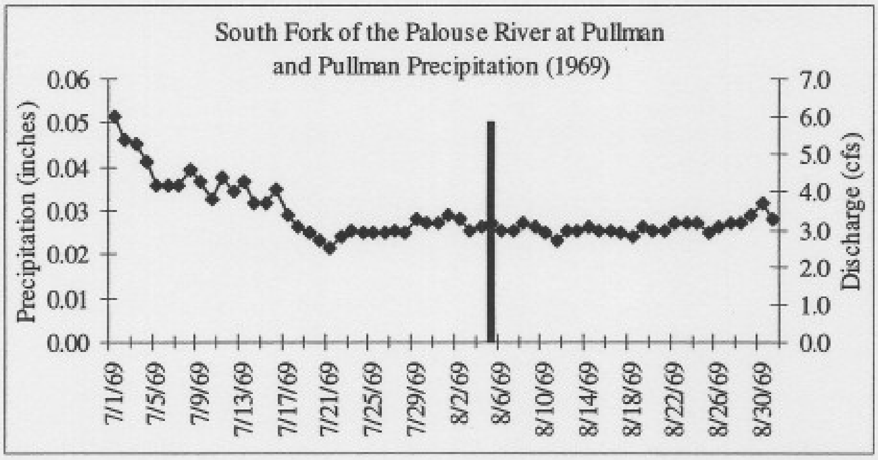
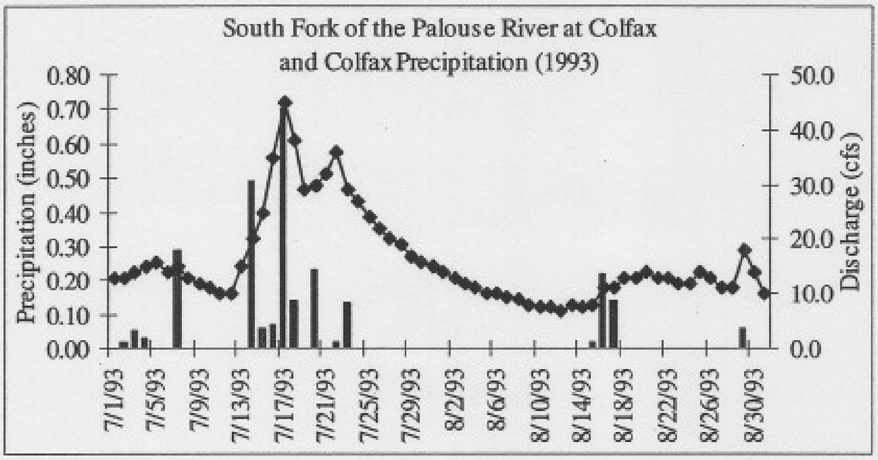
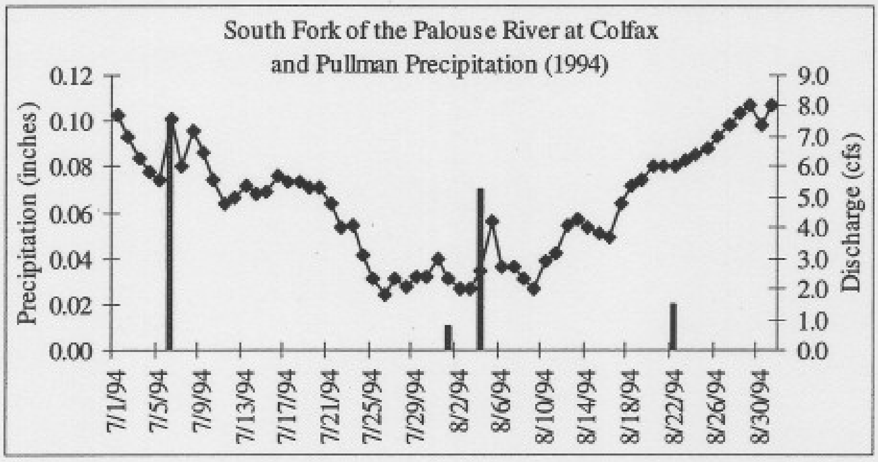


Figure 19. Plots of the hydrographs of the South Fork of the Palouse River taken at the USGS gaging station in Pullman, WA and/or Colfax, WA (diamonds) and the Precipitation in Pullman, WA and/or Colfax, WA taken for the same time period (bar chart).





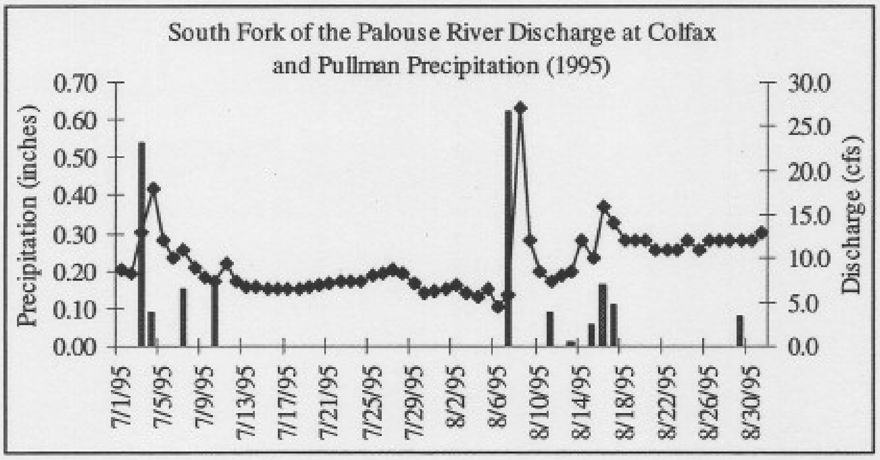


Figure 19. Plots of the hydrographs of the South Fork of the Palouse River taken at the USGS gaging station in Pullman, WA and/or Colfax, WA (diamonds) and the Precipitation in Pullman, WA and/or Colfax, WA taken for the same time period (bar chart) (continued from previous page).

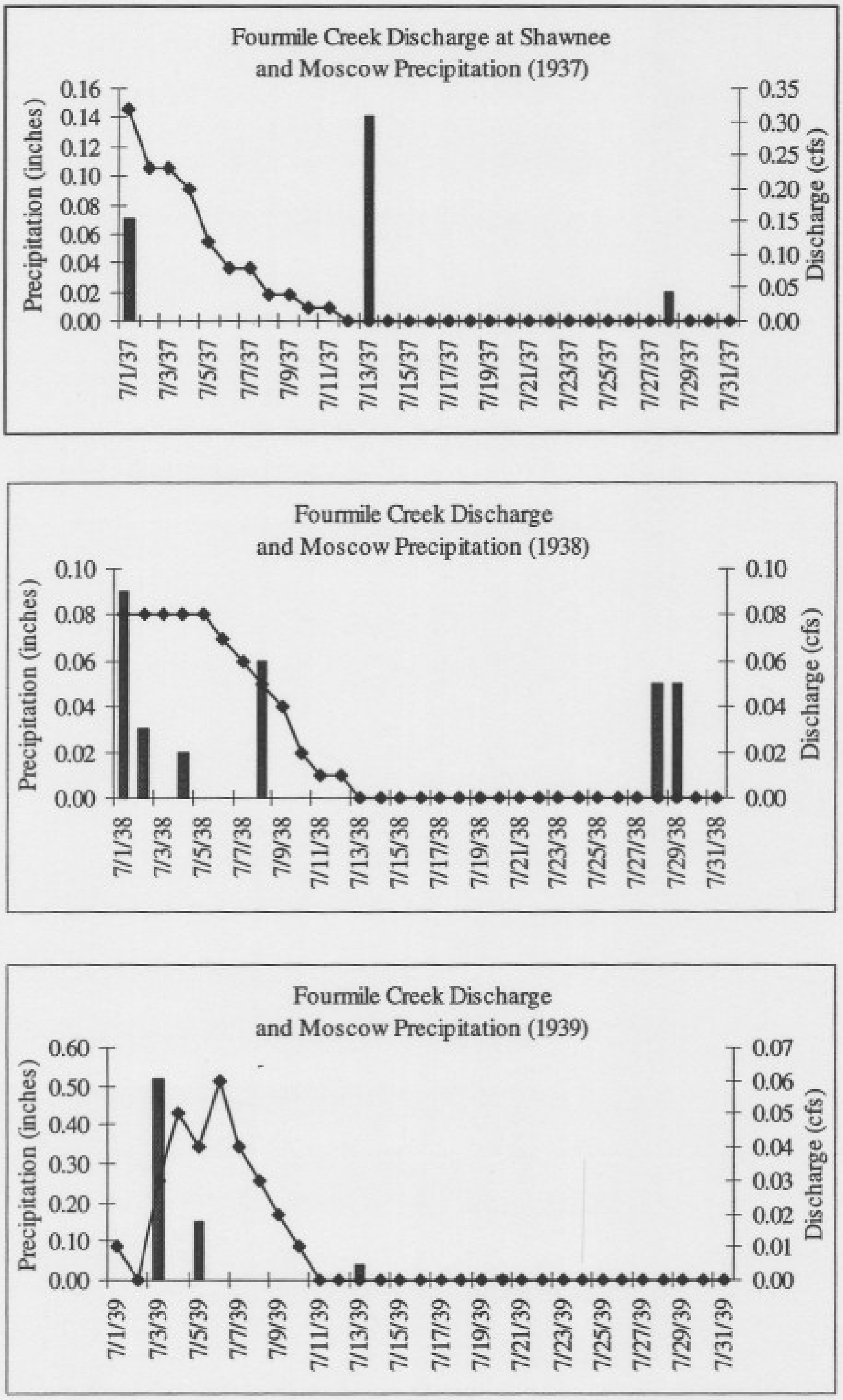


Figure 20. Plots of the hydrographs of Fourmile Creek taken at the USGS gaging station near Shawnee, WA (diamonds) and the precipitation in Moscow, ID taken for the same time period (bar chart).

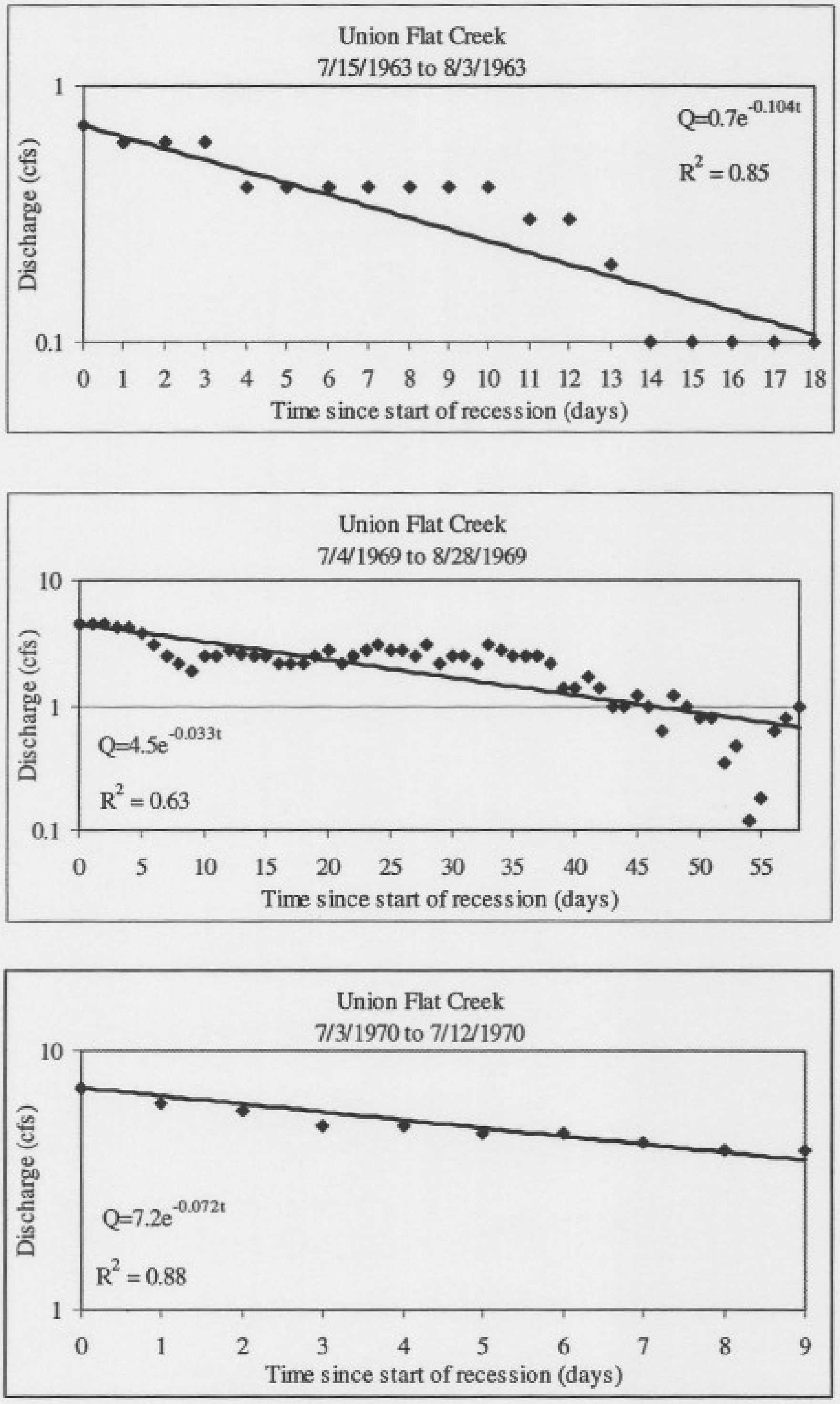


Figure 21. Semi-logarithmic plots of the hydrographs for Union Flat Creek fit with Equation 1.

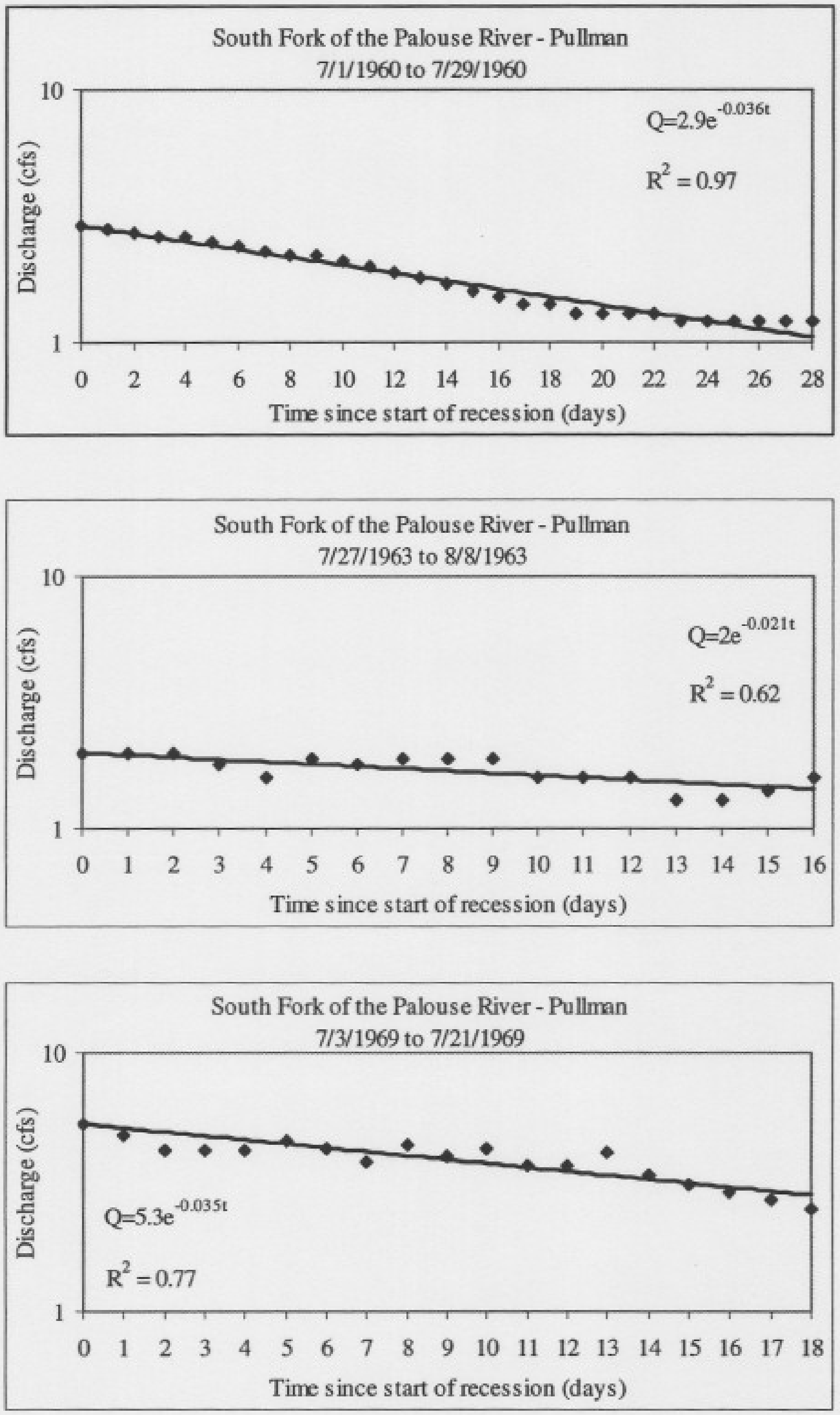
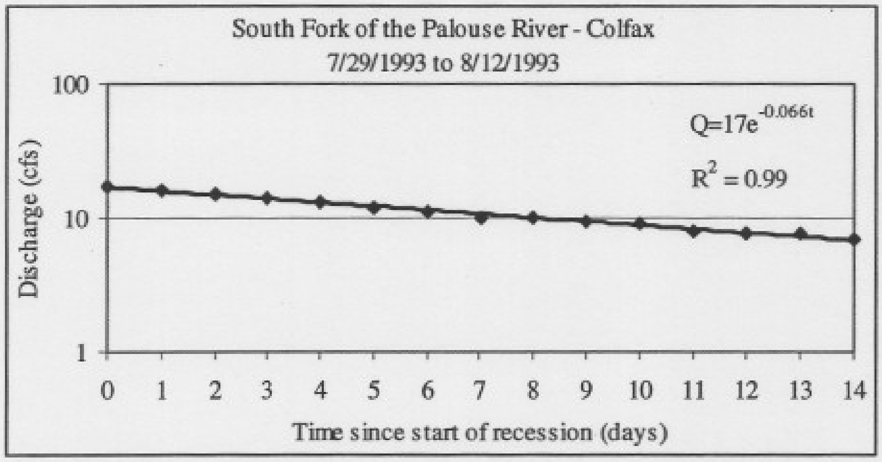
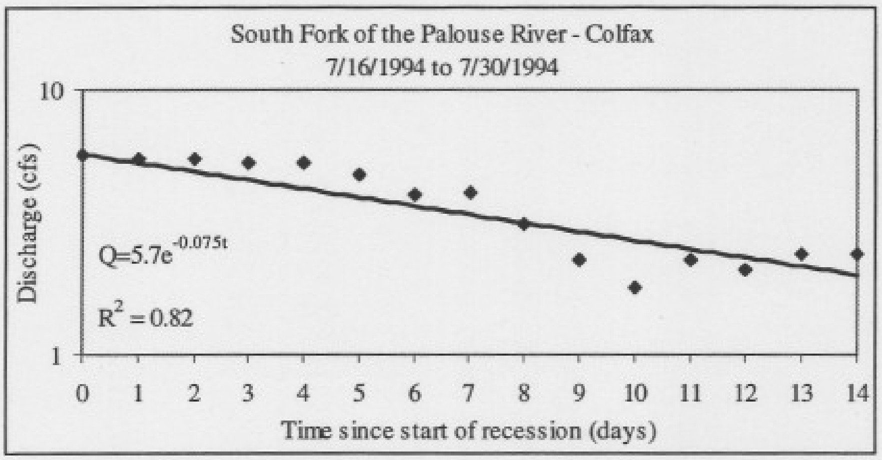


Figure 22. Semi-logarithmic plots of the hydrographs for the South Fork of the Palouse River fit with Equation 1.





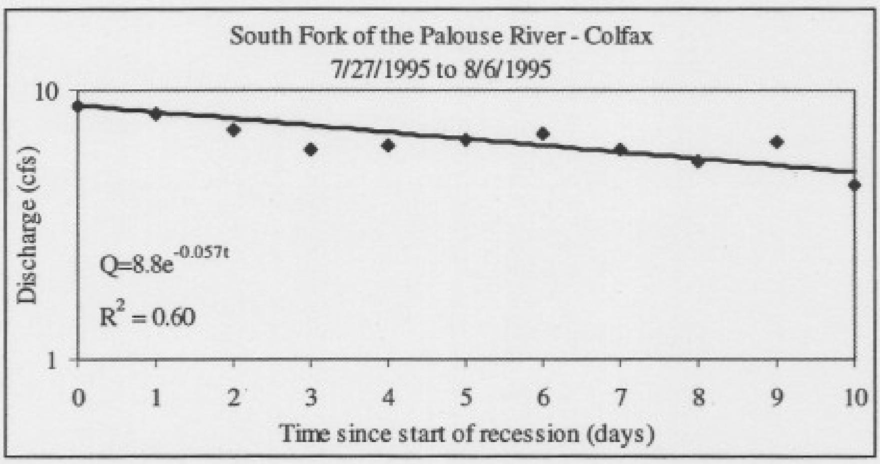


Figure 22. Semi-logarithmic plots of the hydrographs for the South Fork of the Palouse River fit with Equation 1 (continued from previous page).

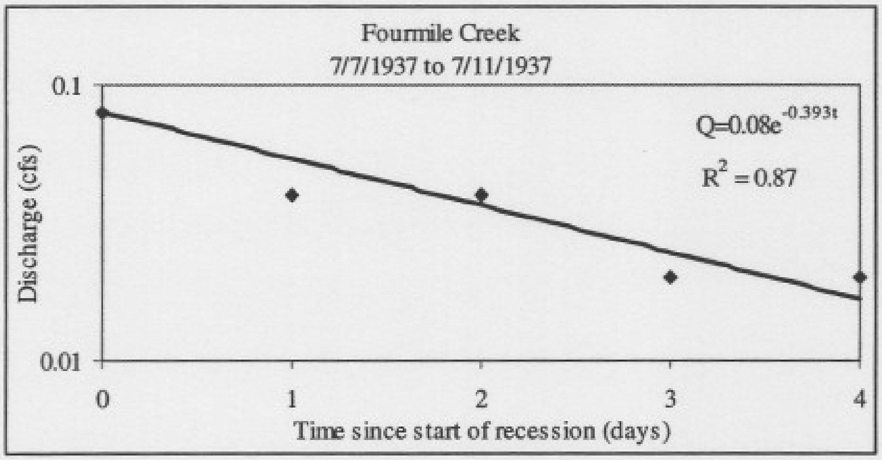


Figure 23. Semi-logarithmic plots of the hydrographs for Fourmile Creek fit with Equation 1.

The streamflow in Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek represent the combined flow discharging from the granitic and metamorphic highlands, the basaltic lowlands, and the Palouse Hills. The baseflow contributions from the granites and metamorphics, however, can be considered as negligible. To evaluate the hydrogeologic unit dominating the baseflow recession characteristics of these streams, estimates of specific yield of the loess, storativity of the basalt, and the distance to the sub-basin dividederived, and the derived recession constants were plugged into equation 9 (Tables 5 and 6). Values of hydraulic conductivity were calculated based on properties of the loess and the basalt and then compared to estimates of hydraulic conductivity taken from the literature.

Measurement Site	Year	Recession Constant	R^2
South Fork of the Palouse River - Pullman	1960	0.036	0.97
South Fork of the Palouse River - Pullman	1963	0.021	0.62
South Fork of the Palouse River - Pullman	1969	0.035	0.77
South Fork of the Palouse River - Colfax	1993	0.066	0.99
South Fork of the Palouse River - Colfax	1994	0.075	0.82
South Fork of the Palouse River - Colfax	1995	0.057	0.60
Union Flat Creek	1963	0.104	0.85
Union Flat Creek	1969	0.033	0.63
Union Flat Creek	1970	0.072	0.88
Fourmile Creek	1937	0.393	0.87

Table 4. Table showing the recession constants, coefficients of determination, and the years for which the discharge data were taken for the streams in the study area.

Table 5 shows the results from Equation 9 based on the hydrogeologic characteristics of the loess. The calculated values of hydraulic conductivity based on the storativity of the basalt, appear to have a slightly better fit to the range of estimated hydraulic conductivity values found by Vacarro (1999). The range of hydraulic conductivity values calculated for Union Flat Creek for 1963 is the only calculated range, based on properties of the basalt that does not fall within the range of accepted hydraulic conductivity values for the Wanapum basalts. Most of the calculated values of hydraulic conductivity, based on

Gaging Station Site	Recession Constant from Hydrograph (day^{-1})	Specific Yield for Loess (%) [Boll, 2003]	Distance to Divide (ft)		Hydraulic Conductivity for Loess (in/hr) [Soil Survey]		Calculated Hydraulic Conductivity (in/hr) [Eq. 12]		
			min	max	min	max	min	max	median
SFPR-Pullman-1960	0.036	4	3900	10400	0.4	2	2.8	7.5	6.55
SFPR-Pullman-1963	0.021	4	3900	10400	0.4	2	1.6	4.4	3.82
SFPR-Pullman-1969	0.035	4	3900	10400	0.4	2	2.7	7.3	6.37
SFPR-Pullman-AVG	0.031	4	3900	10400	0.4	2	2.4	6.4	5.58
SFPR-Colfax-1993	0.066	4	500	4600	0.4	2	0.7	6.1	3.70
SFPR-Colfax-1994	0.075	4	500	4600	0.4	2	0.8	6.9	4.20
SFPR-Colfax-1995	0.057	4	500	4600	0.4	2	0.6	5.2	3.19
SFPR-Colfax-AVG	0.066	4	500	4600	0.4	2	0.7	6.1	3.70
UFC-1963	0.104	4	600	2400	0.4	2	1.2	5.0	3.74
UFC-1969	0.033	4	600	2400	0.4	2	0.4	1.6	1.19
UFC-1970	0.072	4	600	2400	0.4	2	0.9	3.5	2.59
UFC-AVG	0.070	4	600	2400	0.4	2	0.8	3.3	2.51
4MILE-1937	0.393	4	1300	3600	0.4	2	10.2	28.3	24.37

Table 5. Table of hydraulic parameter values of the loess and the resultant values for hydraulic conductivity using Equations 9 for the streams.

Gaging Station Site	Recession Constant from Hydrograph (day^{-1})	Storativity for Basalt (-) [Lum et al., 1990]		Distance to Divide (ft)		Hydraulic Conductivity for Basalt (ft/day) [Vaccaro, 1999]		Calculated Hydraulic Conductivity (ft/day) [Eq. 12]		
		min	max	min	max	min	max	min	max	median
SFPR-Pullman-1960	0.036	0.00047	0.006	3900	10400	0.0873	6.42	0.066	2.246	1.19
SFPR-Pullman-1963	0.021	0.00047	0.006	3900	10400	0.0873	6.42	0.038	1.310	0.69
SFPR-Pullman-1969	0.035	0.00047	0.006	3900	10400	0.0873	6.42	0.064	2.184	1.16
SFPR-Pullman-AVG	0.031	0.00047	0.006	3900	10400	0.0873	6.42	0.056	1.914	1.01
SFPR-Colfax-1993	0.066	0.00047	0.006	500	4600	0.0873	6.42	0.016	1.822	0.93
SFPR-Colfax-1994	0.075	0.00047	0.006	500	4600	0.0873	6.42	0.018	2.070	1.05
SFPR-Colfax-1995	0.057	0.00047	0.006	500	4600	0.0873	6.42	0.013	1.573	0.80
SFPR-Colfax-AVG	0.066	0.00047	0.006	500	4600	0.0873	6.42	0.016	1.822	0.93
UFC-1963	0.104	0.00047	0.006	600	2400	0.0873	6.42	0.029	1.498	0.78
UFC-1969	0.033	0.00047	0.006	600	2400	0.0873	6.42	0.009	0.475	0.25
UFC-1970	0.072	0.00047	0.006	600	2400	0.0873	6.42	0.020	1.037	0.54
UFC-AVG	0.070	0.00047	0.006	600	2400	0.0873	6.42	0.020	1.003	0.52
4MILE-1937	0.393	0.00047	0.006	1300	3600	0.0873	6.42	0.240	8.489	4.48

Table 6. Table of hydraulic parameter values of the basalt and the resultant values for hydraulic conductivity using Equation 9 for the streams.

the properties of the loess, also fit with the estimates of hydraulic conductivity found in the soil survey for Whitman County. Only one median value of calculated hydraulic conductivity based on the specific yield of the loess, however, falls within the range of hydraulic conductivity listed in the soil survey, while all of the median values based on the basalt storativity fall within the accepted range of Vaccaro (1999). The difference of the recession constants for the springs relative to the recession constants for the streams of one to two orders of magnitude implies that they discharge from aquifers within different geologic materials or within different sizes. The consistency of the stream recession constants with the hydrogeologic characteristics of the basalt, along with the larger recession constants, implies that the springs measured for this recession analysis drain from a shallower flow system than the major streams in the study area. The stream recession characteristics appear to reflect basalt derived flow systems during the low flow period of the year.

Flow Systems

In order to derive a conceptual understanding of ground water recharge and discharge mechanisms in the Moscow-Pullman basin, it is essential to consider the flow systems within the basin. Toth (1963) coined the concepts of local, intermediate, and regional flow systems using a mathematical model to describe steady-state flow patterns in two-dimensional, small, homogeneous and isotropic ground water basins. Freeze and Witherspoon (1967) elaborated on this work and also included nonhomogeneous cases. In both cases, the models were used to test various factors and their effects on flow systems in small basins. One of these factors included the effects of hummocky terrain on flow systems in a small ground water basin with a major valley as one flow boundary, similar to the hydrogeologic characteristics of the Moscow-Pullman basin.

To address flow systems in the Moscow-Pullman basin, a topographical cross-section of the land surface was created extending from the Snake River (A) to north of Moscow (A') (Figure 24). The cross-section was developed based on elevation contours of 20 feet taken from digital raster graphics (DRG's) at a frequency of 0.5 miles from A to A'. Based on the idea that the water table mimics the form of the land surface, this cross-section was then qualitatively analyzed based on the expected effects of hummocky water-table configurations on flow patterns in a small ground water basin (Toth, 1963; Freeze and Witherspoon, 1967).

A profile of land surface elevations extending from the Snake River (A) to north of Moscow (A') was created to reflect the shallow water table characteristics for the Moscow-Pullman basin (Figures 24 and 25). Assuming steady-state flow and homogeneous and isotropic basin conditions, this profile can be used to help predict the expected flow patterns for a small, homogeneous and isotropic basin with a hummocky water-table configuration (Toth, 1963; Freeze and Witherspoon, 1967). Figure 25 shows a land-surface profile with a vertical exaggeration of four. This profile shows the Moscow-Pullman basin to exhibit hummocky terrain composed of the loess hills and a major valley at the western boundary of the basin, the Snake River. Figure 26 shows the results from the use of mathematical models to describe steady-state flow patterns in a small, homogeneous and isotropic basin with a hummocky water-table condition and a major valley as the western boundary of the basin (Toth, 1963; Freeze and Witherspoon, 1967).

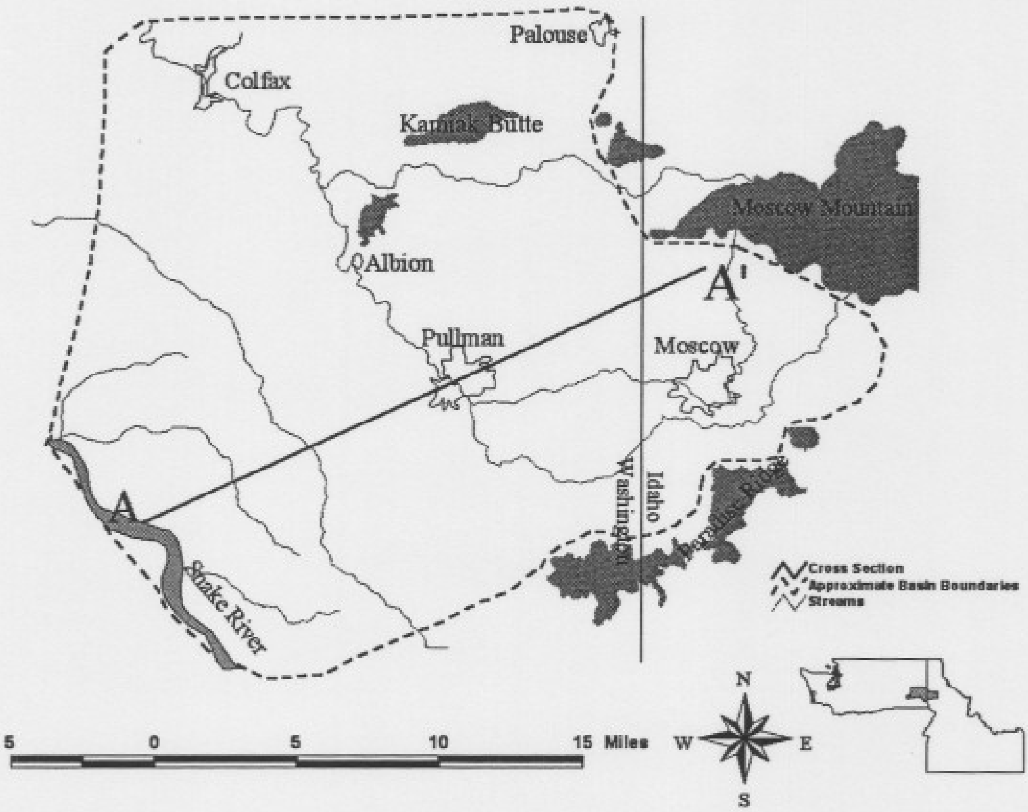


Figure 24. Map showing the location of the land surface profile extending from A to A'.

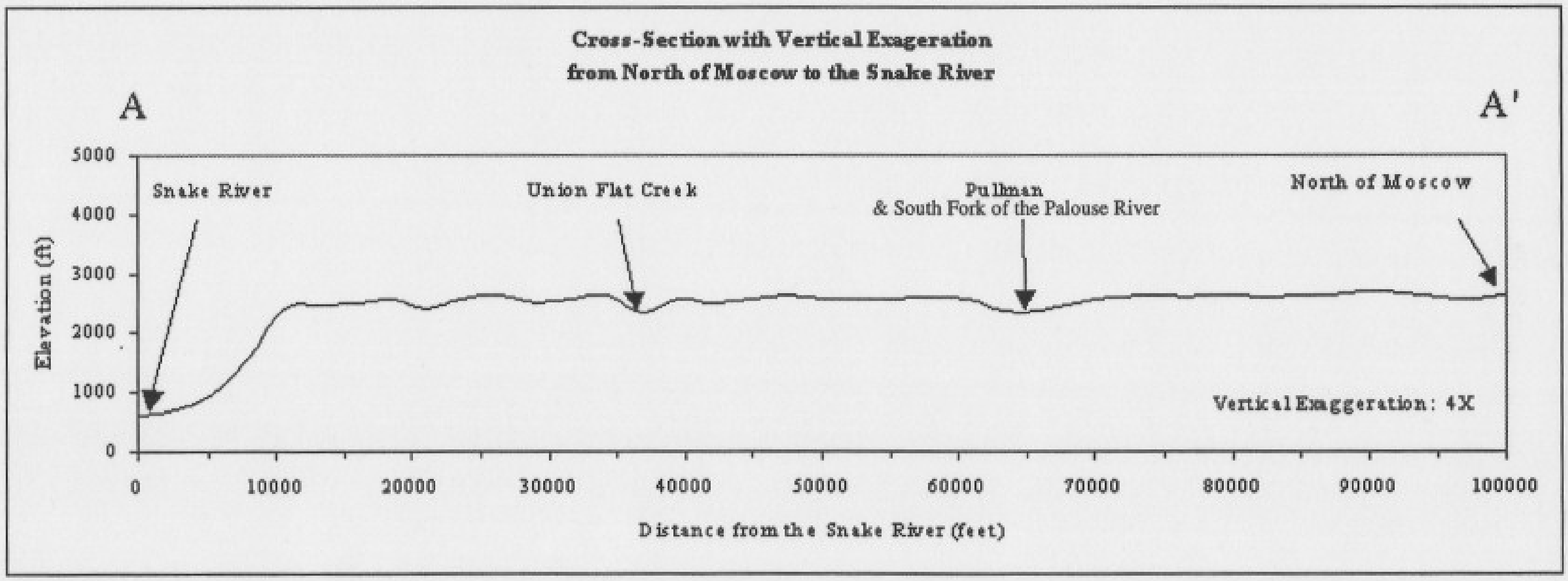
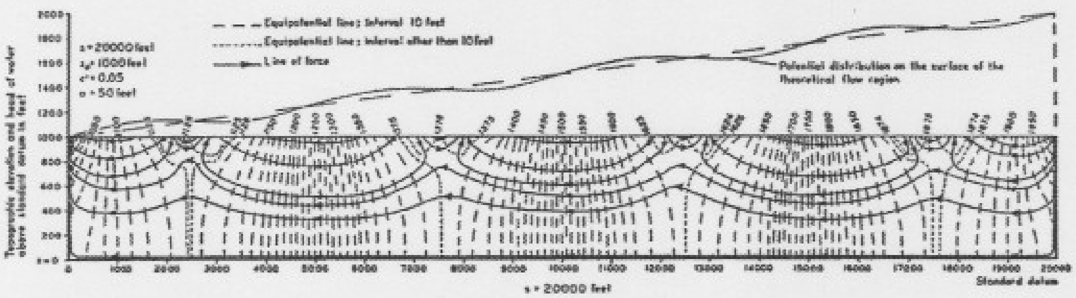


Figure 25. Profile of the land surface from the Snake River (A) to north of Moscow (A'). Note: vertical scale is exaggerated 4x.

A



B

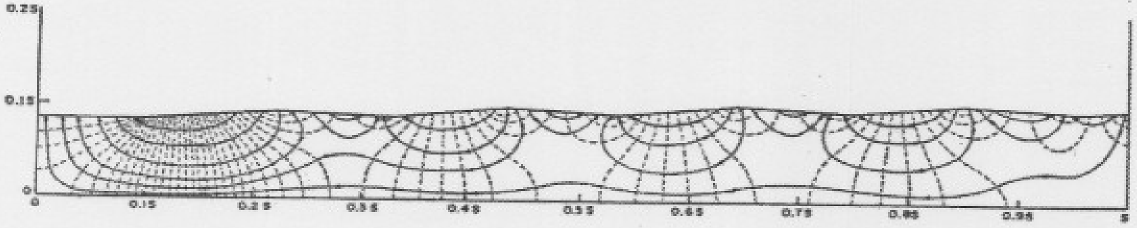


Figure 26. Effects of hummocky water-table configuration on flow systems in a small, homogeneous and isotropic basin with a major valley as a flow boundary. A) Toth (1963) and B) Freeze and Witherspoon (1967).

The flonets in Figure 26 show three types of ground water flow systems: local, intermediate, and regional flow systems (Toth, 1963). The hummocky terrain in the Moscow-Pullman basin as well as the major valley bounding the western edge of the basin, create a uniquely similar situation to those shown in Figure 26. Whether the hummocky water-table configuration is slightly more or less than those shown in Figure 26 can be debated, but qualitatively, the general hydrogeologic factors involved are similar, assuming homogeneous and isotropic conditions and steady-state flow.

Conceptually, this flow analysis implies that the Moscow-Pullman basin should also exhibit local, intermediate, and regional flow systems. This concept is consistent with results from the spring and stream recession analyses. Based on the configuration of the water-table and with the existence of a major river as a basin boundary, local flow systems would be expected to occur in the hummocky terrain of the Palouse, creating the small magnitude springs along the stream valleys. Intermediate flow systems would also be expected to contribute directly to the flow of the major streams in the basin, as was suggested by the recession analyses. A regional flow system could also be expected with a recharge area near Moscow and a major discharge area at the Snake River.

Discharge to the Snake River

The streamflows for Almota Creek, Little Almota Creek, and Wawawai Creek are rather small, considering they are the only visible potential discharge from the Moscow-Pullman basin to the Snake River. On January 9, 2001 Little Almota Creek had a discharge of 1.2 cfs, and on January 10, 2001 Almota Creek had a discharge of 6.0 cfs and Wawawai Creek had a discharge of 1.4 cfs. A total of 8.5 cfs is all the water that was visibly discharging into the Snake River from the Moscow-Pullman basin during low flow the second week of January 2001.

Comparison of isotope ratios in ground water is one geochemical method that can be used to examine sources of recharge to ground water basins. If isotope ratios significantly differ from those of local precipitation, it can be determined that the recharge is not from a local modern source. Specifically, the oxygen isotope ratio is a comparison of the amount of ^{18}O to ^{16}O in the water samples taken from the ground water as compared to local precipitation. These ratios reflect the environmental conditions of the time during which the recharge occurred. Based on knowledge of ancient environmental conditions, therefore, a time period for the recharge can be inferred. Larson (2000) used this predictable behavior of the stable isotopes of oxygen ($\delta^{18}O$) to compare the different recharge scenarios for the varying systems at depth in the Moscow-Pullman basin.

Geochemical data collected for the streams prior to the discharge measurements, are not consistent with the values for the deep basalt aquifers of the Grande Ronde (Figures 27 and 28). Larson (2000) found that surficial, Wanapum, and Idaho Batholith samples were not statistically different from each other, but that all were statistically different from the Grande Ronde water samples. Water samples collected on October 14, 2000 from Almota Creek, Little Almota Creek, and Wawawai Creek appear to be similar to the loess, even though the Oxygen-18 values are not statistically different from the water of the Wanapum, the Idaho Batholith, or surficial water (Figure 28).
Little Almota Creek appeared to gain water uniformly from the headwaters to the confluence with the Snake River. In contrast, virtually all of the discharge from

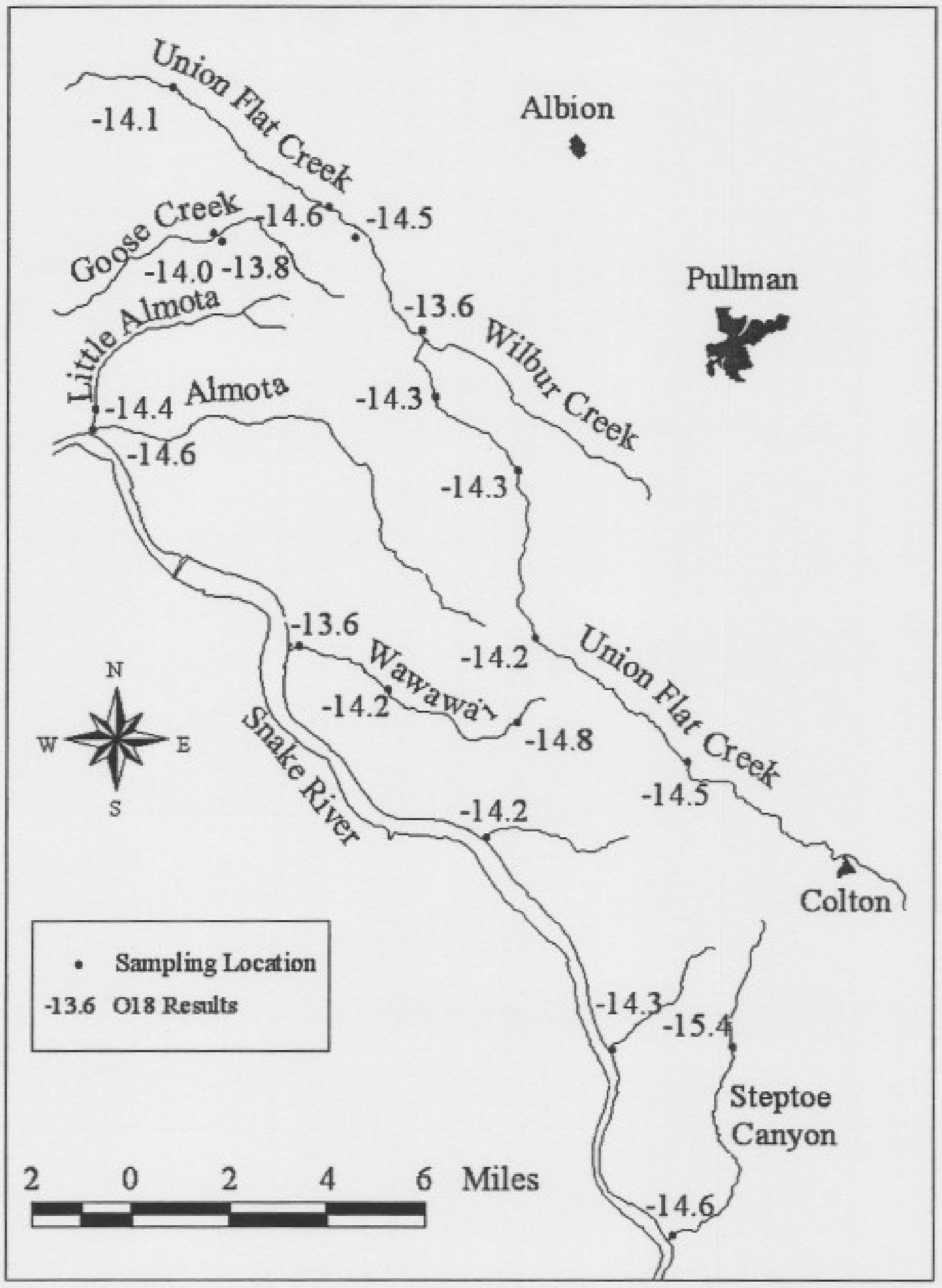


Figure 27. Map showing the sampling locations and Oxygen-18 results from research conducted by Kirk (2000).

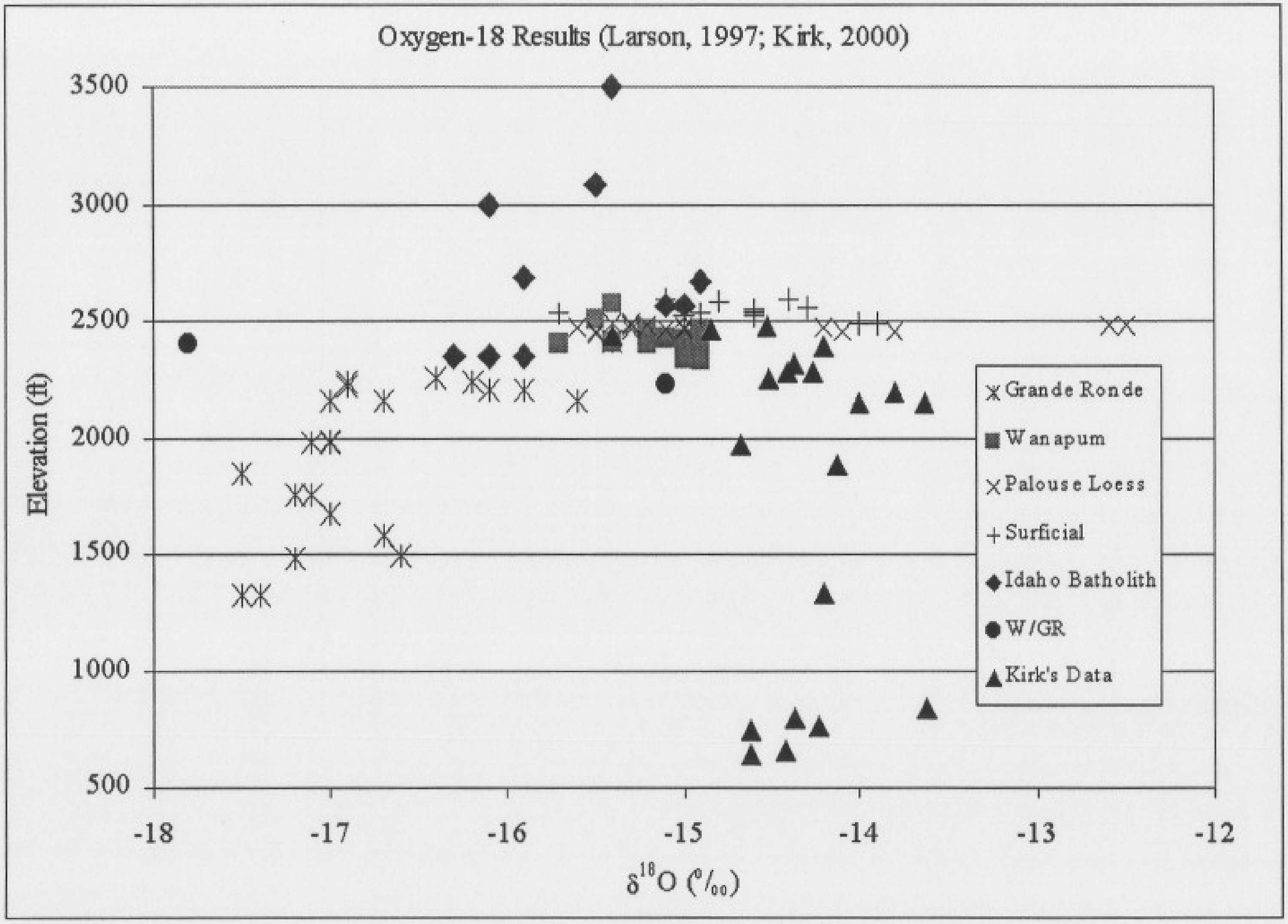


Figure 28. Oxygen-18 results from Larson (1997) and Kirk (2000) for the Moscow-Pullman Basin.

Wawawai Creek appears as a spring approximately one mile east of the confluence. The spring discharges from alluvium approximately 300 feet above the water level in the Snake River. Upstream observations for Almota Creek were not possible because permission to access the land was denied by the owner. The uniform gain of discharge in Little Almota Creek can possibly be attributed to drainage of the surrounding loess hills. Based on the geochemical data, the Grande Ronde is not the likely source of ground water discharge in Wawawai Creek. The spring may be a surface manifestation of primarily subsurface flow in the streambed sediments over most of the length of the stream. The streamflow might consist of a mixture of discharge from the Palouse Formation and discharge from the Wanapum. This explanation is consistent with the appearance on aerial photographs of seepage faces or very small springs, manifested as vegetated patches, located high on the canyon walls.

Assessment of the Palouse Formation

The Palouse Formation constitutes virtually all of the overburden in the western part of the Moscow-Pullman basin. In the eastern part of the basin, however, the overburden consists of both the Palouse Formation and the Sediments of Bovill, which generally consist of coarser grained sediments underlying the loess hills. It was impossible to distinguish between the Palouse Formation and the Sediments of Bovill in the Moscow area, because the sediments overlying the basalts are typically referred to as the overburden in well logs and are not differentiated. Thickness of the overburden for all available well logs was plotted spatially to produce the isopach map, shown in Figure 29.

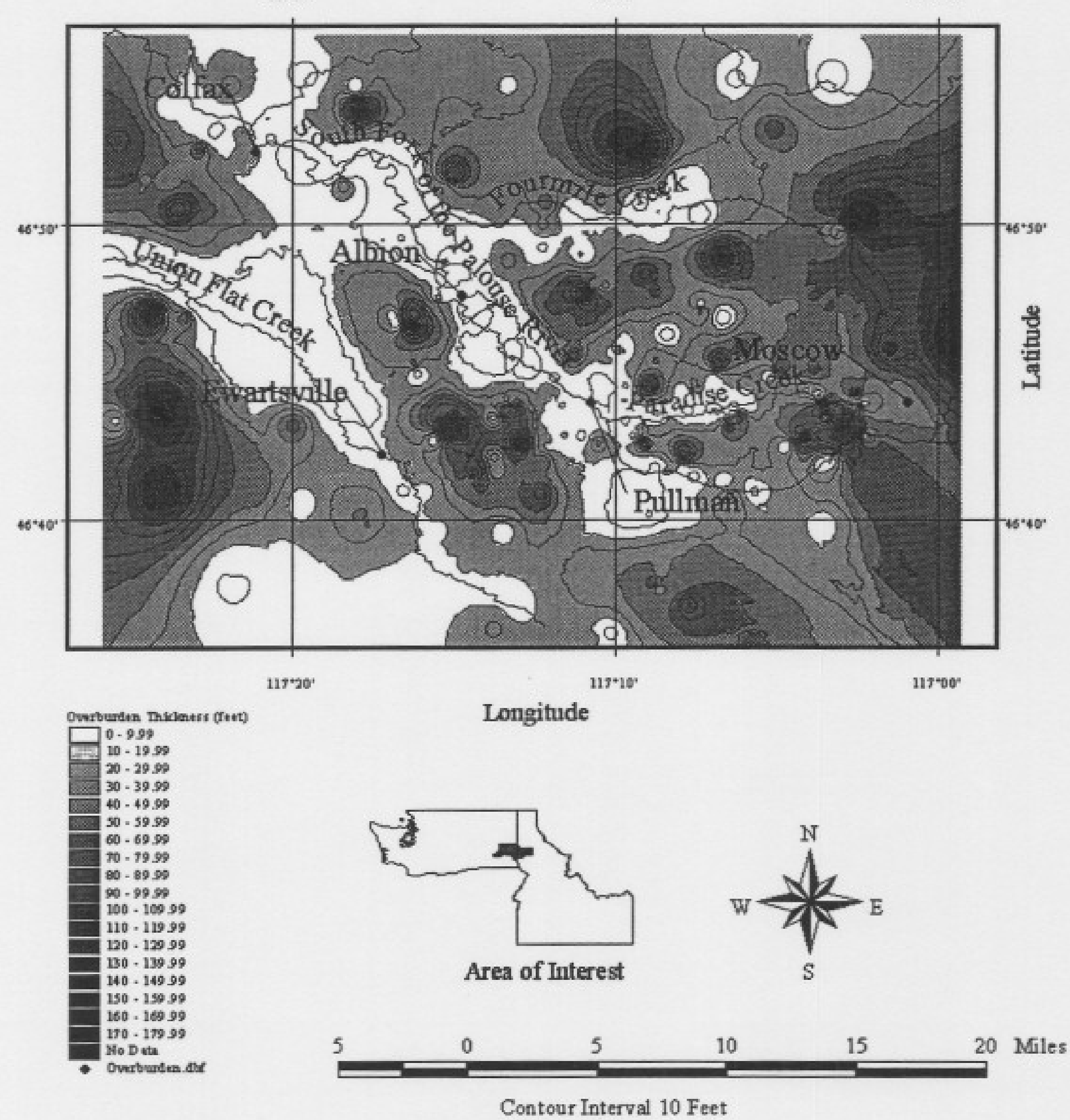


Figure 29. Isopach map showing the thickness of the overburden in the Moscow-Pullman basin. The overburden in the central and western portion of the mapped area consists primarily of the Palouse Formation while in the eastern portion, the overburden includes both the Palouse Formation and the Sediments of Bovill. Thickness is measured in feet, and latitude and longitude values shown are in degrees. Contours were created in Arcview using an Inverse Distance Weighted interpolator.

The areas with the thickest overburden in the Moscow-Pullman basin appears to be west of Ewartsville, between Union Flat Creek and the Snake River, and near Moscow, where thickness values include the Sediments of Bovill. The overburden appears to thin between Moscow and Union Flat Creek, possibly reflecting a higher basalt surface or a lack of data. The thicker Palouse Formation in the western part of the basin may explain the larger number of springs found along Union Flat Creek as compared to the South Fork of the Palouse River. Not only do the number of springs appear to decrease to the east, but so does the duration during which these springs continue to flow. In the western part of the basin, particularly along Union Flat Creek and the South Fork of the Palouse River flow many springs flow throughout the entire summer. Though no measurements have been taken for springs in the eastern part of the basin, there appear to be fewer springs and they do not flow for the entire summer. This apparent transition from the perennially flowing springs in the west to the seasonally flowing springs in the east may be attributed to the distribution of the loess thickness or may be linked to the existence of tile drainage. Another explanation is that this transition can be attributed to the extent to which the streams in the western part of the basin expose the contact between the loess-basalt contact as opposed to the eastern part of the basin where the streams do not expose this contact, thus precluding surface expression of the water table.

One potential cause of perching conditions along Union Flat Creek and the South Fork of the Palouse River may be clay deposits, which have been found at the contact between the basalts and the overlying soils in parts of the Moscow-Pullman basin. At multiple sites in Latah County, Hosterman found clay deposits that were formed on weathered surfaces of the Columbia River Basalts (1960). These clay deposits may constitute the primary perching layers that, when exposed by valley walls, produce the small magnitude springs along Union Flat Creek and the South Fork of the Palouse River. Evidence of these conditions was found at UFC 11 along Union Flat Creek (Appendix 9).

Maps comparing the location of the springs relative to the top of the basalt are shown in Figures 30 and 31. The springs contributing to measurement sites UFC 1, UFC 3, UFC 9, UFC 11, UFC 16, and UFC 7 along Union Flat Creek and two of the springs contributing to site UFC 13 are above the top of the basalt, while the sources for sites UFC 18, UFC 14, UFC 15, UFC 5, UFC 6, and one of the sources of site UFC 13 are somewhat below the top of the basalt. Many of the springs have been tiled to extend the productive growing area for crops and, therefore, the current locations of the sources are below the original location of the springs. The spring sources that appear below the loess-basalt contact may be an artifact of erosional irregularities in the surface of the basalts. These irregularities may create conduits for flow from which the springs discharge. All of the sources for the springs along the South Fork of the Palouse River are located well above the top of the exposed basalt with the exception of spring 3, which appears to be barely below the top of the basalt. Tile drains have affected all of the sources of the springs along the South Fork of the Palouse River. Therefore, the original sources likely were even further above the tops of the basalts exposed along the valley. From the basalt maps, it is concluded that most of the sources for the springs along Union Flat Creek and the South Fork of the Palouse River are located above or very near the loess-basalt contact which further supports the hypothesis that the springs are draining the

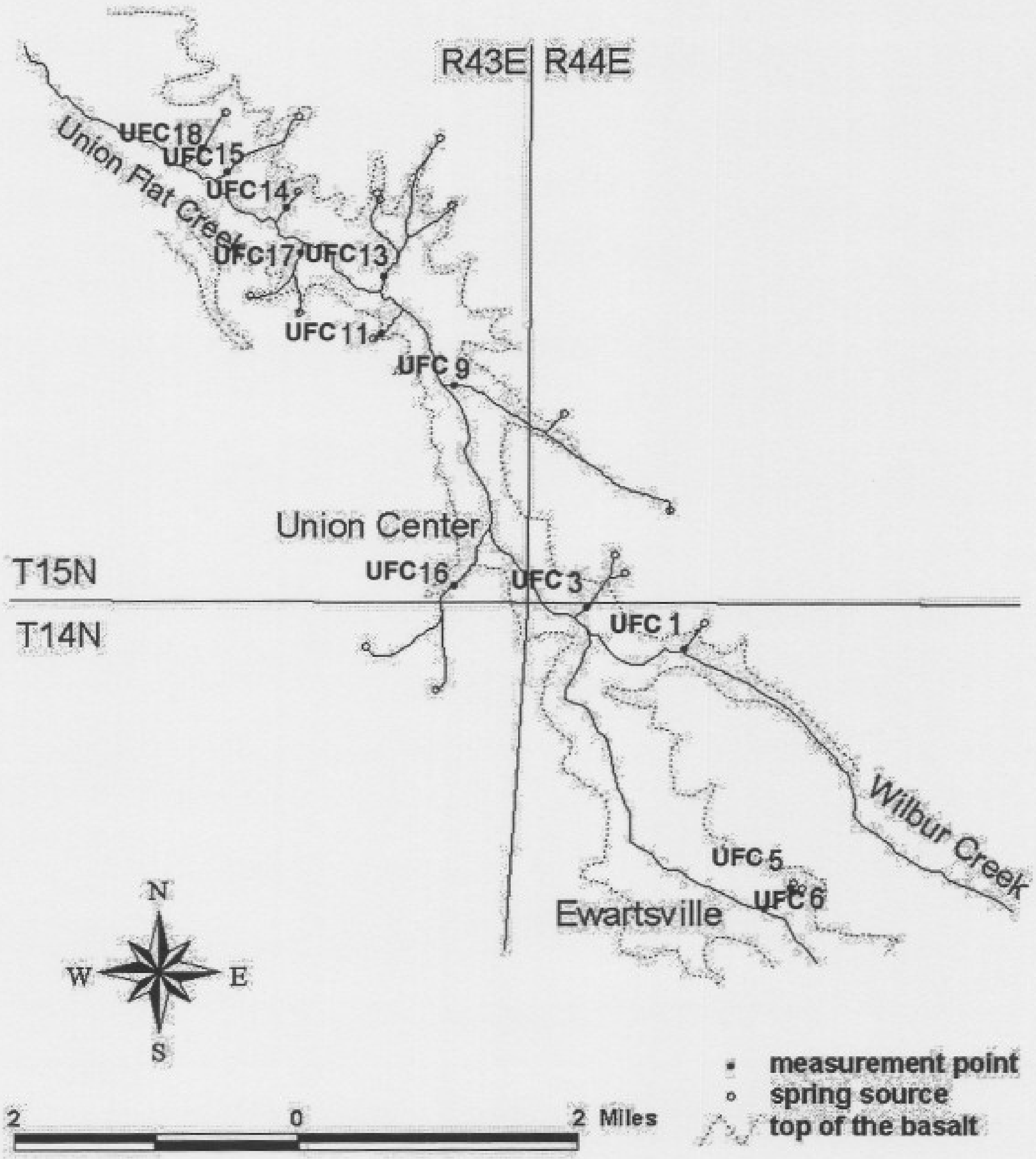


Figure 30. Map comparing the source of the springs on Union Flat Creek to the top of the basalt.

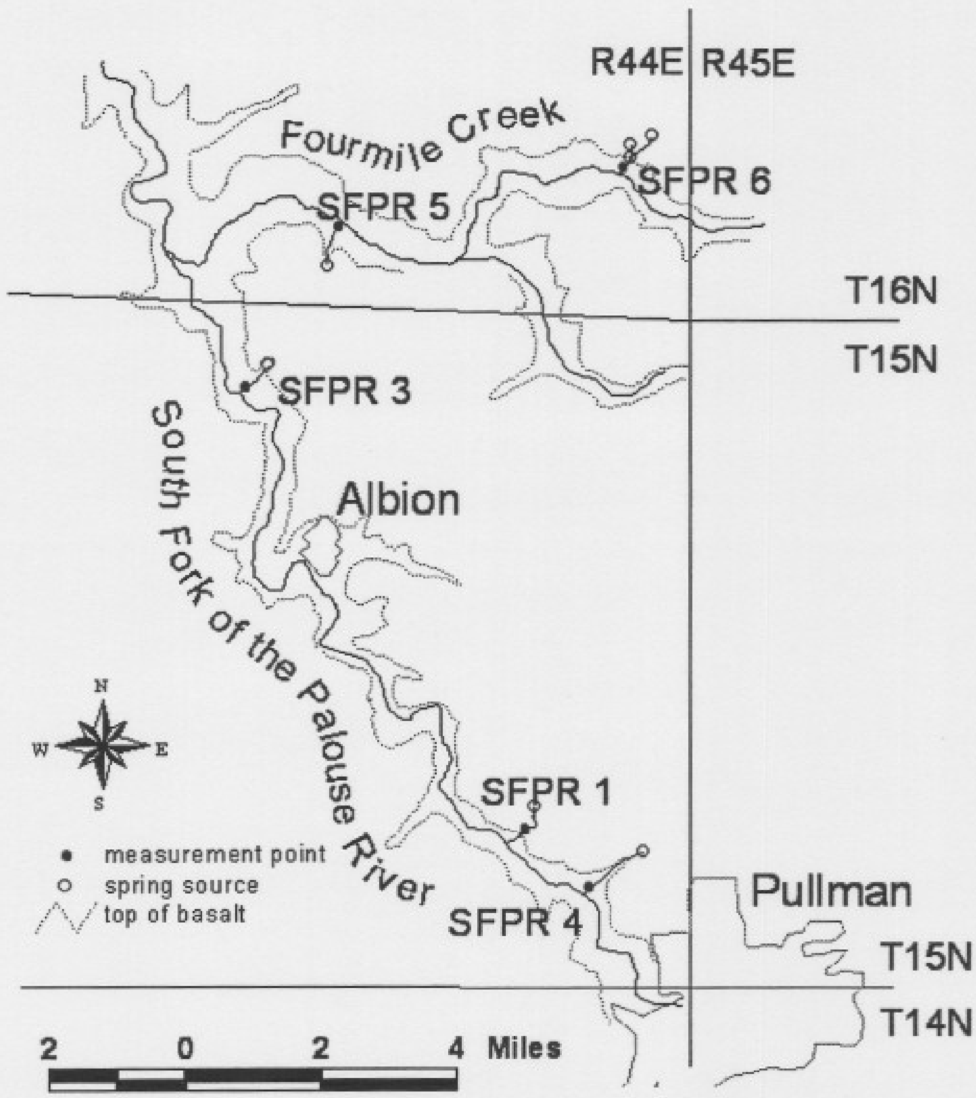


Figure 31. Map comparing the source of the springs on the South Fork of the Palouse River to the top of the basalt.

loess rather than the aquifers within the basalts. It appears that some of the springs may reflect the surface expression of perched water tables well above the loess-basalt contact while others are located near the contact with the basalt (Figure 32). The source at site UFC 11 on Union Flat Creek consists of multiple springs, some of the ground water discharging at these springs then seeps back into the ground. These layered springs are likely a result of well-developed paleosols that are rich in clay creating perched conditions and therefore producing a spring at the contact of the overlying loess and the hydraulically restrictive paleosol. After the ground water is discharged as a spring, it flows at the land surface for a short distance then seeps back into the soil. Subsurface flow occurs until reaching another clay-rich layer or the top of the basalt, finally discharging at the land surface as a permanent spring.

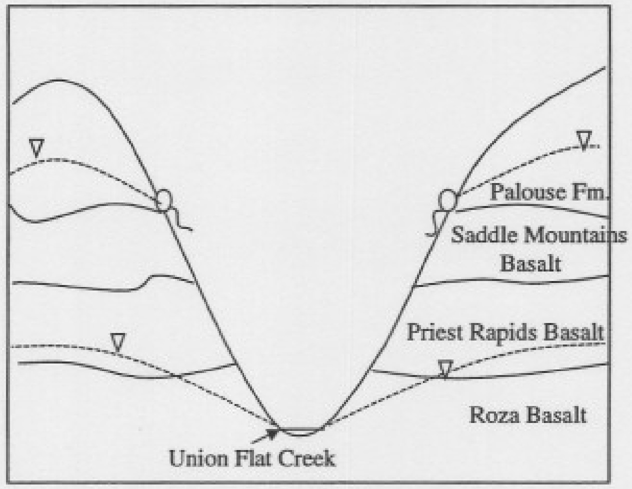


Figure 32. Generalized cross-section showing the shallow flow system perched above the loess-basalt contact and the intermediate flow system of the Wanapum basalts discharging directly into the stream.

Both the isopach map of overburden thickness and the spring source locations relative to the top of the exposed basalts, support the hypothesis that the springs along Union Flat Creek and the South Fork of the Palouse River are discharging from the Palouse Formation. Typically, springs occur at contacts between a higher hydraulic conductivity material and an underlying low hydraulic conductivity material. The low hydraulic conductivity layers appear to be both the clays on top of the basalt, and possibly clay-rich paleosols that are prevalent within the Palouse Formation. According to the Soil Survey of Whitman County (Donaldson, 1980), many of the soil types found at and above the source of the springs discharging into Union Flat Creek and the South Fork of the Palouse River are known to commonly develop perched water tables.

Water Levels above UFC 11 on Union Flat Creek

During the summer of 2001, six piezometers were installed in the soil above the source of UFC 11 along Union Flat Creek. Well logs for those piezometers were used to interpret the hydrogeologic setting of site UFC 11. Water levels in the piezometers, discharge from the original measurement site (UFC 11), and discharge from the apparent source of the spring were recorded. These data were plotted against time to produce hydrographs for recession analyses.

At a depth of approximately five feet below the ground surface, the soil samples consisted dominantly of clay. The open interval of all of the piezometers, with the exception of piezometer G, was located within the clay, which is where the water table was intercepted during augering, and remained dry for the period of measurement. The open interval of Piezometer G was located in the loess. Piezometer G was originally installed to determine the vertical gradient above the source of UFC 11.

The water level hydrographs are shown in Figure 33 and spring discharge hydrographs are shown in Figure 34. Recession constants for the piezometers range from $2X10^{-6}$ to $5X10^{-6}$ with the exception of piezometer B. The water level in piezometer B was not in recession and was rising during the measurement period. The reasons for the increasing water level in piezometer B are unknown; however, explanations for the

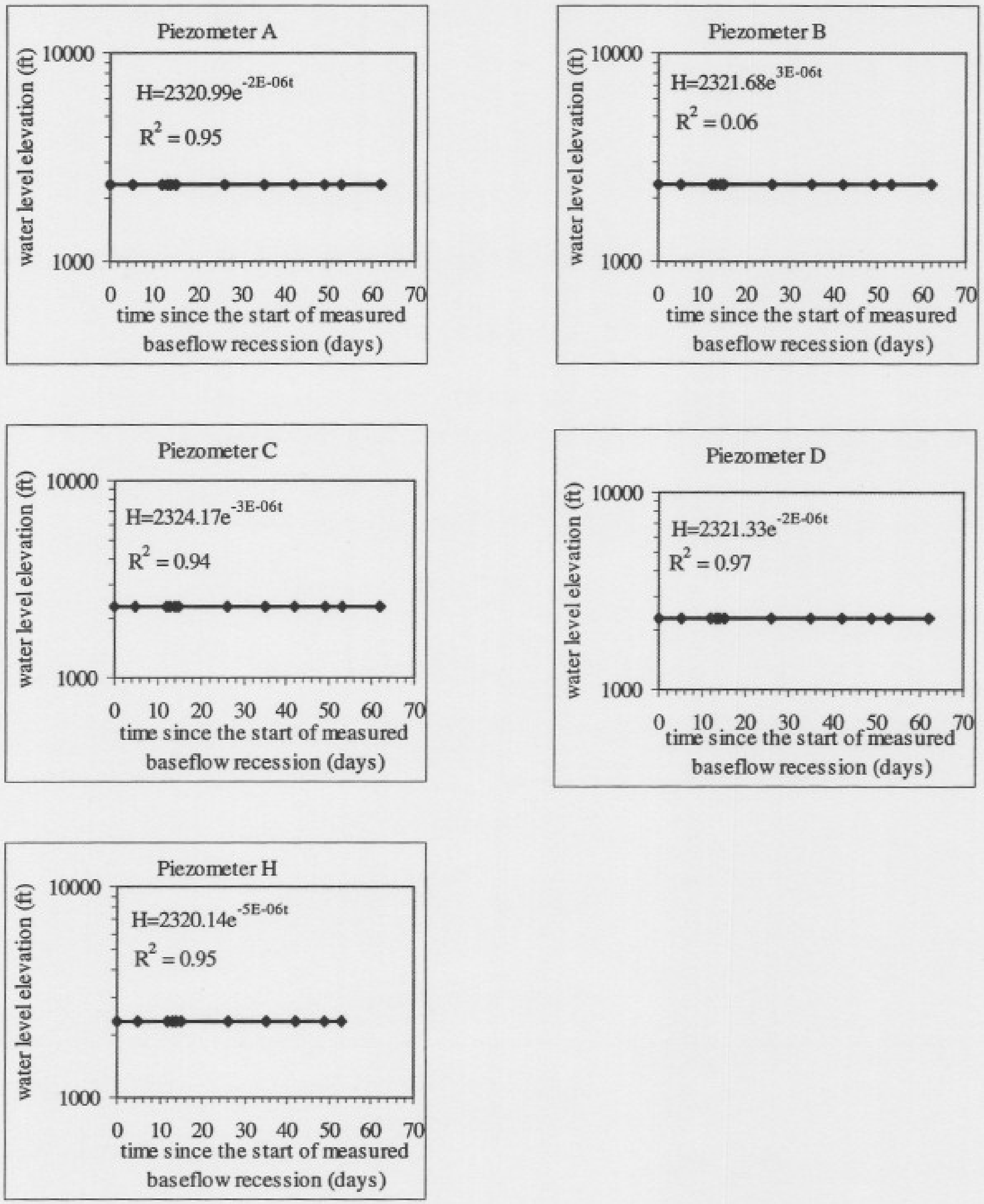


Figure 33. Semi-logarithmic plots of water level versus time for piezometers A, B, C, D, G, and H located upstream of the spring creating the discharge for site 11 on Union Flat Creek.

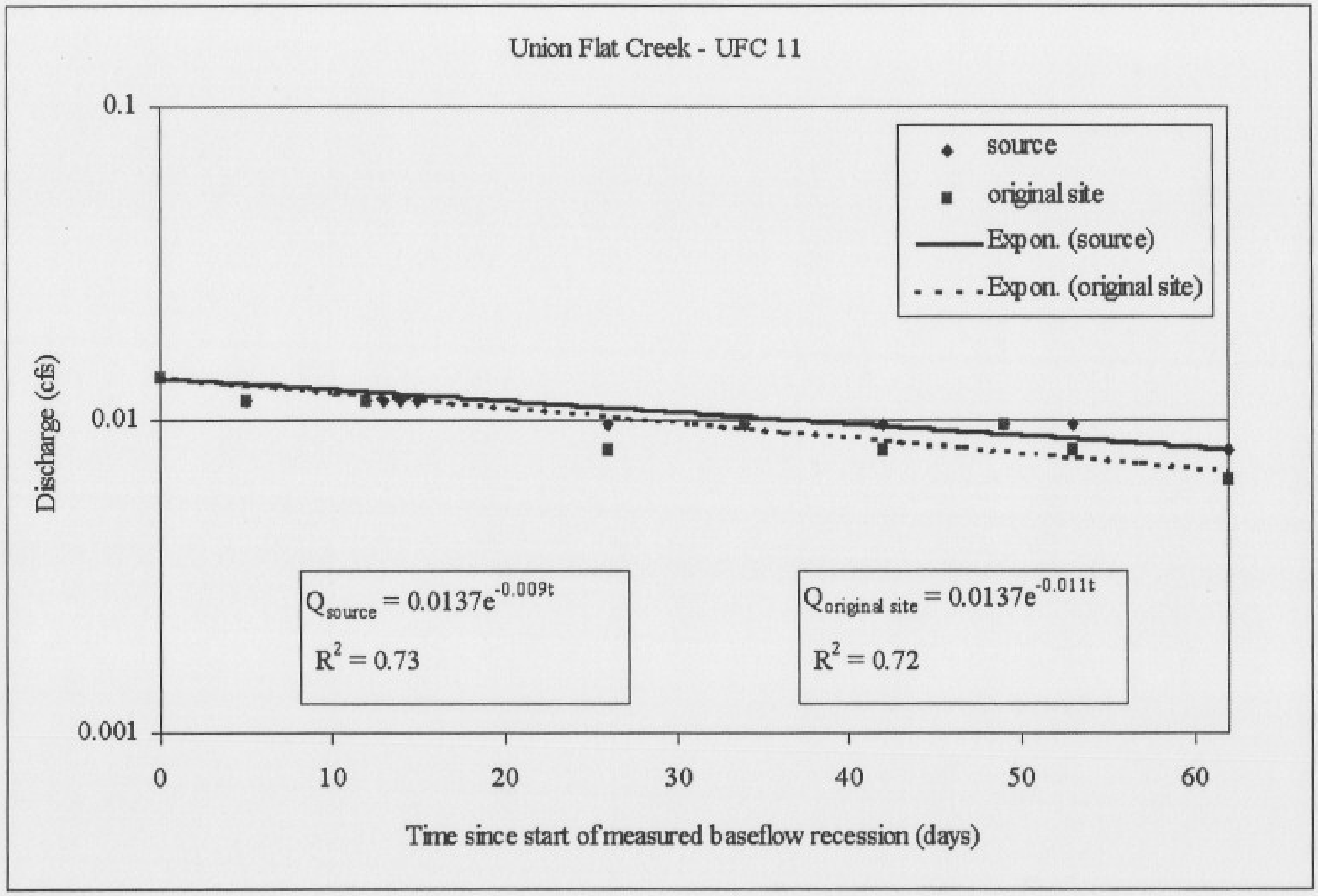


Figure 34. Semi-logarithmic plots of discharge versus time during the summer of 2001 from the spring at the apparent source and at the original measurement site.

remaining hydrographs are possible. Recession constants for the spring at the source and at the original measurement site were 0.009 and 0.011, respectively. The recession constants for the piezometers are three to four orders of magnitude smaller than the recession constants for the springs. These inconsistent values may result from the low hydraulic conductivity of the clay in which the piezometers are located.

From a field investigation, it appears that the spring, above which the piezometers were located, was actually being fed by another small spring which was found approximately a hundred meters upstream of the measuring point. The flow from this smaller spring seeps back into the soil prior to reaching the measuring point. This spring water seeps back into the soils and appears to resurface at the measuring point. Also, based on an interview with a local farmer, the site chosen for the piezometer installation once had a house on it and the spring water was stored using a cistern. It is possible that the natural discharge location for the spring has been altered and/or tiled out and that the water table that feeds UFC 11, and therefore the true source of the spring, is actually perched further uphill from the piezometers. This heterogeneous flow path does not appear to have been intersected by the piezometers, which were installed for this project, making it difficult to interpret the recessions obtained from the piezometers. It appears that the recession constants for the piezometers do not reflect the properties of the system from which the spring is discharging. The piezometers appear to intersect an aquitard, which is not a part of the perched water table from which the true spring is discharging. Due to the nature of the Palouse and the many soil layers and palesols, a layered system with multiple perched water tables with distinct recession constants for each, may be one possible explanation.

CHAPTER 4

SUMMARY AND CONCLUSIONS

Summary

The declining water levels in the Moscow-Pullman basin have caused growing concern over exactly how much water will be available for future water supplies. To better understand how much water will be available, estimates of recharge and discharge to the basin have been made, but have generally been unreliable. Suggested recharge processes generally fall within the following three types: (1) The recharge is areally distributed and infiltrates through the Palouse Formation covering the basin, (2) recharge occurs along the margins of the basin, at the basalt-crystalline bedrock contacts, and (3) losing streams are recharging the basalt aquifers, particularly via infiltration through the Sediments of Bovill in the eastern part of the basin. Natural discharge from the basaltic aquifers generally has been suggested to occur along the major streams in Whitman County and the Snake River (Lum et al., 1990; Heinemann, 1994; Barker, 1979). The purpose of this research was to investigate the baseflow characteristics of the springs and major streams in the Moscow-Pullman basin. Springs along Union Flat Creek and the South Fork of the Palouse River were measured and analyzed, and historical stream discharge measurements were evaluated.

This thesis tested the hypothesis that the springs along Union Flat Creek and the South Fork of the Palouse River are discharging from the Palouse Formation rather than aquifers within the basalts. The hypothesis was tested by using recession analyses of the discharges, evapotranspiration estimates, flow system analyses, investigations of soil properties, and the analysis of spring locations relative to topography and geology. Discharge measurements were taken for seventeen spring fed sites located along streams in southeastern Washington State during periods when streamflow consisted entirely of baseflow. The resultant hydrographs did not fit the expected exponential decay model, but rather exhibited distinct increases in discharge for the month of August in the absence of precipitation. Fifteen of the spring hydrographs showed this increase in discharge, the discharges of the remaining two springs neither increased nor decreased.

The successful fit of the measured recession data to the baseflow recession model with the addition of winter wheat evapotranspiration has implications relative to understanding the geologic sources of the springs. If the springs were discharging from the interflow zones between the basalt units, then evapotranspiration would not be expected to have any measurable effect on the recession curve. The interflow zone would have been too deep and the basalt unit would have been impermeable to the roots of the wheat, preventing the withdrawal of water by plants from between the basalt units. Therefore, this fit to the model of evapotranspiration and measured discharge from the springs along Union Flat Creek and South Fork of the Palouse River supports the conclusion that the flow from the springs is originating from perched water tables within the Palouse Formation. Using Equation 9, values for hydraulic conductivity were estimated based on hydrogeologic parameter values for both the loess and the basalt and they were found to be inconclusive, but they were not inconsistent with the hypothesis that the springs are discharging from a shallow flow system within the Palouse Formation.

1. Recession constants for the streams are one to two orders of magnitude larger than those determined for the springs. Based on the relationships described by Equation 9 and the larger recession constants for the streams, it can concluded that the streams gain water from different flow systems than the springs. The flow systems that discharge into Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek appear to be contained within the basalts.

Evaluation of the Palouse Formation as the source of the springs suggests that ground water flow systems in the soil discharge to form the springs. The area covering the Moscow-Pullman basin with the thickest overburden appears to be west of Ewartsville, between Union Flat Creek and the Snake River, and near Moscow, where thickness values also include the Sediments of Bovill. The thick soil particularly near Union Flat Creek allows for larger perched water tables, which can contribute to spring discharge. The sources of the springs along Union Flat Creek and the South Fork of the Palouse River are located above or very near the loess-basalt contacts, the perched water tables may form on clay deposits found by Hosterman (1960) on the tops of weathered Columbia River Basalts.

Piezometers A, B, C, D, G, and H were installed above the apparent source of the spring which feeds UFC 11 on Union Flat Creek. Piezometer G remained dry for the entire period of measurement. The recession constants derived from the water level hydrographs, which were produced from the water level measurements taken during the summer of 2001, were then compared to the recession constants for the spring at the original measurement site (UFC 11) and the apparent source of the spring. The recession constants for the piezometers were found to be three to four orders of magnitude smaller than those for the springs. These inconsistent values for recession constants are likely the result of placement of the piezometers in an aquitard supporting a different perched water table than the one that feeds the spring discharging to site UFC 11.

Specific Conclusions

- All of the springs with the exception of two showed a decrease in discharge until the end of July, and increasing discharge through August. The two spring hydrographs, UFC 11 and UFC 14, which did not show the marked increase during August, instead showed a leveling out of discharge.

- The distinct shapes of the spring hydrographs can be successfully described by a model that includes evapotranspiration by winter wheat. Increasing evapotranspiration acted to steepen the recession curves during the growing season. Decreased evapotranspiration as the wheat crop matured caused spring discharges to increase starting at the end of July until the wheat was harvested. Fifteen of the 17 hydrographs fit the accepted baseflow recession model with the addition of evapotranspiration from wheat.

- The Palouse Formation is sufficiently thick to contain water tables that exist throughout the summer. The overburden appears to be the thickest to the west of Ewartsville, between Union Flat Creek and the Snake River, and near Moscow, where thickness values also include the Sediments of Bovill. The overburden appears to thin between Moscow and Union Flat Creek.

- The spring sources are located above the top of the basalt or at the contact of the Palouse Formation and the basalt, which may be attributed to perched water table conditions created by clay deposits formed from a weathered basalt surface (Hosterman, 1960). Many of the springs, however, have been modified by tile drains to make the land surrounding the sources arable for crops.

- The recession analyses of the springs and streams support the conclusion that the springs are draining multiple small, shallow flow systems within the Palouse Formation, while Union Flat Creek, the South Fork of the Palouse River, and Fourmile Creek are draining larger flow systems contained within the Wanapum basalts. Even larger, deep flow systems also exist in the Grande Ronde, however, no apparent discharge points have been confirmed.

CHAPTER 5

RECOMMENDATIONS

More research must be pursued in order to develop a more complete conceptual model of ground water flow in the Moscow-Pullman basin. Stream discharge and precipitation measurements are important to the understanding of flow systems in the basin, as well as better estimates of hydraulic coefficients such as hydraulic conductivity and storativity. A more complete understanding of recharge and discharge mechanisms in the basin is essential to conservation of water as a resource for future generations. Included are recommendations for future work, which may aid in the future understanding of the ground water flow characteristics in the Moscow-Pullman basin.

- Perform a recession analysis on Almota Creek, Little Almota Creek, and Wawawai Creek to evaluate whether they are also discharging from shallow flow systems within the Palouse Formation or the deeper flow systems within the Wanapum, or Grande Ronde basalts.

- Conduct further research involving perched water tables within the loess and the effects of evapotranspiration on spring discharge. Paired watersheds could be used to compare vegetated and unvegetated sites. Water levels and spring discharges should be monitored and compared for several years.

- Better values for evaporation, transpiration, and stream discharges are needed to improve estimates of recharge to the Moscow-Pullman basin. Estimates from remote sensing data should be investigated for evaporation from the surface and transpiration from crops and other vegetation in the region. Some type of gaging station should also be installed on all of the major streams in the basin.

- Analysis of the expected regional flow system discharging directly into the Snake River is necessary in order to evaluate the conceptual model developed by this thesis. Geochemical analysis of water from wells near the Snake River may be able to determine the relative length of the contributing flow system.

- Investigate further the perching layers within the Palouse Formation contributing to spring discharge, using a recession analysis method based on an equation that incorporates the slope angle and determine if it improves estimates of calculated hydraulic conductivity for the loess. Alternative values and definitions for L, defined in this thesis as distance to the sub-basin divide, should also be considered.

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APPENDIX 1

Discharge Table

for

Small 60° Trapezoidal Flume

Level		Flow	
Feet	Inches	cfs	gpm
0.01	0.12	0	0
0.02	0.24	0.0001	0.03
0.03	0.36	0.0002	0.08
0.04	0.48	0.0004	0.17
0.05	0.6	0.0007	0.31
0.06	0.72	0.0011	0.49
0.07	0.84	0.0016	0.73
0.08	0.96	0.0023	1.03
0.09	1.08	0.0031	1.39
0.1	1.2	0.0041	1.83
0.11	1.32	0.0052	2.34
0.12	1.44	0.0065	2.93
0.13	1.56	0.008	3.6
0.14	1.68	0.0097	4.36
0.15	1.8	0.0116	5.21
0.16	1.92	0.0137	6.15
0.17	2.04	0.016	7.19
0.18	2.16	0.0186	8.34
0.19	2.28	0.0214	9.58
0.2	2.4	0.0244	10.94
0.21	2.52	0.0276	12.41
0.22	2.64	0.0312	13.99
0.23	2.76	0.035	15.69
0.24	2.88	0.039	17.51
0.25	3	0.0434	19.46
0.26	3.12	0.048	21.53
0.27	3.24	0.0529	23.73
0.28	3.36	0.0581	26.06
0.29	3.48	0.0636	28.53
0.3	3.6	0.0694	31.14
0.31	3.72	0.0755	33.89
0.32	3.84	0.082	36.79
0.33	3.96	0.0887	39.82
0.34	4.08	0.0958	43.01

APPENDIX 2

Calculated Evapotranspiration Estimates

	(from WSU; Station: Pullman NW)			
Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
10/1/99	68	25	20	-4
10/2/99	63	24	17	-4
10/3/99	58	27	14	-3
10/4/99	68	37	20	3
10/5/99	76	44	24	7
10/6/99	66	41	19	5
10/7/99	59	41	15	5
10/8/99	58	49	14	9
10/9/99	64	42	18	6
10/10/99	54	30	12	-1
10/11/99	60	41	16	5
10/12/99	58	45	14	7
10/13/99	63	46	17	8
10/14/99	73	32	23	0
10/15/99	54	28	12	-2
10/16/99	51	25	11	-4
10/17/99	54	33	12	1
10/18/99	60	24	16	-4
10/19/99	62	28	17	-2
10/20/99	64	35	18	2
10/21/99	69	32	21	0
10/22/99	74	46	23	8
10/23/99	74	40	23	4
10/24/99	73	48	23	9
10/25/99	58	38	14	3
10/26/99	62	44	17	7
10/27/99	48	31	9	-1
10/28/99	49	41	9	5
10/29/99	52	37	11	3
10/30/99	51	43	11	6
10/31/99	63	44	17	7
11/1/99	48	26	9	-3
11/2/99	48	32	9	0
11/3/99	52	30	11	-1
11/4/99	55	32	13	0
11/5/99	46	27	8	-3
11/6/99	48	34	9	1
11/7/99	59	50	15	10
11/8/99	65	39	18	4
11/9/99	54	38	12	3
11/10/99	52	45	11	7
11/11/99	52	42	11	6
11/12/99	56	50	13	10
11/13/99	71	42	22	6
11/14/99	67	44	19	7
11/15/99	65	45	18	7
11/16/99	52	40	11	4
11/17/99	57	38	14	3
11/18/99	42	31	6	-1
11/19/99	47	38	8	3
11/20/99	49	39	9	4
11/21/99	44	32	7	0
Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
11/22/99	34	26	1	-3
11/23/99	32	27	0	-3
11/24/99	47	33	8	1
11/25/99	48	32	9	0
11/26/99	49	44	9	7
11/27/99	45	30	7	-1
11/28/99	40	33	4	1
11/29/99	48	38	9	3
11/30/99	50	38	10	3
12/1/99	44	33	7	1
12/2/99	41	32	5	0
12/3/99	38	26	3	-3
12/4/99	38	26	3	-3
12/5/99	36	30	2	-1
12/6/99	38	31	3	-1
12/7/99	41	32	5	0
12/8/99	34	24	1	-4
12/9/99	34	30	1	-1
12/10/99	33	30	1	-1
12/11/99	35	30	2	-1
12/12/99	44	37	7	3
12/13/99	41	29	5	-2
12/14/99	32	29	0	-2
12/15/99	37	30	3	-1
12/16/99	46	36	8	2
12/17/99	46	31	8	-1
12/18/99	44	38	7	3
12/19/99	44	29	7	-2
12/20/99	36	28	2	-2
12/21/99	39	31	4	-1
12/22/99	36	28	2	-2
12/23/99	31	29	-1	-2
12/24/99	28	27	-2	-3
12/25/99	28	26	-2	-3
12/26/99	28	27	-2	-3
12/27/99	27	24	-3	-4
12/28/99	24	22	-4	-6
12/29/99	26	23	-3	-5
12/30/99	27	23	-3	-5
12/31/99	29	23	-2	-5
1/1/00	33	30	1	-1
1/2/00	31	19	-1	-7
1/3/00	26	18	-3	-8
1/4/00	32	27	0	-3
1/5/00	37	30	3	-1
1/6/00	38	20	3	-7
1/7/00	30	28	-1	-2
1/8/00	37	28	3	-2
1/9/00	37	30	3	-1
1/10/00	40	24	4	-4
1/11/00	32	28	0	-2
1/12/00	32	26	0	-3

Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
1/13/00	32	25	0	-4
1/14/00	34	30	1	-1
1/15/00	34	25	1	-4
1/16/00	42	29	6	-2
1/17/00	40	29	4	-2
1/18/00	31	28	-1	-2
1/19/00	32	25	0	-4
1/20/00	32	22	0	-6
1/21/00	31	25	-1	-4
1/22/00	32	21	0	-6
1/23/00	33	22	1	-6
1/24/00	27	22	-3	-6
1/25/00	33	28	1	-2
1/26/00	31	26	-1	-3
1/27/00	32	27	0	-3
1/28/00	33	20	1	-7
1/29/00	32	21	0	-6
1/30/00	32	20	0	-7
1/31/00	33	20	1	-7
2/1/00	37	29	3	-2
2/2/00	46	34	8	1
2/3/00	47	29	8	-2
2/4/00	43	27	6	-3
2/5/00	35	31	2	-1
2/6/00	40	30	4	-1
2/7/00	40	31	4	-1
2/8/00	48	33	9	1
2/9/00	49	30	9	-1
2/10/00	42	24	6	-4
2/11/00	44	26	7	-3
2/12/00	30	24	-1	-4
2/13/00	34	25	1	-4
2/14/00	34	30	1	-1
2/15/00	38	30	3	-1
2/16/00	38	28	3	-2
2/17/00	44	20	7	-7
2/18/00	32	22	0	-6
2/19/00	38	24	3	-4
2/20/00	40	30	4	-1
2/21/00	45	35	7	2
2/22/00	48	37	9	3
2/23/00	45	31	7	-1
2/24/00	40	30	4	-1
2/25/00	39	26	4	-3
2/26/00	41	31	5	-1
2/27/00	43	37	6	3
2/28/00	44	35	7	2
2/29/00	42	34	6	1
3/1/00	43	28	6	-2
3/2/00	49	35	9	2
3/3/00	44	34	7	1
3/4/00	49	40	9	4

Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
3/5/00	46	31	8	-1
3/6/00	36	30	2	-1
3/7/00	32	31	0	-1
3/8/00	43	30	6	-1
3/9/00	50	39	10	4
3/10/00	42	30	6	-1
3/11/00	49	33	9	1
3/12/00	42	28	6	-2
3/13/00	44	30	7	-1
3/14/00	52	32	11	0
3/15/00	45	24	7	-4
3/16/00	44	32	7	0
3/17/00	40	28	4	-2
3/18/00	35	29	2	-2
3/19/00	42	28	6	-2
3/20/00	38	20	3	-7
3/21/00	42	29	6	-2
3/22/00	48	36	9	2
3/23/00	50	30	10	-1
3/24/00	43	28	6	-2
3/25/00	50	34	10	1
3/26/00	47	29	8	-2
3/27/00	51	34	11	1
3/28/00	55	30	13	-1
3/29/00	45	29	7	-2
3/30/00	43	25	6	-4
3/31/00	49	26	9	-3
4/1/00	55	33	13	1
4/2/00	60	38	16	3
4/3/00	60	40	16	4
4/4/00	70	41	21	5
4/5/00	61	30	16	-1
4/6/00	44	32	7	0
4/7/00	44	27	7	-3
4/8/00	54	37	12	3
4/9/00	66	37	19	3
4/10/00	63	33	17	1
4/11/00	63	36	17	2
4/12/00	69	43	21	6
4/13/00	69	48	21	9
4/14/00	59	40	15	4
4/15/00	51	42	11	6
4/16/00	51	37	11	3
4/17/00	53	42	12	6
4/18/00	63	40	17	4
4/19/00	64	39	18	4
4/20/00	60	33	16	1
4/21/00	63	40	17	4
4/22/00	70	44	21	7
4/23/00	53	32	12	0
4/24/00	50	29	10	-2
4/25/00	58	38	14	3

Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
4/26/00	50	30	10	-1
4/27/00	60	44	16	7
4/28/00	76	32	24	0
4/29/00	53	31	12	-1
4/30/00	55	38	13	3
5/1/00	72	50	22	10
5/2/00	68	46	20	8
5/3/00	61	46	16	8
5/4/00	56	38	13	3
5/5/00	56	38	13	3
5/6/00	52	31	11	-1
5/7/00	56	27	13	-3
5/8/00	61	37	16	3
5/9/00	66	44	19	7
5/10/00	54	35	12	2
5/11/00	49	30	9	-1
5/12/00	50	36	10	2
5/13/00	54	39	12	4
5/14/00	64	47	18	8
5/15/00	69	41	21	5
5/16/00	71	44	22	7
5/17/00	74	46	23	8
5/18/00	65	40	18	4
5/19/00	65	47	18	8
5/20/00	68	46	20	8
5/21/00	70	54	21	12
5/22/00	75	47	24	8
5/23/00	72	50	22	10
5/24/00	67	42	19	6
5/25/00	70	45	21	7
5/26/00	66	47	19	8
5/27/00	66	47	19	8
5/28/00	63	44	17	7
5/29/00	61	39	16	4
5/30/00	65	35	18	2
5/31/00	60	37	16	3
6/1/00	54	37	12	3
6/2/00	65	48	18	9
6/3/00	69	42	21	6
6/4/00	69	40	21	4
6/5/00	79	50	26	10
6/6/00	77	49	25	9
6/7/00	69	46	21	8
6/8/00	73	50	23	10
6/9/00	55	49	13	9
6/10/00	58	42	14	6
6/11/00	55	39	13	4
6/12/00	55	49	13	9
6/13/00	63	45	17	7
6/14/00	66	50	19	10
6/15/00	76	46	24	8
6/16/00	67	36	19	2

Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
6/17/00	70	42	21	6
6/18/00	74	47	23	8
6/19/00	75	46	24	8
6/20/00	77	48	25	9
6/21/00	74	50	23	10
6/22/00	80	52	27	11
6/23/00	76	40	24	4
6/24/00	75	48	24	9
6/25/00	74	40	23	4
6/26/00	74	40	23	4
6/27/00	84	48	29	9
6/28/00	80	46	27	8
6/29/00	86	52	30	11
6/30/00	84	47	29	8
7/1/00	83	52	28	11
7/2/00	74	43	23	6
7/3/00	68	41	20	5
7/4/00	61	44	16	7
7/5/00	66	43	19	6
7/6/00	68	52	20	11
7/7/00	67	47	19	8
7/8/00	79	46	26	8
7/9/00	75	48	24	9
7/10/00	76	41	24	5
7/11/00	78	42	26	6
7/12/00	83	45	28	7
7/13/00	87	57	31	14
7/14/00	88	45	31	7
7/15/00	80	44	27	7
7/16/00	74	37	23	3
7/17/00	84	44	29	7
7/18/00	89	59	32	15
7/19/00	85	52	29	11
7/20/00	87	48	31	9
7/21/00	90	47	32	8
7/22/00	93	56	34	13
7/23/00	86	48	30	9
7/24/00	78	45	26	7
7/25/00	87	56	31	13
7/26/00	88	52	31	11
7/27/00	82	47	28	8
7/28/00	84	50	29	10
7/29/00	93	50	34	10
7/30/00	92	50	33	10
7/31/00	96	60	36	16
8/1/00	98	60	37	16
8/2/00	88	48	31	9
8/3/00	90	47	32	8
8/4/00	94	54	34	12
8/5/00	89	49	32	9
8/6/00	90	49	32	9
8/7/00	89	49	32	9

Date	T_{max} (°F)	T_{min} (°F)	T_{max} (°C)	T_{min} (°C)
8/8/00	90	47	32	8
8/9/00	94	50	34	10
8/10/00	96	50	36	10
8/11/00	87	50	31	10
8/12/00	78	36	26	2
8/13/00	80	39	27	4
8/14/00	77	43	25	6
8/15/00	80	40	27	4
8/16/00	82	38	28	3
8/17/00	84	38	29	3
8/18/00	86	51	30	11
8/19/00	78	49	26	9
8/20/00	71	41	22	5
8/21/00	70	33	21	1
8/22/00	76	39	24	4
8/23/00	86	50	30	10
8/24/00	96	67	36	19
8/25/00	90	47	32	8
8/26/00	84	52	29	11
8/27/00	72	39	22	4
8/28/00	68	32	20	0
8/29/00	76	38	24	3
8/30/00	80	52	27	11
8/31/00	78	40	26	4

Spring Source Locations		
Site	Latitude	Longitude
UFC 1	46.734	-117.301
UFC 3	46.738	-117.314
UFC 3	46.740	-117.315
UFC 5	46.707	-117.288
UFC 6	46.705	-117.287
UFC 9	46.745	-117.306
UFC 9	46.755	-117.322
UFC 11	46.763	-117.352
UFC 13	46.779	-117.350
UFC 13	46.783	-117.341
UFC 13	46.776	-117.339
UFC 14	46.778	-117.361
UFC 15	46.785	-117.363
UFC 16	46.730	-117.340
UFC 17	46.767	-117.369
UFC 17	46.764	-117.361
UFC 18	46.786	-117.374
SFPR 1	46.759	-117.209
SFPR 3	46.817	-117.259
SFPR 4	46.752	-117.193
SFPR 5	46.830	-117.247
SFPR 6	46.844	-117.191
SFPR 6	46.846	-117.190
SFPR 6	46.847	-117.187

From Allen et al., 1998:

Crop	Evapotranspiration Crop Coefficient		
	K_{cini}	K_{cmid}	K_{cend}
Winter Wheat	0.40	1.15	0.25

Crop	Length of growth stages (days)					Plant Date	Region
	Initial	Development	Middle	Late	Total		
Winter Wheat	160	75	75	25	335	October	Idaho, USA

APPENDIX 3

Spring Discharge Measurements

and

Calculated Evapotranspiration Estimates

Union Flat Creek - Site 1			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/17/00	0.0762	0.0109	0.0870
6/6/00	0.0518	0.0126	0.0644
6/13/00	0.0484	0.0091	0.0575
6/26/00	0.0308	0.0124	0.0432
7/7/00	0.0259	0.0098	0.0358
7/12/00	0.0182	0.0141	0.0323
7/21/00	0.0125	0.0155	0.0280
7/27/00	0.0118	0.0131	0.0249
8/3/00	0.0159	0.0146	0.0306
8/14/00	0.0223	0.0079	0.0301
8/21/00	0.0268	0.0046	0.0314
8/29/00	0.0300	0.0024	0.0325

Union Flat Creek - Site 3			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/17/00	0.0581	0.0156	0.0737
6/6/00	0.0390	0.0180	0.0570
6/13/00	0.0480	0.0130	0.0610
6/26/00	0.0137	0.0177	0.0314
7/7/00	0.0186	0.0141	0.0327
7/12/00	0.0097	0.0203	0.0300
7/21/00	0.0031	0.0222	0.0253
7/27/00	0.0031	0.0188	0.0219
8/3/00	0.0004	0.0210	0.0214
8/14/00	0.0023	0.0113	0.0136
8/21/00	0.0023	0.0066	0.0089
8/29/00	0.0031	0.0035	0.0066

Union Flat Creek - Site 5			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/17/00	0.0186	0.0094	0.0280
6/6/00	0.0137	0.0109	0.0246
6/13/00	0.0137	0.0079	0.0216
6/26/00	0.0052	0.0107	0.0159
7/7/00	0.0031	0.0085	0.0116
7/12/00	0.0023	0.0122	0.0145
7/21/00	0.0011	0.0134	0.0145
7/27/00	0.0007	0.0113	0.0120
8/3/00	0.0016	0.0127	0.0143
8/14/00	0.0023	0.0068	0.0091
8/21/00	0.0041	0.0040	0.0081
8/29/00	0.0041	0.0021	0.0062

Union Flat Creek - Site 6			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/17/00	0.0346	0.0153	0.0498
6/6/00	0.0249	0.0176	0.0425
6/13/00	0.0251	0.0128	0.0379
6/26/00	0.0164	0.0173	0.0337
7/7/00	0.0136	0.0138	0.0274
7/12/00	0.0110	0.0198	0.0309
7/21/00	0.0087	0.0217	0.0304
7/27/00	0.0077	0.0184	0.0261
8/3/00	0.0081	0.0205	0.0287
8/14/00	0.0092	0.0111	0.0202
8/21/00	0.0100	0.0065	0.0165
8/29/00	0.0098	0.0034	0.0132

Union Flat Creek - Site 9			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/26/00	0.0887	0.0535	0.1422
7/7/00	0.0581	0.0427	0.1008
7/12/00	0.0434	0.0612	0.1046
7/21/00	0.0276	0.0670	0.0946
7/27/00	0.0186	0.0568	0.0754
8/3/00	0.0350	0.0634	0.0984
8/14/00	0.0390	0.0341	0.0731
8/21/00	0.0390	0.0201	0.0591
8/29/00	0.0529	0.0105	0.0634

Union Flat Creek - Site 11			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/25/00	0.0186	0.0089	0.0275
6/13/00	0.0186	0.0075	0.0261
6/26/00	0.0116	0.0102	0.0218
7/7/00	0.0116	0.0082	0.0198
7/12/00	0.0097	0.0117	0.0214
7/21/00	0.0080	0.0128	0.0208
7/27/00	0.0080	0.0109	0.0189
8/3/00	0.0080	0.0121	0.0201
8/14/00	0.0080	0.0065	0.0145
8/21/00	0.0080	0.0038	0.0118
8/29/00	0.0080	0.0020	0.0100

Union Flat Creek - Site 13			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/25/00	0.1650	0.0711	0.2361
6/13/00	0.1899	0.0605	0.2504
6/26/00	0.1089	0.0823	0.1912
7/7/00	0.1008	0.0656	0.1664
7/12/00	0.0673	0.0942	0.1615
7/21/00	0.0555	0.1031	0.1585
7/27/00	0.0525	0.0873	0.1399
8/3/00	0.0608	0.0975	0.1582
8/14/00	0.0702	0.0524	0.1226
8/21/00	0.0827	0.0308	0.1136
8/29/00	0.0842	0.0161	0.1003

Union Flat Creek - Site 14			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/13/00	0.0390	0.0036	0.0426
6/26/00	0.0350	0.0050	0.0400
7/7/00	0.0350	0.0039	0.0389
7/12/00	0.0350	0.0057	0.0407
7/21/00	0.0312	0.0062	0.0374
7/27/00	0.0312	0.0053	0.0365
8/3/00	0.0312	0.0059	0.0371
8/14/00	0.0312	0.0032	0.0344
8/21/00	0.0312	0.0019	0.0331
8/29/00	0.0312	0.0010	0.0322

Union Flat Creek - Site 15			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/25/00	0.0581	0.0385	0.0966
6/13/00	0.0694	0.0328	0.1022
6/26/00	0.0390	0.0446	0.0836
7/7/00	0.0434	0.0355	0.0789
7/12/00	0.0312	0.0510	0.0822
7/21/00	0.0244	0.0558	0.0802
7/27/00	0.0244	0.0473	0.0717
8/3/00	0.0350	0.0528	0.0878
8/14/00	0.0390	0.0284	0.0674
8/21/00	0.0434	0.0167	0.0601
8/29/00	0.0480	0.0087	0.0567

Union Flat Creek - Site 16			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/26/00	0.0694	0.0300	0.0994
7/7/00	0.0636	0.0239	0.0875
7/12/00	0.0390	0.0343	0.0733
7/21/00	0.0312	0.0375	0.0687
7/27/00	0.0244	0.0318	0.0562
8/3/00	0.0214	0.0355	0.0569
8/14/00	0.0186	0.0191	0.0377
8/21/00	0.0186	0.0112	0.0298
8/29/00	0.0214	0.0059	0.0273

Union Flat Creek - Site 17			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/13/00	0.0480	0.0131	0.0611
6/26/00	0.0276	0.0178	0.0454
7/7/00	0.0276	0.0141	0.0417
7/12/00	0.0186	0.0203	0.0389
7/21/00	0.0186	0.0222	0.0408
7/27/00	0.0160	0.0188	0.0348
8/3/00	0.0186	0.0210	0.0396
8/14/00	0.0186	0.0113	0.0299
8/21/00	0.0244	0.0067	0.0311
8/29/00	0.0244	0.0035	0.0279

Union Flat Creek - Site 18			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/13/00	0.0390	0.0072	0.0462
6/26/00	0.0276	0.0099	0.0375
7/7/00	0.0244	0.0079	0.0323
7/12/00	0.0214	0.0113	0.0327
7/21/00	0.0186	0.0123	0.0309
7/27/00	0.0186	0.0104	0.0290
8/3/00	0.0214	0.0117	0.0331
8/14/00	0.0214	0.0063	0.0277
8/21/00	0.0244	0.0037	0.0281
8/29/00	0.0244	0.0019	0.0263

South Fork of the Palouse River - Site 1			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/23/00	0.0694	0.0254	0.0948
6/7/00	0.0694	0.0251	0.0945
6/14/00	0.0755	0.0221	0.0976
6/27/00	0.0312	0.0347	0.0659
7/10/00	0.0214	0.0298	0.0512
7/13/00	0.0214	0.0308	0.0522
7/20/00	0.0160	0.0349	0.0509
7/26/00	0.0137	0.0342	0.0479
8/2/00	0.0116	0.0336	0.0452
8/10/00	0.0097	0.0308	0.0405
8/15/00	0.0116	0.0189	0.0305
8/22/00	0.0137	0.0114	0.0251
8/31/00	0.0160	0.0000	0.0160

South Fork of the Palouse River - Site 3			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/23/00	0.0755	0.0143	0.0898
6/7/00	0.0581	0.0142	0.0723
6/14/00	0.0636	0.0125	0.0761
6/27/00	0.0312	0.0196	0.0508
7/10/00	0.0244	0.0168	0.0412
7/13/00	0.0186	0.0174	0.0360
7/20/00	0.0116	0.0197	0.0313
7/26/00	0.0065	0.0193	0.0258
8/2/00	0.0065	0.0190	0.0255
8/10/00	0.0065	0.0174	0.0239
8/15/00	0.0097	0.0107	0.0204
8/22/00	0.0116	0.0064	0.0180
8/31/00	0.0137	0.0000	0.0137

South Fork of the Palouse River - Site 4			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
5/23/00	0.0377	0.0118	0.0495
6/7/00	0.0468	0.0117	0.0586
6/14/00	0.0489	0.0103	0.0592
6/27/00	0.0185	0.0162	0.0347
7/10/00	0.0119	0.0139	0.0258
7/13/00	0.0089	0.0144	0.0233
7/20/00	0.0054	0.0163	0.0217
7/26/00	0.0043	0.0160	0.0202
8/2/00	0.0039	0.0157	0.0196
8/10/00	0.0042	0.0144	0.0186
8/15/00	0.0044	0.0088	0.0132
8/22/00	0.0048	0.0053	0.0101
8/31/00	0.0050	0.0000	0.0050

South Fork of the Palouse River - Site 5			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/7/00	0.0244	0.0078	0.0322
6/14/00	0.0244	0.0068	0.0312
6/27/00	0.0137	0.0107	0.0244
7/10/00	0.0137	0.0092	0.0229
7/13/00	0.0097	0.0095	0.0192
7/20/00	0.0065	0.0108	0.0173
7/26/00	0.0065	0.0106	0.0171
8/2/00	0.0080	0.0104	0.0184
8/10/00	0.0080	0.0095	0.0175
8/15/00	0.0080	0.0059	0.0139
8/22/00	0.0097	0.0035	0.0132
8/31/00	0.0097	0.0000	0.0097

South Fork of the Palouse River - Site 6			
Date	Measured Discharge (cfs)	Calculated Evapotranspiration (cfs)	Total (cfs)
6/7/00	0.0758	0.0225	0.0983
6/14/00	0.0741	0.0198	0.0939
6/27/00	0.0504	0.0311	0.0815
7/10/00	0.0456	0.0267	0.0723
7/13/00	0.0423	0.0276	0.0699
7/20/00	0.0381	0.0313	0.0694
7/26/00	0.0359	0.0307	0.0666
8/2/00	0.0322	0.0301	0.0623
8/10/00	0.0333	0.0276	0.0609
8/15/00	0.0333	0.0170	0.0502
8/22/00	0.0344	0.0102	0.0446
8/31/00	0.0336	0.0000	0.0336

APPENDIX 4

Estimates of Overburden Thickness by Location

Longitude (west)	Latitude (north)	overburden thickness (ft)	Longitude (west)	Latitude (north)	overburden thickness (ft)	Longitude (west)	Latitude (north)	overburden thickness (ft)
-117.1248	46.5457	27	-117.2205	46.7275	90	-117.1767	46.7319	16
-117.1553	46.5551	79	-117.2300	46.7245	13	-117.1781	46.7348	10
-117.1678	46.5419	21	-117.2233	46.7347	26	-117.1790	46.7307	15
-117.1279	46.5350	46	-117.2553	46.7200	176	-117.1759	46.7310	21
-117.1650	46.5105	10	-117.2580	46.7283	74	-117.1684	46.7289	5
-117.1338	46.5112	17	-117.3000	46.7295	4	-117.1789	46.7324	22
-117.1381	46.5052	15	-117.3182	46.7309	6	-117.1778	46.7308	10
-117.1378	46.5059	62	-117.2638	46.7116	10	-117.1777	46.7306	12
-117.1338	46.5071	12	-117.2155	46.7109	125	-117.1729	46.7288	13
-117.0906	46.5437	21	-117.2032	46.7000	50	-117.1694	46.7287	15
-117.0862	46.5315	18	-117.2292	46.6945	31	-117.1684	46.7319	13
-117.0803	46.4698	47	-117.2301	46.7021	25	-117.1685	46.7321	0
-117.3745	46.6367	12	-117.2405	46.6931	76	-117.1761	46.7340	0
-117.3755	46.6305	3	-117.2426	46.6910	30	-117.1982	46.7351	5
-117.3384	46.6264	13	-117.2424	46.6930	80	-117.1966	46.7351	28
-117.3448	46.6314	12	-117.2775	46.6983	19	-117.1991	46.7335	10
-117.3442	46.6314	20	-117.2746	46.6921	35	-117.1934	46.7317	6
-117.2721	46.6330	14	-117.2747	46.6919	23	-117.1973	46.7123	7
-117.2944	46.6249	12	-117.3021	46.7033	15	-117.1970	46.7128	20
-117.2328	46.6266	17	-117.2990	46.6777	36	-117.1947	46.7128	15
-117.2168	46.6187	13	-117.2811	46.6837	3	-117.1947	46.7134	11
-117.2295	46.6049	32	-117.2875	46.6901	13	-117.1926	46.7154	12
-117.2909	46.5833	16	-117.2698	46.6835	14	-117.1815	46.7142	5
-117.1383	46.6318	36	-117.2047	46.6812	64	-117.1962	46.7124	17
-117.1379	46.6366	30	-117.2609	46.6614	19	-117.1991	46.7118	30
-117.1269	46.6320	40	-117.3015	46.6643	29	-117.1996	46.7085	14
-117.1931	46.6176	30	-117.3065	46.6744	37	-117.1920	46.7146	29
-117.1735	46.6302	40	-117.3045	46.6696	48	-117.1626	46.7187	20
-117.1325	46.6212	50	-117.2614	46.6610	19	-117.1629	46.7110	20
-117.1383	46.6272	27	-117.2254	46.6603	14	-117.1720	46.7098	44
-117.1406	46.6307	60	-117.0878	46.7300	12	-117.1531	46.7137	3
-117.1411	46.6311	60	-117.0925	46.7238	60	-117.1571	46.7139	14
-117.1361	46.6302	45	-117.0949	46.7199	49	-117.1472	46.7102	72
-117.1220	46.6186	82	-117.1082	46.7291	2	-117.1232	46.7052	56
-117.1743	46.5996	21	-117.1074	46.7285	18	-117.1085	46.7048	35
-117.1657	46.6021	5	-117.0963	46.7303	2	-117.1253	46.6953	12
-117.0841	46.5865	54	-117.1055	46.7284	3	-117.1347	46.6936	23
-117.1529	46.5753	10	-117.0998	46.7272	4	-117.1193	46.6915	2
-117.1805	46.5770	31	-117.0987	46.7196	69	-117.1237	46.7044	90
-117.1881	46.5809	13	-117.1172	46.7285	11	-117.1237	46.7044	90
-117.1272	46.5711	23	-117.1223	46.7282	8	-117.1477	46.6922	7
-117.3431	46.7201	55	-117.1568	46.7222	6	-117.1554	46.6912	10
-117.4187	46.7284	170	-117.1435	46.7226	8	-117.1558	46.6908	0
-117.4419	46.7228	18	-117.1458	46.7195	50	-117.1460	46.6962	14
-117.4474	46.6842	65	-117.1400	46.7272	7	-117.1403	46.6916	4
-117.4178	46.6835	124	-117.1465	46.7226	8	-117.1569	46.7010	20
-117.3664	46.6860	50	-117.1446	46.7209	12	-117.1404	46.6958	1
-117.3378	46.6763	13	-117.1575	46.7338	21	-117.1757	46.6850	17

Longitude (west)	Latitude (north)	overburden thickness (ft)	Longitude (west)	Latitude (north)	overburden thickness (ft)	Longitude (west)	Latitude (north)	overburden thickness (ft)
-117.2219	46.7285	64	-117.2233	46.7630	18	-117.1082	46.7451	12
-117.1699	46.7296	23	-117.2754	46.7548	45	-117.0763	46.7480	9
-117.1585	46.6886	8	-117.2733	46.7496	6	-117.0521	46.7514	55
-117.1281	46.6773	13	-117.2728	46.7492	7	-117.0701	46.7524	61
-117.1023	46.6889	11	-117.2419	46.7455	16	-117.0555	46.7398	18
-117.0986	46.6782	46	-117.2422	46.7438	16	-117.0493	46.7368	4
-117.0845	46.6826	8	-117.2373	46.7551	5	-117.3364	46.9176	2
-117.0972	46.6715	35	-117.2295	46.7586	5	-117.3776	46.9114	38
-117.1518	46.6692	7	-117.2260	46.7600	3	-117.4444	46.8909	56
-117.1470	46.6704	5	-117.2004	46.7353	33	-117.4136	46.8999	13
-117.1453	46.6700	12	-117.2008	46.7405	27	-117.3840	46.8881	8
-117.0448	46.7248	14	-117.1044	46.8146	106	-117.3874	46.8870	8
-117.0464	46.7295	104	-117.1788	46.8150	14	-117.3572	46.8942	0
-117.0552	46.7191	50	-117.1817	46.8163	8	-117.3682	46.8915	18
-117.0576	46.7136	160	-117.1823	46.7943	85	-117.3692	46.8918	10
-117.0665	46.7086	14	-117.1801	46.7948	132	-117.3570	46.8946	25
-117.0585	46.7139	21	-117.1757	46.7985	45	-117.3323	46.8996	17
-117.0683	46.7077	12	-117.1690	46.7994	25	-117.3473	46.8883	14
-117.0427	46.6997	8	-117.1757	46.7988	21	-117.3324	46.8969	24
-117.0475	46.6979	9	-117.1407	46.7951	54	-117.3545	46.8822	5
-117.0456	46.6646	15	-117.1462	46.8053	65	-117.3506	46.8846	21
-117.4322	46.8115	15	-117.1288	46.8036	38	-117.3681	46.8737	28
-117.4061	46.7972	11	-117.1034	46.7806	0	-117.3719	46.8854	31
-117.3903	46.7843	6	-117.1150	46.7879	12	-117.3879	46.8854	6
-117.3966	46.7882	6	-117.1153	46.7844	45	-117.3896	46.8852	10
-117.3990	46.7943	12	-117.1478	46.7915	41	-117.3933	46.8856	12
-117.3990	46.7941	16	-117.1862	46.7857	52	-117.3964	46.8760	56
-117.4229	46.7842	120	-117.1889	46.7808	45	-117.4413	46.8810	73
-117.4041	46.7808	51	-117.1335	46.7710	3	-117.4470	46.8775	57
-117.3556	46.7712	9	-117.0921	46.7635	56	-117.4342	46.8622	69
-117.3557	46.7712	9	-117.1050	46.7563	74	-117.4348	46.8629	44
-117.3420	46.7599	8	-117.1403	46.7566	41	-117.4353	46.8663	51
-117.3513	46.7624	10	-117.1707	46.7508	16	-117.4269	46.8595	34
-117.4509	46.7575	21	-117.1666	46.7594	9	-117.4138	46.8579	30
-117.2042	46.8202	6	-117.1676	46.7587	34	-117.4077	46.8419	80
-117.2070	46.8159	15	-117.1668	46.7583	22	-117.4277	46.8534	39
-117.2219	46.8132	35	-117.1591	46.7622	0	-117.3966	46.8281	38
-117.2578	46.8117	29	-117.1601	46.7622	33	-117.2221	46.9120	18
-117.2878	46.7993	40	-117.1861	46.7600	60	-117.2786	46.9117	23
-117.2631	46.7893	38	-117.1984	46.7398	29	-117.3078	46.9111	12
-117.2742	46.7836	72	-117.1962	46.7425	19	-117.3059	46.8984	119
-117.2756	46.7845	73	-117.1719	46.7473	0	-117.2270	46.8766	34
-117.2871	46.7825	13	-117.1728	46.7390	3	-117.2975	46.8725	16
-117.2760	46.7765	113	-117.1788	46.7367	22	-117.3225	46.8837	21
-117.2853	46.7777	10	-117.1436	46.7421	91	-117.3227	46.8621	7
-117.2376	46.7778	18	-117.1566	46.7425	8	-117.2933	46.8655	5
-117.2127	46.7566	10	-117.1252	46.7398	11	-117.2525	46.8622	80
-117.2203	46.7580	25	-117.1188	46.7433	34	-117.2175	46.8641	31

Longitude (west)	Latitude (north)	overburden thickness (ft)
-117.2022	46.8455	48
-117.2203	46.8385	20
-117.2580	46.8522	20
-117.2865	46.8480	10
-117.3146	46.8557	41
-117.2815	46.8258	11
-117.2376	46.8308	15
-117.2148	46.8298	12
-117.2036	46.8331	33
-117.0740	46.9006	34
-117.0963	46.9156	6
-117.1155	46.9173	21
-117.1257	46.8959	30
-117.0740	46.8881	58
-117.1486	46.8767	143
-117.1613	46.8804	110
-117.1290	46.8579	11
-117.1189	46.8594	14
-117.0929	46.8495	25
-117.0933	46.8478	27
-117.1163	46.8390	0
-117.1494	46.8454	5
-117.1895	46.8401	11
-117.1565	46.8325	17
-117.1391	46.8273	13
-117.0440	46.9166	0
-117.0639	46.9162	25
-117.0601	46.9103	20
-117.0295	46.7350	10
-117.0239	46.7318	10
-117.0241	46.7316	15
-117.0240	46.7318	12
-117.0238	46.7318	10
-117.0239	46.7315	12
-117.0241	46.7320	16
-117.0287	46.7379	80
-117.0260	46.7298	62
-117.0257	46.7296	70
-117.0325	46.7214	108
-117.0308	46.7226	78
-117.0323	46.7173	91
-117.0333	46.7180	124
-117.0354	46.7189	141
-117.0232	46.7141	9
-117.0099	46.7628	85
-116.9590	46.7717	132
-116.9688	46.7657	145
-117.0283	46.8363	133
-117.0376	46.8298	19
-117.3401	46.7578	0
-117.3325	46.7437	0
-117.3468	46.7660	0
-117.3418	46.7613	0
-117.3610	46.7727	0
-117.3731	46.7774	0
-117.3921	46.7854	0
-117.3988	46.7889	0
-117.4129	46.8006	0
-117.4218	46.8053	0
-117.4309	46.8099	0
-117.4463	46.8140	0
-117.1968	46.7463	0
-117.2133	46.7537	0
-117.2112	46.7524	0
-117.2260	46.7612	0
-117.2312	46.7714	0
-117.2459	46.7853	0
-117.2623	46.7917	0
-117.2565	46.8032	0
-117.2574	46.8096	0
-117.2660	46.8132	0
-117.2721	46.8237	0
-117.2720	46.8236	0
-117.2791	46.8345	0
-117.2808	46.8458	0
-117.2868	46.8588	0
-117.3023	46.8709	0
-117.3126	46.8623	0
-117.3328	46.8696	0
-117.3453	46.8754	0

APPENDIX 5

Piezometer Locations,

Water Level Data,

and

UFC 11 Spring Discharge Data

(Summer 2001)

	Depth to Water from top of the Piezometer (ft)				
Date	Piezometer A	Piezometer B	Piezometer C	Piezometer D	Piezometer H
6/5/01	5.785	9.77	6.21	6.71	-
6/13/01	5.72	9.23	6.24	6.73	7.83
6/18/01	5.73	9.105	6.27	6.765	7.865
6/25/01	5.74	8.99	6.34	6.79	7.95
6/26/01	5.75	9.01	6.355	6.78	7.95
6/27/01	5.77	9	6.37	6.78	7.92
6/28/01	5.77	8.99	6.39	6.79	7.91
7/9/01	5.81	8.94	6.44	6.87	8.12
7/17/01	-	-	-	-	-
7/18/01	5.87	8.9	6.47	6.87	8.19
7/25/01	5.9	8.9	6.51	6.91	8.32
8/1/01	5.93	8.89	6.54	6.93	8.39
8/5/01	5.97	8.89	6.57	6.94	8.52
8/14/01	6.04	8.89	6.61	7.02	9.39

Date	UFC 1 -@ source	UFC 11-@ old site
6/5/01	-	-
6/13/01	0.0137	0.0137
6/18/01	0.0116	0.0116
6/25/01	0.0116	0.0116
6/26/01	0.0116	-
6/27/01	0.0116	-
6/28/01	0.0116	-
7/9/01	0.0097	0.008
7/17/01	0.0097	0.0097
7/18/01	-	-
7/25/01	0.0097	0.008
8/1/01	0.0097	0.0097
8/5/01	0.0097	0.008
8/14/01	0.008	0.0065

		Water Level Elevations (ft)				
Date	Days	Piezometer A	Piezometer B	Piezometer C	Piezometer D	Piezometer H
6/5/01		2320.93	2321.14	2324.20	2321.35	-
6/13/01	0	2320.99	2321.68	2324.17	2321.33	2320.14
6/18/01	5	2320.98	2321.81	2324.14	2321.29	2320.11
6/25/01	12	2320.97	2321.92	2324.07	2321.27	2320.02
6/26/01	13	2320.96	2321.90	2324.05	2321.28	2320.02
6/27/01	14	2320.94	2321.91	2324.04	2321.28	2320.05
6/28/01	15	2320.94	2321.92	2324.02	2321.27	2320.06
7/9/01	26	2320.90	2321.97	2323.97	2321.19	2319.85
7/18/01	35	2320.84	2322.01	2323.94	2321.19	2319.78
7/25/01	42	2320.81	2322.01	2323.90	2321.15	2319.65
8/1/01	49	2320.78	2322.02	2323.87	2321.13	2319.58
8/5/01	53	2320.74	2322.02	2323.84	2321.12	2319.45
8/14/01	62	2320.67	2322.02	2323.80	2321.04	2318.58

Adjusted Geodetic Coordinates and Water Level Reference Elevations:
Site 11 Field Area
6/18/01

Location	Latitude (degrees)	Longitude (degrees)	Ground Surface Elevation m	Ground Surface Elevation ft	Height of Piezometer m
Piezometer A	46.76254750	-117.35204894	708.946	2326.05	0.202
Piezometer B	46.76248605	-117.35217744	709.786	2328.81	0.641
Piezometer C	46.76245325	-117.35203782	709.629	2328.29	0.645
Piezometer D	46.76251692	-117.35204948	709.248	2327.04	0.309
Piezometer G	46.76255014	-117.35204955	708.835	2325.69	0.913
Piezometer H	46.76254953	-117.35204393	708.894	2325.88	0.638
Spring Source	46.76264559	-117.35196003	706.828	2319.10	N/A
Site 11 (old site)	46.76312770	-117.35082530	700.460	2298.21	N/A

Location	Height of Piezometer ft	Water Level Reference Elevation m	Water Level Reference Elevation ft
Piezometer A	0.66	709.148	2326.71
Piezometer B	2.10	710.427	2330.91
Piezometer C	2.12	710.274	2330.41
Piezometer D	1.01	709.557	2328.06
Piezometer G	3.00	709.748	2328.68
Piezometer H	2.09	709.532	2327.97
Spring Source	N/A	N/A	N/A
Site 11 (old site)	N/A	N/A	N/A

APPENDIX 6

Historical Discharge Data from USGS Gaging Stations

South Fork of the Palouse River at Pullman		South Fork of the Palouse River at Pullman		South Fork of the Palouse River at Pullman		South Fork of the Palouse River at Pullman		South Fork of the Palouse River at Pullman		South Fork of the Palouse River at Pullman	
date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)
7/1/60	2.9	8/1/60	6.3	7/1/63	2.7	8/1/63	1.9	7/1/69	6	8/1/69	3.4
7/2/60	2.8	8/2/60	8.4	7/2/63	2.7	8/2/63	1.9	7/2/69	5.4	8/2/69	3.3
7/3/60	2.7	8/3/60	4.5	7/3/63	3	8/3/63	1.9	7/3/69	5.3	8/3/69	3
7/4/60	2.6	8/4/60	3	7/4/63	2.8	8/4/63	1.6	7/4/69	4.8	8/4/69	3.1
7/5/60	2.6	8/5/60	2.6	7/5/63	2.4	8/5/63	1.6	7/5/69	4.2	8/5/69	3.2
7/6/60	2.5	8/6/60	2.3	7/6/63	2.4	8/6/63	1.6	7/6/69	4.2	8/6/69	3
7/7/60	2.4	8/7/60	2	7/7/63	2.2	8/7/63	1.3	7/7/69	4.2	8/7/69	3
7/8/60	2.3	8/8/60	1.8	7/8/63	2.7	8/8/63	1.3	7/8/69	4.6	8/8/69	3.2
7/9/60	2.2	8/9/60	1.8	7/9/63	3.2	8/9/63	1.4	7/9/69	4.3	8/9/69	3.1
7/10/60	2.2	8/10/60	1.8	7/10/63	3	8/10/63	1.6	7/10/69	3.8	8/10/69	2.9
7/11/60	2.1	8/11/60	1.8	7/11/63	3.2	8/11/63	1.9	7/11/69	4.4	8/11/69	2.7
7/12/60	2	8/12/60	1.6	7/12/63	2.7	8/12/63	1.9	7/12/69	4	8/12/69	3
7/13/60	1.9	8/13/60	1.4	7/13/63	2.7	8/13/63	3	7/13/69	4.3	8/13/69	3
7/14/60	1.8	8/14/60	1.4	7/14/63	2.4	8/14/63	1.9	7/14/69	3.7	8/14/69	3.1
7/15/60	1.7	8/15/60	1.4	7/15/63	1.9	8/15/63	1.8	7/15/69	3.7	8/15/69	3
7/16/60	1.6	8/16/60	1.5	7/16/63	1.9	8/16/63	1.8	7/16/69	4.1	8/16/69	3
7/17/60	1.5	8/17/60	1.3	7/17/63	1.9	8/17/63	1.6	7/17/69	3.4	8/17/69	2.9
7/18/60	1.4	8/18/60	1.2	7/18/63	1.8	8/18/63	1.6	7/18/69	3.1	8/18/69	2.8
7/19/60	1.4	8/19/60	1.2	7/19/63	2	8/19/63	1.4	7/19/69	2.9	8/19/69	3.1
7/20/60	1.3	8/20/60	1.2	7/20/63	2	8/20/63	1.4	7/20/69	2.7	8/20/69	3
7/21/60	1.3	8/21/60	1	7/21/63	1.8	8/21/63	1.6	7/21/69	2.5	8/21/69	3
7/22/60	1.3	8/22/60	1.2	7/22/63	1.6	8/22/63	1.8	7/22/69	2.8	8/22/69	3.2
7/23/60	1.3	8/23/60	1.6	7/23/63	1.8	8/23/63	2.4	7/23/69	3	8/23/69	3.2
7/24/60	1.2	8/24/60	1.9	7/24/63	1.9	8/24/63	2.4	7/24/69	2.9	8/24/69	3.2
7/25/60	1.2	8/25/60	1.9	7/25/63	2	8/25/63	2.8	7/25/69	2.9	8/25/69	2.9
7/26/60	1.2	8/26/60	1.8	7/26/63	2	8/26/63	1.4	7/26/69	2.9	8/26/69	3.1
7/27/60	1.2	8/27/60	1.6	7/27/63	2	8/27/63	1.6	7/27/69	3	8/27/69	3.2
7/28/60	1.2	8/28/60	1.8	7/28/63	1.8	8/28/63	1.6	7/28/69	2.9	8/28/69	3.2
7/29/60	1.2	8/29/60	1.5	7/29/63	1.6	8/29/63	1.6	7/29/69	3.3	8/29/69	3.4
7/30/60	1.3	8/30/60	1.8	7/30/63	1.9	8/30/63	1.8	7/30/69	3.2	8/30/69	3.7
7/31/60	1.5	8/31/60	1.5	7/31/63	1.8	8/31/63	1.8	7/31/69	3.2	8/31/69	3.3

South Fork of the Palouse River at Colfax		South Fork of the Palouse River at Colfax		South Fork of the Palouse River at Colfax		South Fork of the Palouse River at Colfax		South Fork of the Palouse River at Colfax		South Fork of the Palouse River at Colfax	
date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)
7/1/93	13	8/1/93	14	7/1/94	7.7	8/1/94	2.3	7/1/95	8.8	8/1/95	6.6
7/2/93	13	8/2/93	13	7/2/94	7	8/2/94	2	7/2/95	8.2	8/2/95	6.9
7/3/93	14	8/3/93	12	7/3/94	6.3	8/3/94	2	7/3/95	13	8/3/95	6
7/4/93	15	8/4/93	11	7/4/94	5.8	8/4/94	2.6	7/4/95	18	8/4/95	5.5
7/5/93	16	8/5/93	10	7/5/94	5.6	8/5/94	4.2	7/5/95	12	8/5/95	6.5
7/6/93	14	8/6/93	10	7/6/94	7.6	8/6/94	2.7	7/6/95	10	8/6/95	4.5
7/7/93	15	8/7/93	9.5	7/7/94	6	8/7/94	2.7	7/7/95	11	8/7/95	5.9
7/8/93	13	8/8/93	9	7/8/94	7.2	8/8/94	2.3	7/8/95	9	8/8/95	27
7/9/93	12	8/9/93	8	7/9/94	6.5	8/9/94	2	7/9/95	7.8	8/9/95	12
7/10/93	11	8/10/93	7.5	7/10/94	5.6	8/10/94	2.9	7/10/95	7.3	8/10/95	8.4
7/11/93	10	8/11/93	7.5	7/11/94	4.8	8/11/94	3.2	7/11/95	9.5	8/11/95	7.5
7/12/93	10	8/12/93	7	7/12/94	5	8/12/94	4.1	7/12/95	7.3	8/12/95	8.1
7/13/93	15	8/13/93	8	7/13/94	5.4	8/13/94	4.3	7/13/95	6.8	8/13/95	8.6
7/14/93	20	8/14/93	7.6	7/14/94	5.1	8/14/94	4	7/14/95	6.7	8/14/95	12
7/15/93	25	8/15/93	7.9	7/15/94	5.2	8/15/94	3.8	7/15/95	6.6	8/15/95	10
7/16/93	35	8/16/93	11	7/16/94	5.7	8/16/94	3.7	7/16/95	6.6	8/16/95	16
7/17/93	45	8/17/93	11	7/17/94	5.5	8/17/94	4.8	7/17/95	6.6	8/17/95	14
7/18/93	38	8/18/93	13	7/18/94	5.5	8/18/94	5.4	7/18/95	6.6	8/18/95	12
7/19/93	29	8/19/93	13	7/19/94	5.3	8/19/94	5.6	7/19/95	6.8	8/19/95	12
7/20/93	30	8/20/93	14	7/20/94	5.3	8/20/94	6	7/20/95	7	8/20/95	12
7/21/93	32	8/21/93	13	7/21/94	4.8	8/21/94	6	7/21/95	7.2	8/21/95	11
7/22/93	36	8/22/93	13	7/22/94	4	8/22/94	6	7/22/95	7.5	8/22/95	11
7/23/93	29	8/23/93	12	7/23/94	4.1	8/23/94	6.2	7/23/95	7.5	8/23/95	11
7/24/93	27	8/24/93	12	7/24/94	3.1	8/24/94	6.4	7/24/95	7.4	8/24/95	12
7/25/93	24	8/25/93	14	7/25/94	2.3	8/25/94	6.6	7/25/95	8	8/25/95	11
7/26/93	22	8/26/93	13	7/26/94	1.8	8/26/94	7	7/26/95	8.2	8/26/95	12
7/27/93	20	8/27/93	11	7/27/94	2.3	8/27/94	7.4	7/27/95	8.8	8/27/95	12
7/28/93	19	8/28/93	11	7/28/94	2.1	8/28/94	7.8	7/28/95	8.2	8/28/95	12
7/29/93	17	8/29/93	18	7/29/94	2.4	8/29/94	8	7/29/95	7.1	8/29/95	12
7/30/93	16	8/30/93	14	7/30/94	2.4	8/30/94	7.4	7/30/95	6	8/30/95	12
7/31/93	15	8/31/93	10	7/31/94	3	8/31/94	8	7/31/95	6.2	8/31/95	13

Union Flat Creek near Colfax		Union Flat Creek near Colfax		Union Flat Creek near Colfax		Union Flat Creek near Colfax		Union Flat Creek near Colfax		Union Flat Creek near Colfax	
date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)
7/1/63	2.6	8/1/63	0.1	7/1/69	5.9	8/1/69	3.1	7/1/70	9.2	8/1/70	3.8
7/2/63	2.4	8/2/63	0.1	7/2/69	5.4	8/2/69	2.2	7/2/70	8.2	8/2/70	3.8
7/3/63	2.2	8/3/63	0.1	7/3/69	5	8/3/69	2.5	7/3/70	7.2	8/3/70	3.4
7/4/63	2	8/4/63	0.1	7/4/69	4.5	8/4/69	2.5	7/4/70	6.3	8/4/70	3.1
7/5/63	1.6	8/5/63	0.1	7/5/69	4.5	8/5/69	2.2	7/5/70	5.9	8/5/70	3.1
7/6/63	1.2	8/6/63	0	7/6/69	4.5	8/6/69	3.1	7/6/70	5.1	8/6/70	2.8
7/7/63	1	8/7/63	0	7/7/69	4.2	8/7/69	2.8	7/7/70	5.1	8/7/70	2.8
7/8/63	1	8/8/63	0	7/8/69	4.2	8/8/69	2.5	7/8/70	4.8	8/8/70	2.6
7/9/63	1	8/9/63	0	7/9/69	3.8	8/9/69	2.5	7/9/70	4.8	8/9/70	2.3
7/10/63	1	8/10/63	0	7/10/69	3.1	8/10/69	2.5	7/10/70	4.4	8/10/70	2.3
7/11/63	1	8/11/63	0	7/11/69	2.5	8/11/69	2.2	7/11/70	4.1	8/11/70	2.3
7/12/63	0.8	8/12/63	8.7	7/12/69	2.2	8/12/69	1.4	7/12/70	4.1	8/12/70	2.3
7/13/63	0.8	8/13/63	0.8	7/13/69	1.9	8/13/69	1.4	7/13/70	6.8	8/13/70	2.1
7/14/63	0.8	8/14/63	0.4	7/14/69	2.5	8/14/69	1.7	7/14/70	6.8	8/14/70	1.8
7/15/63	0.7	8/15/63	0.1	7/15/69	2.5	8/15/69	1.4	7/15/70	7.7	8/15/70	1.8
7/16/63	0.7	8/16/63	0.1	7/16/69	2.8	8/16/69	1	7/16/70	6.3	8/16/70	1.8
7/17/63	0.6	8/17/63	0	7/17/69	2.6	8/17/69	1	7/17/70	5.1	8/17/70	1.8
7/18/63	0.6	8/18/63	0	7/18/69	2.5	8/18/69	1.2	7/18/70	4.1	8/18/70	1.6
7/19/63	0.6	8/19/63	0	7/19/69	2.5	8/19/69	1	7/19/70	4.1	8/19/70	1.8
7/20/63	0.4	8/20/63	0	7/20/69	2.2	8/20/69	0.63	7/20/70	3.8	8/20/70	1.8
7/21/63	0.4	8/21/63	0	7/21/69	2.2	8/21/69	1.2	7/21/70	3.4	8/21/70	1.8
7/22/63	0.4	8/22/63	0	7/22/69	2.2	8/22/69	1	7/22/70	3.1	8/22/70	1.8
7/23/63	0.4	8/23/63	0	7/23/69	2.5	8/23/69	0.81	7/23/70	2.8	8/23/70	1.8
7/24/63	0.4	8/24/63	0	7/24/69	2.8	8/24/69	0.81	7/24/70	2.8	8/24/70	1.8
7/25/63	0.4	8/25/63	0	7/25/69	2.2	8/25/69	0.35	7/25/70	3.1	8/25/70	1.6
7/26/63	0.4	8/26/63	0	7/26/69	2.5	8/26/69	0.47	7/26/70	3.1	8/26/70	1.6
7/27/63	0.3	8/27/63	0	7/27/69	2.8	8/27/69	0.12	7/27/70	3.4	8/27/70	1.6
7/28/63	0.3	8/28/63	0	7/28/69	3.1	8/28/69	0.18	7/28/70	5.1	8/28/70	1.4
7/29/63	0.2	8/29/63	0	7/29/69	2.8	8/29/69	0.63	7/29/70	7.7	8/29/70	1.6
7/30/63	0.1	8/30/63	0	7/30/69	2.8	8/30/69	0.81	7/30/70	4.4	8/30/70	1.6
7/31/63	0.1	8/31/63	0.1	7/31/69	2.5	8/31/69	1	7/31/70	4.1	8/31/70	1.8

Fourmile Creek at Shawnee		Fourmile Creek at Shawnee		Fourmile Creek at Shawnee	
date	discharge (cfs)	date	discharge (cfs)	date	discharge (cfs)
7/1/37	0.32	7/1/38	0.08	7/1/39	0.01
7/2/37	0.23	7/2/38	0.08	7/2/39	0
7/3/37	0.23	7/3/38	0.08	7/3/39	0.03
7/4/37	0.2	7/4/38	0.08	7/4/39	0.05
7/5/37	0.12	7/5/38	0.08	7/5/39	0.04
7/6/37	0.08	7/6/38	0.07	7/6/39	0.06
7/7/37	0.08	7/7/38	0.06	7/7/39	0.04
7/8/37	0.04	7/8/38	0.05	7/8/39	0.03
7/9/37	0.04	7/9/38	0.04	7/9/39	0.02
7/10/37	0.02	7/10/38	0.02	7/10/39	0.01
7/11/37	0.02	7/11/38	0.01	7/11/39	0
7/12/37	0	7/12/38	0.01	7/12/39	0
7/13/37	0	7/13/38	0	7/13/39	0
7/14/37	0	7/14/38	0	7/14/39	0
7/15/37	0	7/15/38	0	7/15/39	0
7/16/37	0	7/16/38	0	7/16/39	0
7/17/37	0	7/17/38	0	7/17/39	0
7/18/37	0	7/18/38	0	7/18/39	0
7/19/37	0	7/19/38	0	7/19/39	0
7/20/37	0	7/20/38	0	7/20/39	0
7/21/37	0	7/21/38	0	7/21/39	0
7/22/37	0	7/22/38	0	7/22/39	0
7/23/37	0	7/23/38	0	7/23/39	0
7/24/37	0	7/24/38	0	7/24/39	0
7/25/37	0	7/25/38	0	7/25/39	0
7/26/37	0	7/26/38	0	7/26/39	0
7/27/37	0	7/27/38	0	7/27/39	0
7/28/37	0	7/28/38	0	7/28/39	0
7/29/37	0	7/29/38	0	7/29/39	0
7/30/37	0	7/30/38	0	7/30/39	0
7/31/37	0	7/31/38	0	7/31/39	0

APPENDIX 7

Historical Precipitation Data

Pullman, WA		Pullman, WA		Pullman, WA		Pullman, WA		Pullman, WA		Pullman, WA	
date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)
7/1/60	0	8/1/60	1.28	7/1/63	0	8/1/63	0	7/1/69	0	8/1/69	0
7/2/60	0	8/2/60	0	7/2/63	0	8/2/63	0	7/2/69	0	8/2/69	0
7/3/60	0	8/3/60	0	7/3/63	0	8/3/63	0	7/3/69	0	8/3/69	0
7/4/60	0	8/4/60	0	7/4/63	0	8/4/63	0	7/4/69	0	8/4/69	0
7/5/60	0	8/5/60	0	7/5/63	0	8/5/63	0	7/5/69	0	8/5/69	0.05
7/6/60	0	8/6/60	0	7/6/63	0	8/6/63	0	7/6/69	0	8/6/69	0
7/7/60	0	8/7/60	0	7/7/63	0	8/7/63	0	7/7/69	0	8/7/69	0
7/8/60	0	8/8/60	0	7/8/63	0.26	8/8/63	0	7/8/69	0	8/8/69	0
7/9/60	0	8/9/60	0	7/9/63	0.04	8/9/63	0	7/9/69	0	8/9/69	0
7/10/60	0	8/10/60	0	7/10/63	0.06	8/10/63	0	7/10/69	0	8/10/69	0
7/11/60	0	8/11/60	0	7/11/63	0	8/11/63	0	7/11/69	0	8/11/69	0
7/12/60	0	8/12/60	0	7/12/63	0	8/12/63	0.18	7/12/69	0	8/12/69	0
7/13/60	0	8/13/60	0	7/13/63	0	8/13/63	0	7/13/69	0	8/13/69	0
7/14/60	0	8/14/60	0	7/14/63	0	8/14/63	0	7/14/69	0	8/14/69	0
7/15/60	0	8/15/60	0.14	7/15/63	0	8/15/63	0	7/15/69	0	8/15/69	0
7/16/60	0	8/16/60	0	7/16/63	0	8/16/63	0	7/16/69	0	8/16/69	0
7/17/60	0	8/17/60	0	7/17/63	0	8/17/63	0	7/17/69	0	8/17/69	0
7/18/60	0	8/18/60	0	7/18/63	0.01	8/18/63	0	7/18/69	0	8/18/69	0
7/19/60	0	8/19/60	0	7/19/63	0	8/19/63	0	7/19/69	0	8/19/69	0
7/20/60	0	8/20/60	0	7/20/63	0	8/20/63	0	7/20/69	0	8/20/69	0
7/21/60	0	8/21/60	0.01	7/21/63	0	8/21/63	0	7/21/69	0	8/21/69	0
7/22/60	0	8/22/60	0	7/22/63	0	8/22/63	0	7/22/69	0	8/22/69	0
7/23/60	0	8/23/60	0.19	7/23/63	0	8/23/63	0.25	7/23/69	0	8/23/69	0
7/24/60	0	8/24/60	0.07	7/24/63	0	8/24/63	0	7/24/69	0	8/24/69	0
7/25/60	0	8/25/60	0.02	7/25/63	0	8/25/63	0	7/25/69	0	8/25/69	0
7/26/60	0	8/26/60	0	7/26/63	0	8/26/63	0	7/26/69	0	8/26/69	0
7/27/60	0	8/27/60	0.01	7/27/63	0	8/27/63	0	7/27/69	0	8/27/69	0
7/28/60	0	8/28/60	0	7/28/63	0	8/28/63	0	7/28/69	0	8/28/69	0
7/29/60	0	8/29/60	0	7/29/63	0	8/29/63	0	7/29/69	0	8/29/69	0
7/30/60	0	8/30/60	0	7/30/63	0	8/30/63	0	7/30/69	0	8/30/69	0
7/31/60	0	8/31/60	0	7/31/63	0	8/31/63	0	7/31/69	0	8/31/69	0

Colfax, WA		Colfax, WA		Pullman, WA		Pullman, WA		Pullman, WA		Pullman, WA	
date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)
7/1/93	0	8/1/93	0	7/1/94	0	8/1/94	0.01	7/1/95	0	8/1/95	0
7/2/93	0.02	8/2/93	0	7/2/94	0	8/2/94	0	7/2/95	0	8/2/95	0
7/3/93	0.05	8/3/93	0	7/3/94	0	8/3/94	0	7/3/95	0.54	8/3/95	0
7/4/93	0.03	8/4/93	0	7/4/94	0	8/4/94	0.07	7/4/95	0.09	8/4/95	0
7/5/93	0	8/5/93	0	7/5/94	0	8/5/94	0	7/5/95	0	8/5/95	0
7/6/93	0	8/6/93	0	7/6/94	0.1	8/6/94	0	7/6/95	0	8/6/95	0
7/7/93	0.29	8/7/93	0	7/7/94	0	8/7/94	0	7/7/95	0.15	8/7/95	0.62
7/8/93	0	8/8/93	0	7/8/94	0	8/8/94	0	7/8/95	0	8/8/95	0
7/9/93	0	8/9/93	0	7/9/94	0	8/9/94	0	7/9/95	0	8/9/95	0
7/10/93	0	8/10/93	0	7/10/94	0	8/10/94	0	7/10/95	0.17	8/10/95	0
7/11/93	0	8/11/93	0	7/11/94	0	8/11/94	0	7/11/95	0	8/11/95	0.09
7/12/93	0	8/12/93	0	7/12/94	0	8/12/94	0	7/12/95	0	8/12/95	0
7/13/93	0	8/13/93	0	7/13/94	0	8/13/94	0	7/13/95	0	8/13/95	0.01
7/14/93	0.49	8/14/93	0	7/14/94	0	8/14/94	0	7/14/95	0	8/14/95	0
7/15/93	0.06	8/15/93	0.02	7/15/94	0	8/15/94	0	7/15/95	0	8/15/95	0.06
7/16/93	0.07	8/16/93	0.22	7/16/94	0	8/16/94	0	7/16/95	0	8/16/95	0.16
7/17/93	0.7	8/17/93	0.14	7/17/94	0	8/17/94	0	7/17/95	0	8/17/95	0.11
7/18/93	0.14	8/18/93	0	7/18/94	0	8/18/94	0	7/18/95	0	8/18/95	0
7/19/93	0	8/19/93	0	7/19/94	0	8/19/94	0	7/19/95	0	8/19/95	0
7/20/93	0.23	8/20/93	0	7/20/94	0	8/20/94	0	7/20/95	0	8/20/95	0
7/21/93	0	8/21/93	0	7/21/94	0	8/21/94	0	7/21/95	0	8/21/95	0
7/22/93	0.02	8/22/93	0	7/22/94	0	8/22/94	0.02	7/22/95	0	8/22/95	0
7/23/93	0.13	8/23/93	0	7/23/94	0	8/23/94	0	7/23/95	0	8/23/95	0
7/24/93	0	8/24/93	0	7/24/94	0	8/24/94	0	7/24/95	0	8/24/95	0
7/25/93	0	8/25/93	0	7/25/94	0	8/25/94	0	7/25/95	0	8/25/95	0
7/26/93	0	8/26/93	0	7/26/94	0	8/26/94	0	7/26/95	0	8/26/95	0
7/27/93	0	8/27/93	0	7/27/94	0	8/27/94	0	7/27/95	0	8/27/95	0
7/28/93	0	8/28/93	0	7/28/94	0	8/28/94	0	7/28/95	0	8/28/95	0
7/29/93	0	8/29/93	0.06	7/29/94	0	8/29/94	0	7/29/95	0	8/29/95	0.08
7/30/93	0	8/30/93	0	7/30/94	0	8/30/94	0	7/30/95	0	8/30/95	0
7/31/93	0	8/31/93	0	7/31/94	0	8/31/94	0	7/31/95	0	8/31/95	0

Colfax, WA		Colfax, WA		Colfax, WA		Colfax, WA		Colfax, WA		Colfax, WA	
date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)	date	precipitation (inches)
7/1/63	0	8/1/63	0	7/1/69	0	8/1/69	0	7/1/70	0	8/1/70	0
7/2/63	0	8/2/63	0	7/2/69	0	8/2/69	0	7/2/70	0	8/2/70	0
7/3/63	0	8/3/63	0	7/3/69	0	8/3/69	0	7/3/70	0	8/3/70	0.01
7/4/63	0	8/4/63	0.01	7/4/69	0	8/4/69	0	7/4/70	0	8/4/70	0
7/5/63	0	8/5/63	0	7/5/69	0	8/5/69	0	7/5/70	0	8/5/70	0
7/6/63	0	8/6/63	0	7/6/69	0	8/6/69	0	7/6/70	0	8/6/70	0.02
7/7/63	0	8/7/63	0	7/7/69	0	8/7/69	0	7/7/70	0	8/7/70	0
7/8/63	0.11	8/8/63	0	7/8/69	0	8/8/69	0	7/8/70	0	8/8/70	0
7/9/63	0	8/9/63	0	7/9/69	0	8/9/69	0	7/9/70	0	8/9/70	0
7/10/63	0.07	8/10/63	0	7/10/69	0	8/10/69	0	7/10/70	0	8/10/70	0
7/11/63	0	8/11/63	0	7/11/69	0	8/11/69	0	7/11/70	0	8/11/70	0
7/12/63	0	8/12/63	0.27	7/12/69	0	8/12/69	0	7/12/70	0	8/12/70	0
7/13/63	0	8/13/63	0	7/13/69	0	8/13/69	0	7/13/70	1.37	8/13/70	0
7/14/63	0	8/14/63	0.01	7/14/69	0	8/14/69	0	7/14/70	0.13	8/14/70	0
7/15/63	0	8/15/63	0	7/15/69	0	8/15/69	0	7/15/70	0	8/15/70	0
7/16/63	0	8/16/63	0	7/16/69	0	8/16/69	0	7/16/70	0	8/16/70	0
7/17/63	0	8/17/63	0	7/17/69	0	8/17/69	0	7/17/70	0.05	8/17/70	0
7/18/63	0	8/18/63	0	7/18/69	0	8/18/69	0	7/18/70	0	8/18/70	0
7/19/63	0	8/19/63	0	7/19/69	0	8/19/69	0	7/19/70	0	8/19/70	0
7/20/63	0	8/20/63	0	7/20/69	0	8/20/69	0	7/20/70	0	8/20/70	0.01
7/21/63	0	8/21/63	0	7/21/69	0	8/21/69	0	7/21/70	0.04	8/21/70	0
7/22/63	0	8/22/63	0	7/22/69	0	8/22/69	0	7/22/70	0	8/22/70	0
7/23/63	0	8/23/63	0.01	7/23/69	0	8/23/69	0	7/23/70	0	8/23/70	0
7/24/63	0	8/24/63	0.14	7/24/69	0	8/24/69	0	7/24/70	0	8/24/70	0
7/25/63	0	8/25/63	0	7/25/69	0	8/25/69	0	7/25/70	0	8/25/70	0
7/26/63	0	8/26/63	0	7/26/69	0	8/26/69	0	7/26/70	0.12	8/26/70	0
7/27/63	0	8/27/63	0	7/27/69	0	8/27/69	0	7/27/70	0	8/27/70	0
7/28/63	0	8/28/63	0	7/28/69	0	8/28/69	0	7/28/70	0.33	8/28/70	0
7/29/63	0	8/29/63	0	7/29/69	0	8/29/69	0	7/29/70	0	8/29/70	0
7/30/63	0	8/30/63	0	7/30/69	0	8/30/69	0	7/30/70	0	8/30/70	0
7/31/63	0	8/31/63	0	7/31/69	0	8/31/69	0	7/31/70	0	8/31/70	0

Moscow, ID		Moscow, ID		Moscow, ID	
date	**precipitation (inches)**	**date**	**precipitation (inches)**	**date**	**precipitation (inches)**
7/1/37	0.07	7/1/38	0.09	7/1/39	0
7/2/37	0	7/2/38	0.03	7/2/39	0
7/3/37	0	7/3/38	0	7/3/39	0.52
7/4/37	0	7/4/38	0.02	7/4/39	0
7/5/37	0	7/5/38	0	7/5/39	0.15
7/6/37	0	7/6/38	0	7/6/39	0
7/7/37	0	7/7/38	0	7/7/39	0
7/8/37	0	7/8/38	0.06	7/8/39	0
7/9/37	0	7/9/38	0	7/9/39	0
7/10/37	0	7/10/38	0	7/10/39	0
7/11/37	0	7/11/38	0	7/11/39	0
7/12/37	0	7/12/38	0	7/12/39	0
7/13/37	0.14	7/13/38	0	7/13/39	0.04
7/14/37	0	7/14/38	0	7/14/39	0
7/15/37	0	7/15/38	0	7/15/39	0
7/16/37	0	7/16/38	0	7/16/39	0
7/17/37	0	7/17/38	0	7/17/39	0
7/18/37	0	7/18/38	0	7/18/39	0
7/19/37	0	7/19/38	0	7/19/39	0
7/20/37	0	7/20/38	0	7/20/39	0.01
7/21/37	0	7/21/38	0	7/21/39	0
7/22/37	0	7/22/38	0	7/22/39	0
7/23/37	0	7/23/38	0	7/23/39	0
7/24/37	0	7/24/38	0	7/24/39	0
7/25/37	0	7/25/38	0	7/25/39	0
7/26/37	0	7/26/38	0	7/26/39	0
7/27/37	0	7/27/38	0	7/27/39	0
7/28/37	0.02	7/28/38	0.05	7/28/39	0
7/29/37	0	7/29/38	0.05	7/29/39	0
7/30/37	0	7/30/38	0	7/30/39	0
7/31/37	0	7/31/38	0	7/31/39	0

APPENDIX 8

Velocity-Area Method Data for

Almota Creek, Little Almota Creek,

and Wawawai Creek

and Oxygen-18 Data

Almota Creek - Velocity Area Method					
distance from bank, b_i (ft)	depth, d_i (ft)	flow #1 (ft/s)	flow #2 (ft/s)	average flow, v_i (ft/s)	Incremental Discharge, q_i (cfs)
0.000	0.000	0.000	0.000	0.000	-
0.45	0.20	0.944	0.885	0.915	0.123
1.35	0.45	2.670	2.720	2.695	1.091
2.25	0.65	2.420	2.170	2.295	1.343
3.15	0.80	1.760	1.750	1.755	1.264
4.05	0.90	1.300	1.290	1.295	1.049
4.95	0.72	1.030	1.060	1.045	0.677
5.85	0.48	0.703	0.890	0.797	0.344
6.75	0.30	0.259	0.431	0.345	0.093
7.65	0.25	0.000	0.000	0.000	0.000
8.55	0.10	0.000	0.000	0.000	0.000
9.00	0.00	0.000	0.000	0.000	-
			Total discharge, Q =		5.984

Little Almota Creek - Velocity-Area Method					
distance from bank, b_i (ft)	depth, d_i (ft)	flow #1 (ft/s)	flow #2 (ft/s)	average flow, v_i (ft/s)	Incremental Discharge, q_i (cfs)
0.00	0.00	0.000	0.000	0.000	-
0.30	0.20	0.000	0.000	0.000	0.000
0.90	0.50	0.000	0.000	0.000	0.000
1.50	0.40	0.000	0.000	0.000	0.000
2.10	0.50	0.558	0.539	0.549	0.165
2.70	0.45	0.847	0.915	0.881	0.238
3.30	0.50	0.587	0.510	0.549	0.165
3.90	0.55	0.759	0.671	0.715	0.236
4.50	0.50	0.956	1.060	1.008	0.302
5.10	0.62	0.000	0.000	0.000	0.000
5.70	0.40	0.503	0.283	0.393	0.094
6.30	0.10	0.000	0.000	0.000	0.000
6.32	0.00	0.000	0.000	0.000	-
			Total discharge, Q =		1.200

Wawawai Canyon - Velocity-Area Method					
distance from bank, b_i (ft)	depth, d_i (ft)	flow #1 (ft/s)	flow #2 (ft/s)	average flow, v_i (ft/s)	Incremental Discharge, q_i (cfs)
0.00	0.00	0.000	0.000	0.000	-
0.30	0.11	0.000	0.000	0.000	0.000
0.90	0.15	0.292	0.374	0.333	0.030
1.50	0.1	0.000	0.000	0.000	0.000
2.10	0.2	0.000	0.000	0.000	0.000
2.70	0.2	1.460	1.550	1.505	0.181
3.30	0.2	2.490	2.590	2.540	0.305
3.90	0.21	0.698	0.711	0.705	0.089
4.50	0.18	2.610	2.510	2.560	0.276
5.10	0.25	1.580	1.500	1.540	0.231
5.70	0.15	2.070	2.150	2.110	0.190
6.30	0.16	0.712	0.793	0.753	0.063
6.75	0.00	0.000	0.000	0.000	-
			Total discharge, Q =		1.365

From Larson, 1997 (elevation was converted from meters to feet):

Elevation (ft)	Grande Ronde O-18 Results
1322	-17.4
1322	-17.5
1480	-17.2
2162	-15.6
2202	-16.1
2202	-15.9
2241	-16.2
1847	-17.5
2412	-15.4
1493	-16.6
1581	-16.7
1673	-17
1755	-17.2
1755	-17.1
1975	-17
1982	-17.1
1988	-17
2159	-17
2159	-16.7
2221	-16.9
2238	-16.9
2261	-16.4

Elevation (ft)	Wanapum O-18 Results
2346	-15
2392	-14.9
2405	-15.7
2415	-15.4
2467	-14.9
2579	-15.4
2343	-15
2402	-15.2
2418	-14.9
2418	-15
2431	-15.1
2333	-14.9
2441	-14.9
2467	-15.2
2507	-15.5

Elevation (ft)	Palouse Loess O-18 Results
2451	-15.5
2454	-13.8
2457	-15.5
2461	-14.1
2464	-15.1
2464	-15.3
2464	-15
2477	-14.2
2477	-15.6
2477	-15
2484	-12.6
2484	-12.5
2484	-15.2
2484	-15.3
2484	-15.2
2490	-15.4
2490	-15.3
2490	-15.3
2517	-15

Elevation (ft)	W/GR O-18 Results
2231	-15.1
2408	-17.8

Elevation (ft)	Surficial O-18 Results
2490	-13.9
2490	-14
2530	-15
2530	-14.6
2533	-14.9
2533	-15.7
2533	-14.6
2546	-14.6
2556	-14.6
2562	-14.3
2589	-14.8
2595	-15.1
2599	-14.4

Elevation (ft)	Idaho Batholith O-18 Results
2349	-15.9
2349	-16.3
2349	-16.1
2569	-15
2569	-15.1
2671	-14.9
2690	-15.9
2999	-16.1
3084	-15.5
3500	-15.4

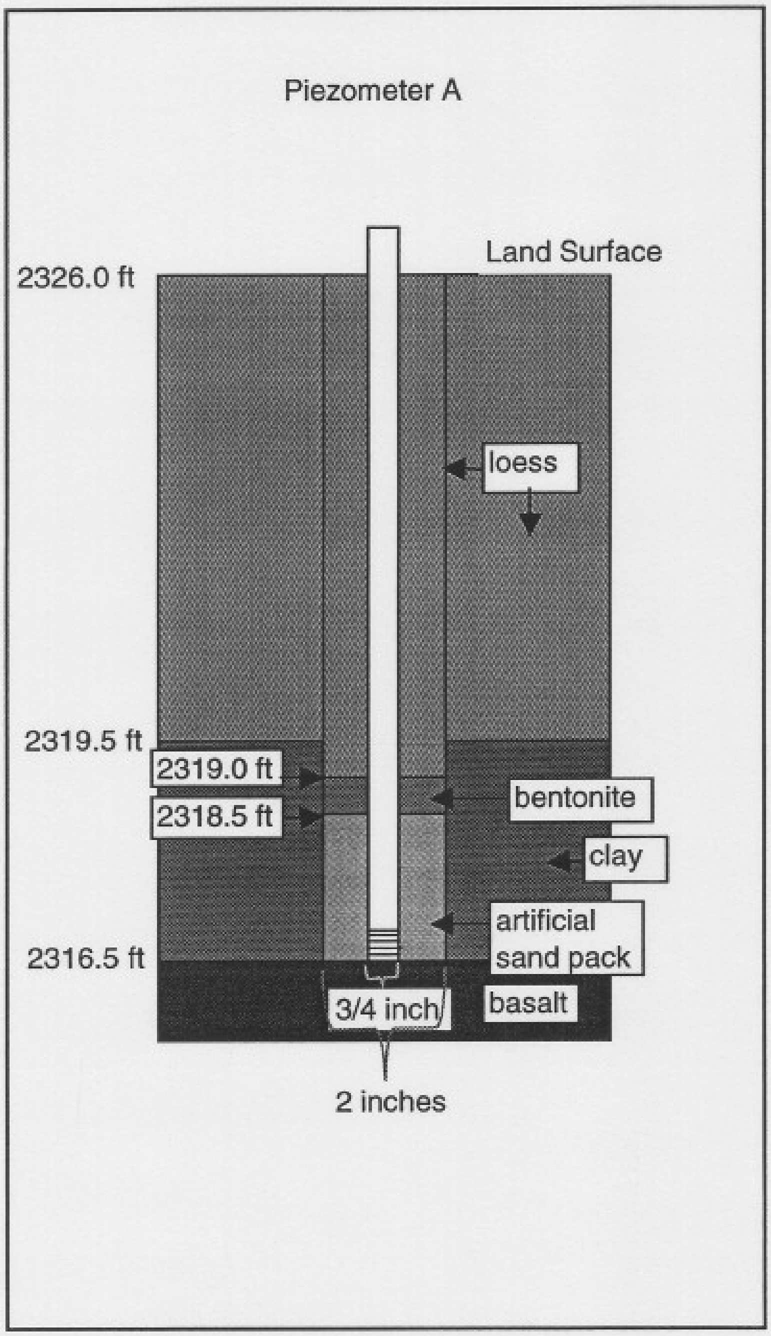
From Kirk, 2000 (elevation was converted from meters to feet):

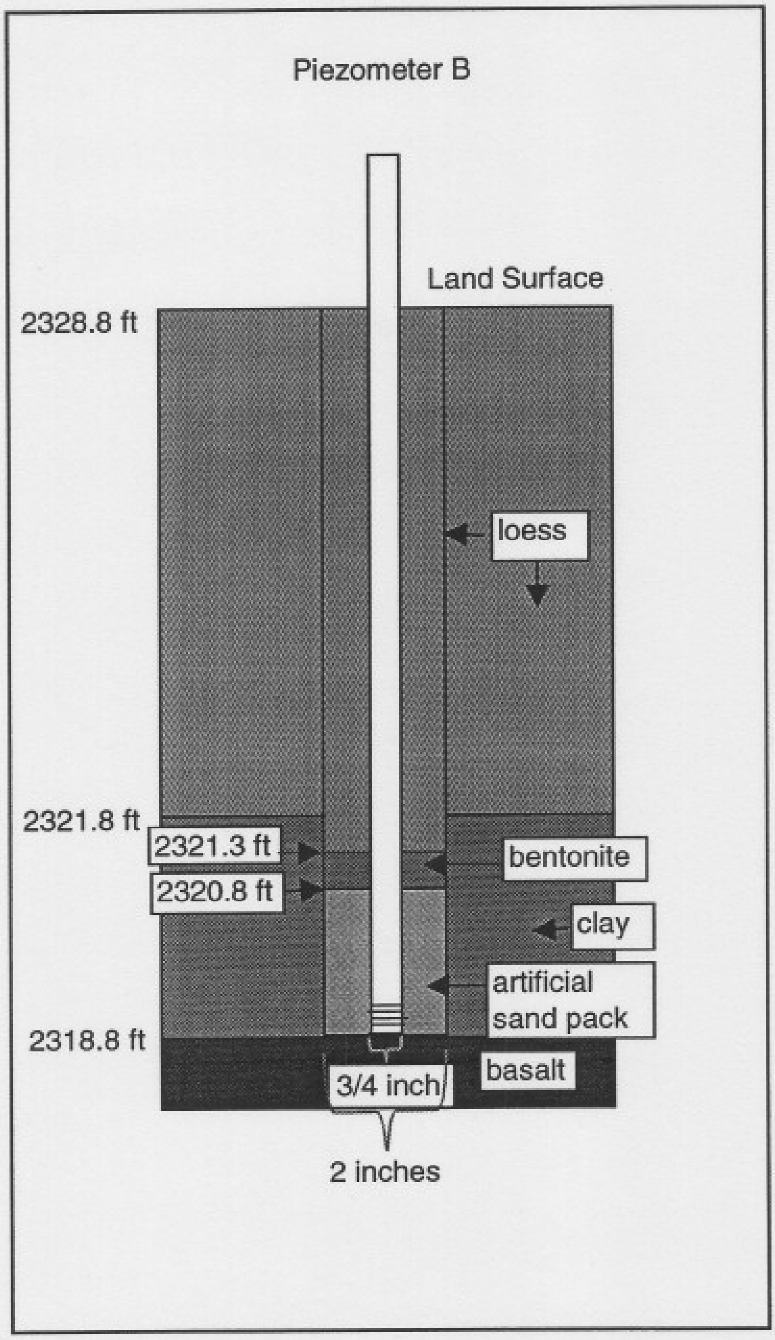
Location	Elevation (ft)	O-18 Results
UFC-Colton	2480	-14.5
UFC	2394	-14.2
UFC	2314	-14.4
UFC-before WC	2280	-14.3
UFC-before WC	2280	-14.4
UFC	1970	-14.7
UFC-Wilcox	1880	-14.1
Wawawai	2465	-14.8
Wawawai	1331	-14.2
Wawawai-SR	840	-13.6
Little Almota	660	-14.4
Almota-SR	640	-14.6
Spring-UFC	2150	-13.6
Spring	2260	-14.5
Steptoe Canyon	2440	-15.4
Steptoe Canyon-SR	740	-14.6
Nasqually Canyon	800	-14.4
Other Trib to SR	760	-14.2
Goose Creek	2150	-14.0
Goose Creek-Springs	2200	-13.8

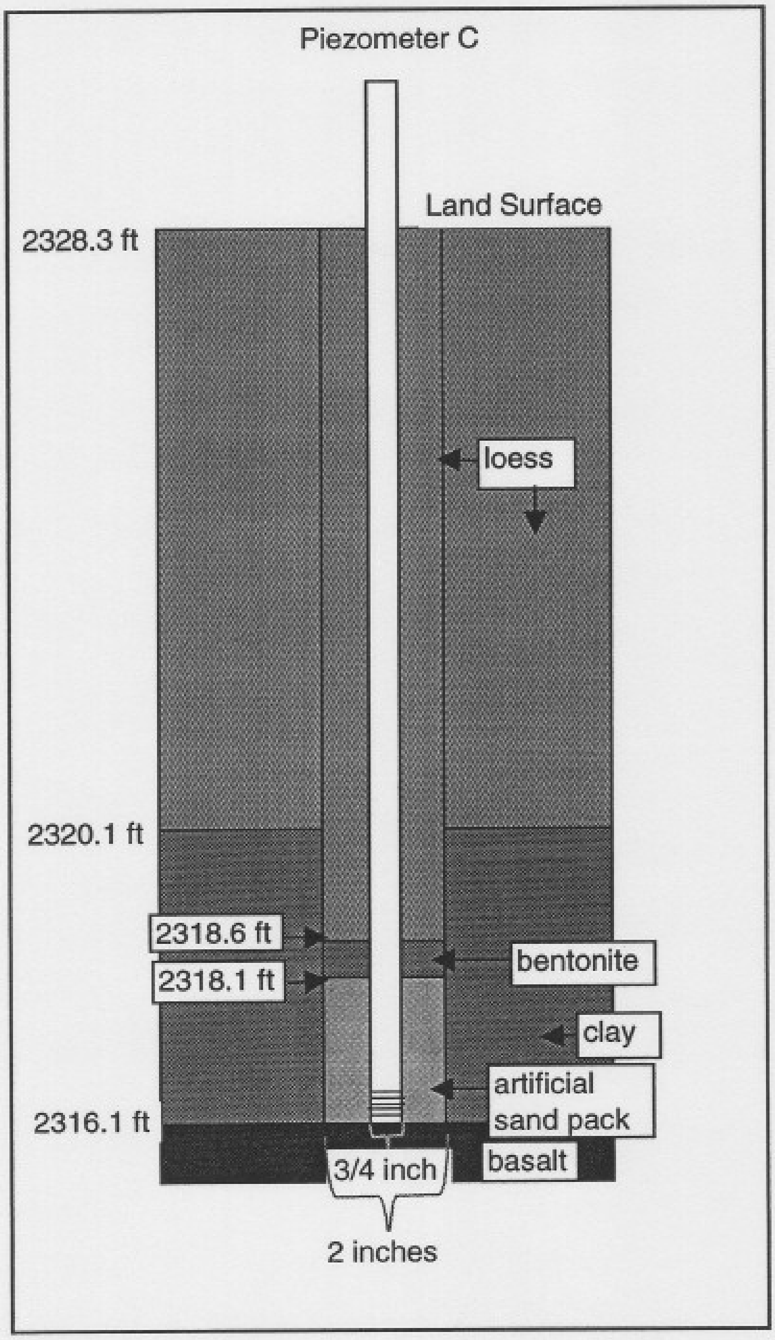
APPENDIX 9

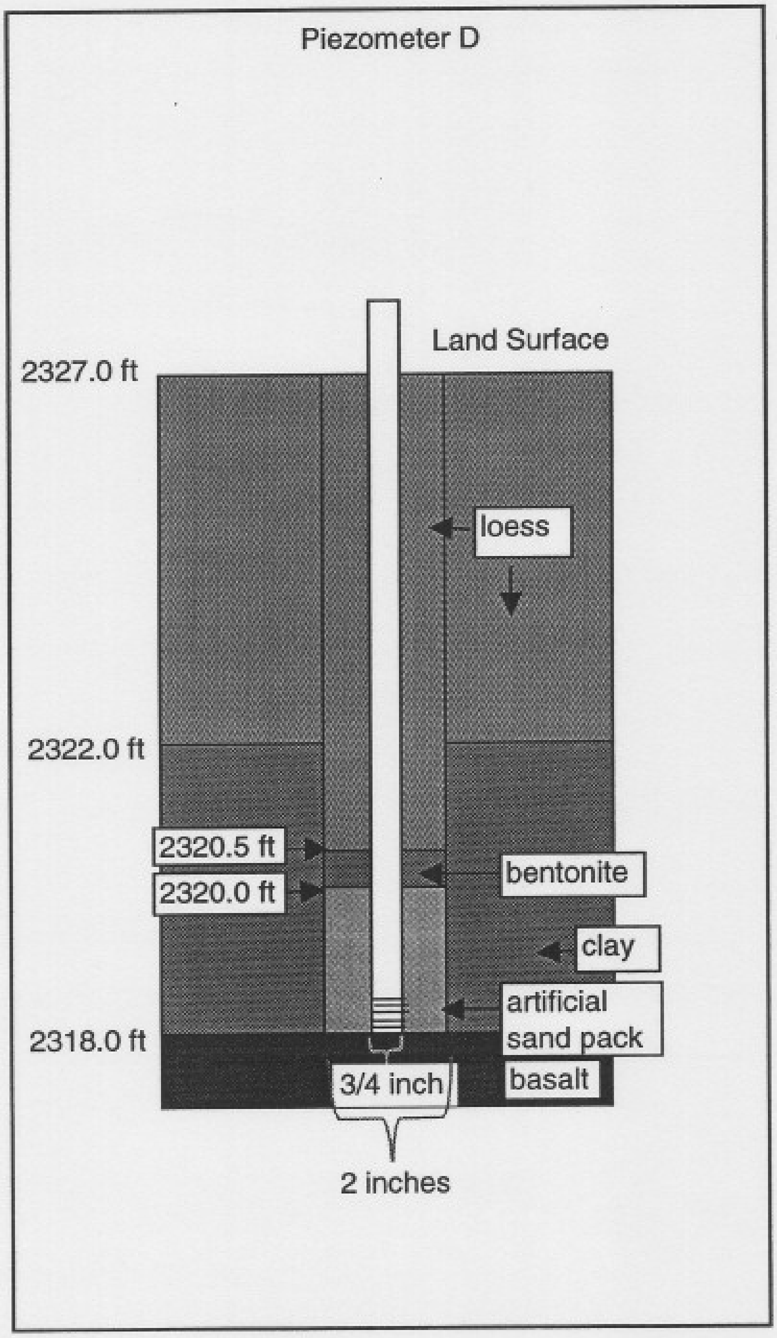
Well Logs for

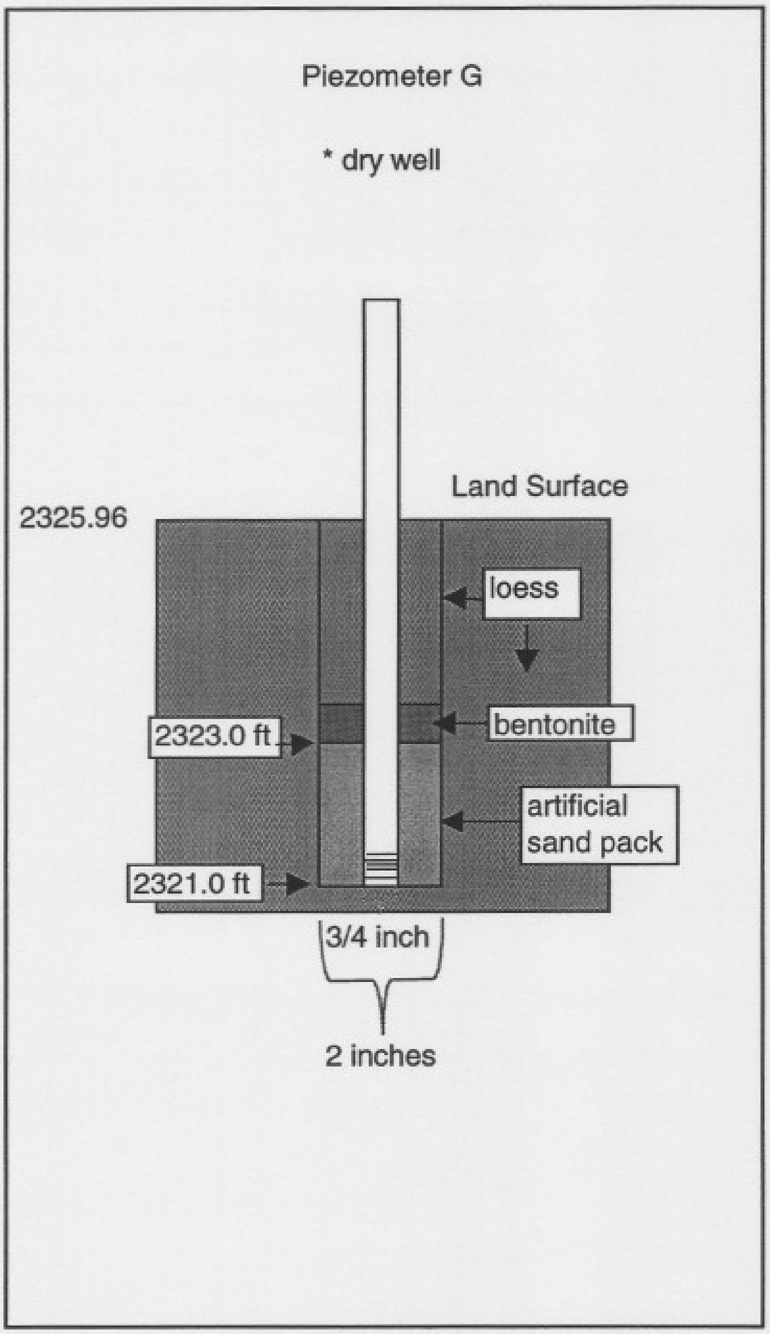
Piezometers A, B, C, D, G and H

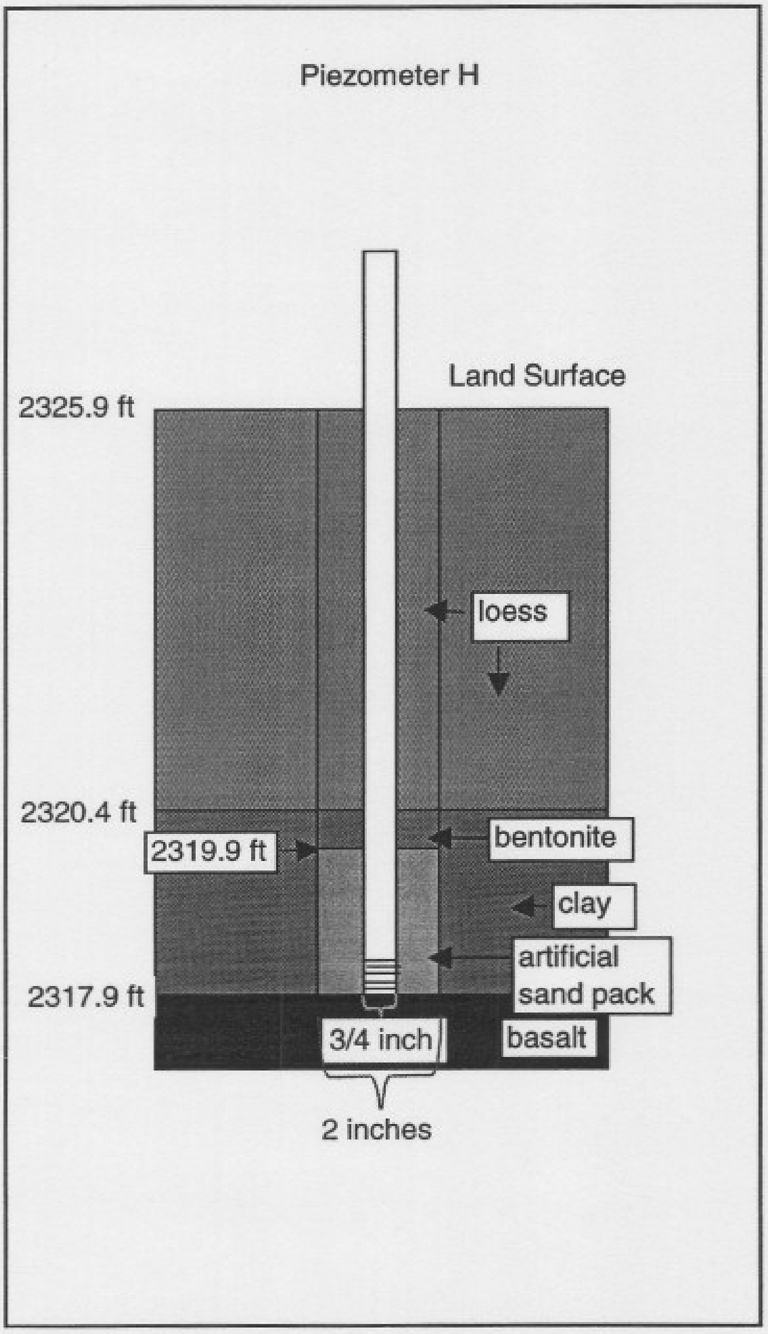

Piezometer A
Land Surface
2326.0 ft
loess
2319.5 ft
2319.0 ft
2318.5 ft
bentonite
clay
artificial
sand pack
2316.5 ft
3/4 inch
basalt
2 inches


Piezometer B
Land Surface
2328.8 ft
loess
2321.8 ft
2321.3 ft
bentonite
2320.8 ft
clay
artificial
sand pack
2318.8 ft
basalt
3/4 inch
2 inches


Piezometer C
Land Surface
2328.3 ft
loess
2320.1 ft
2318.6 ft
bentonite
2318.1 ft
clay
artificial
sand pack
2316.1 ft
basalt
3/4 inch
2 inches


Piezometer D
Land Surface
2327.0 ft
loess
2322.0 ft
2320.5 ft
bentonite
2320.0 ft
clay
artificial sand pack
2318.0 ft
basalt
3/4 inch
2 inches


Piezometer G
* dry well
Land Surface
2325.96
loess
bentonite
2323.0 ft
artificial sand pack
2321.0 ft
3/4 inch
2 inches


Piezometer H
Land Surface
2325.9 ft
loess
2320.4 ft
2319.9 ft
bentonite
clay
artificial
sand pack
2317.9 ft
3/4 inch
basalt
2 inches