RANGEN GROUNDWATER DISCHARGE AND ESPAM2.1 HYDROGEOLOGIC INVESTIGATION

by

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This report is identical to the report of the same name and authorship dated December 20, 2012, with the exception of the following corrections, which have been included here for the reader's convenience:

Page 2, par. 4, ln 4 - change "Site Hydrogeology" to "Site Geology"
Page 3, par. 3, ln 2 - change 44 to 43
Page 3, par. 4, ln 2 and par. 5, ln 3 - change p. 44 to pp. 44-45
Page 5, par. 3, ln 5 - change p. 6 to pp. 8-9; last par., ln 1 - change "East" to "West"
Page 12, par. 3, ln 5 - change pp. 4-10 to pp. 4-11
Page 15, par. 3, ln 3 - change pp. 7-8 to pp. 7-9
Page 16, par. 4, ln 1 - delete "between the"
Page 26, par. 2, ln 1 - change p. 12 to p. 13
Page 27, par. 3, ln 8 - change "relative" to relatively"; par. 4, ln 6 - change 30 cfs to 29 cfs; par. 4, ln 9 - change 5 ft. to 6 ft.
Page 28, par. 2, ln 3 - change 3154 ft. to 3156 ft.; par. 2, ln 6 - change 5.5 cfs to 5.7 cfs
Page 29, par. 5, lns 3 and 6 - change 1984 to 1964 in both lines
Page 38, par. 1, ln 2 - change 319 cfs to 367 cfs; par. 2, ln 2 - change 3127 ft. to 3125 ft.; par. 4, ln 8 - change 3108 ft. to 3106 ft.; par. 5, ln 1 - change p. 15 to p. 16; par. 5, ln 5 - change 3074 ft. to 3073 ft.
Page 40, par. 4, ln 1 - change p. 31 to p. 32; par. 7, ln 2 - change p. 27 to pp. 27-28
Page 41, par. 4, ln 9 - change "Wylie" to "IDWR"
Page 44, par. 2, ln 2 - change 25 ft. to 22 ft.
Page 45, par. 3, ln 1 - change Figure 3 to Figure 31
Page 48, added Nace et al. reference

Figure 22 - In column 13, change ESPAM2.1 head from 3137 to 3136; in column 14, change 3169 to 3166; in column 15, change 3191 to 3187; and in column 16, change 3209 to 3205.

Figure 23 - In column 14, change ESPAM2.1 head from 3108 to 3106; in column 15, change 3074 to 3073; in column 17, change 3086 to 3084.

Figure 25 - In column 12, change ESPAM2.1 head from 3127 to 3125; in column 13, change 3146 to 3144; in column 14, change 3161 to 3158; in column 15, change 3173 to 3170; in column 16, change 3186 to 3182; in column 17, change 3199 to 3195.

Figures 27 and 32 - Modeled output (red line) in each figure changed slightly.

These corrections are provided to bring the report into numerical conformity with the most recent ESPAM2.1 files, and to correct miscellaneous typographical errors. There are no modifications of the report analysis or conclusions.

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INTRODUCTION AND SUMMARY

The objective of this report is to review the hydrogeology of the western edge of the Eastern Snake Plain Aquifer (ESPA) in the Malad Gorge to the Thousand Springs area, with particular reference to the hydrogeology affecting the groundwater supply of Rangen, Inc., and to groundwater flow modeling of the area with the Enhanced Snake Plain Aquifer Model (ESPAM Version 2.1).

The first section of this report – "Hydrogeologic Setting" – outlines the hydrogeologic features of the study area, i.e. the geologic deposits present and their water-bearing characteristics, to establish the context for specific evaluation of the groundwater discharges at Rangen. This section draws upon the rich professional literature on the extraordinary aquifer created by the flood basalts of the eastern Snake River Plain, focusing on those aspects of the hydrogeology most relevant to the Rangen investigation, including stratigraphy, definition of "aquifers", general patterns of groundwater flow, and the important hydrogeologic boundary between the primary aquifer and underlying deposits.

The second section of this report – "Rangen Groundwater Discharge" – focuses on the hydrogeology of the Curren Tunnel and the natural springs that supply groundwater to the Rangen facilities. This section presents a conceptual hydrogeologic model for the Rangen area based on the observable and reasonably-inferred characteristics of the physical system as a foundation from which to evaluate the ESPAM representation of that system.

The third section – "Groundwater Development Opportunity" – evaluates the general feasibility of augmenting the groundwater supply at Rangen with development of wells.

The fourth and final section of the report – "Groundwater Modeling of the Eastern Snake Plain Aquifer" – draws upon the previous sections to inform comparisons between the hydrogeology of the study area and its representation by the ESPAM 2.1 groundwater model. A number of inconsistencies, shortcomings, and conceptual errors are discussed.

Attached to this report as Figure 1 is a map showing the general study area for this investigation.

This investigation was closely coordinated with that of Brendecke (2012), the results and conclusions of which have been submitted as a separate report.

In summary, I conclude:

1. The primary aquifer of the Eastern Snake River Plain is comprised of a series of extraordinarily productive Quaternary-age basalt flows and, at Rangen, by immediately underlying highly-permeable sediments. (See "Stratigraphy", pp. 4-7; "Aquifer Definition", pp. 11-12.)

2. The topography of the base of this primary aquifer is a major control on the discharge of groundwater from the aquifer along the Hagerman Rim, including at the location of Rangen. (See “Base of the Primary Aquifer”, pp. 13-19; “Rangen Groundwater Discharge”, p. 20.)

3. The Curren Tunnel is a horizontal flowing well, increasing groundwater production relative to natural springs, but providing minimal available groundwater drawdown, and discharge rates that are especially vulnerable to small changes in aquifer groundwater levels. (See “Curren Tunnel”, pp. 20-23.)

4. The tunnel was not constructed to maximize sustainable, year-round production for the present application. (See “Curren Tunnel”, p. 20-23.)

5. The geometry of the base of the primary aquifer combines with internal variations in permeability to create more complex groundwater flow patterns and more complex relationships between aquifer water levels and groundwater discharge than have previously been reported. (See “Site Geology”, “Flow Data”, and “Groundwater Gradients”, pp. 23-28.)

6. In the area immediately east of Rangen, in the same aquifer, there are opportunities to develop substantially more robust access to quantities of groundwater comparable to those historically measured at the Curren Tunnel. (See “Groundwater Development Opportunity”, pp. 28-30.)

7. The ESPAM2.1 groundwater model is poorly reflective of actual hydrogeologic conditions in the study area (see “Groundwater Modeling of the Eastern Snake Plain Aquifer”, pp. 30-34) and specifically at Rangen due to:

- its inability to reflect important local changes in transmissivity and aquifer saturated thickness; (See “Aquifer Transmissivity” section, pp. 34-35.)

- its inability to distinguish the primary aquifer from underlying strata, overlooking a regionally important inter-aquifer boundary; (See “Aquifer Anisotropy and Model Layers” section, pp. 35-37.)

- its inability to reflect the detailed paleo-topograhy that is understood to control major groundwater discharge along the Hagerman Rim; (See “Grid Size ” section, p. 37.)

- its inability to accurately represent the westward termination of groundwater flow in the primary aquifer along the Hagerman Rim; (See “Aquifer Discontinuity”, pp. 37-39.)

- its inability to distinguish between groundwater discharges associated with the Curren Tunnel and those associated with lower-elevation, natural springs at Rangen; (See “Rangen ‘Drain’ Modeling” section, pp. 39-41.)

- its inability to represent the observed relationship between aquifer water levels and groundwater discharge; (See “Rangen ‘Drain’ Modeling” section, pp. 39-41.)

- its ambiguity with respect to the critical elevation parameters; (See “Elevation Uncertainties ” section, pp. 41-42.)

- its uncertainty regarding a major component of the water balance, the non-spring gains to the Snake River; (See “Snake River Gains” section, pp. 42-43.)

- its inaccuracies in the representation of local aquifer groundwater levels; (See “Calibration Comparisons” section, pp. 44-45.) and

- its inaccuracies in the volume of groundwater flow and in the magnitude and timing of seasonal fluctuations of groundwater flow at Rangen. (See “Calibration Comparisons” section, pp. 44-45.)

8. These discrepancies between the ESPAM2.1 and the observable characteristics of the Eastern Snake Plain Aquifer, along with poorly understood details of the hydrogeology of the Eastern Snake Plain Aquifer discharge area, create considerable uncertainty in the use of the ESPAM2.1 to inform detailed hydrologic analyses of the groundwater discharges at Rangen.

HYDROGEOLOGIC SETTING

STRATIGRAPHY

This section outlines the basic components of the hydrogeology of the study area, describing the composition and distribution of relevant geologic deposits and their primary groundwater characteristics.

“Stratigraphy” refers to the characteristics and arrangement of the various layers of rock that lie beneath the landscape. The occurrence of a particular rock formation at the surface is called “outcrop”. Subsurface locations can be directly assessed by wells, or estimated by projection from the surface. Formation names are typically derived from the location at which the formation was first identified. Map symbols consist of a capital initial (Q, T, etc.) based on the age of the deposit, followed by the initials of the formation name, e.g. “Qnb” for the Quaternary-age Notch Butte basalt flow. “Quaternary” refers to the last 1.6 million years; “Tertiary” age refers to the period between 66 and 1.6 million years old.

The outcrop geology for the study area is presented on Figure 2; the relevant formation symbols are explained below. Figure 3 presents a summary of the basic stratigraphy, grouped by general rock type. The “Volcanic Deposits” are basalt flows in this case; the “Mixed Lacustrine and Alluvial Deposits” are lake and stream deposits, respectively, consisting of layers of silt, sand, and gravel; the “Bonneville Flood Deposits” are primarily sand and gravel; and the “Mass

Movement Deposits" are talus slopes and landslide deposits. The green and blue arrows on Figure 2 indicate the flow direction of two massive floods in the geologic past.

Both Figures 2 and 3 are duplicated from published geologic mapping by the Idaho Geological Survey (IGS) 1:24,000-scale geologic mapping program (Kauffman et al., 2005; and Othberg et al., 2005). From top to bottom, i.e. in order of increasing age, the deposits of interest to the present study can be grouped into four general sequences:

1. Quaternary Sediments

These are a complex assemblage of Quaternary-age alluvial and lacustrine sediments associated with both the routine erosion and deposition of landscape evolution and the extraordinary history of natural impoundments and flooding along this reach of the Snake River. These include alluvial deposits, talus and landslide deposits, sand dunes, and clay and gravel deposits specifically associated with the Bonneville Flood. These are the materials listed in the upper right on Figure 3. (See Othberg et al., 2005 for details.) These are relatively thin, localized, surficial deposits, of marginal relevance to the present study. Two units of interest are:

> Crowsnest Gravel (Qcg) - 6 ft. of "Stratified sand and pebble gravel" (Othberg et al., 2005)
>
> Yahoo Clay (Qy) - "Laminated to thin-bedded clay and silty clay." (Othberg et al., 2005)

In the study area, the Quaternary sediments are limited to the Hagerman valley and along the Snake and Malad Rivers. The Yahoo Clay is present over much of the area immediately west of the Hagerman rim. Although the stratigraphic column (Figure 3) indicates the Yahoo Clay and the Basalt of McKinley Butte are of similar age, Othberg et al. (2005) conclude that the former was deposited behind a lava dam created by the latter. Thus, within the study area, the Quaternary sediments are consistently younger than, and deposited on top of, the Quaternary basalts discussed below.

Groundwater Characteristics. The Yahoo Clay is hydrologically significant locally in that its relatively low permeability impedes groundwater flow. For example, the overlying relatively-permeable Crowsnest Gravel southwest of Rangen collects precipitation and irrigation recharge, producing springs at its contact with the underlying Yahoo Clay (Covington and Weaver, 1990; spring nos. 20, 21, 26 ("Stewart")). Such springs are not part of the regional aquifer system.

These sediments are not considered a part of the regional aquifer system, but may locally play a role in controlling the occurrence of groundwater discharge by restricting groundwater flow.

2. Quaternary Basalts

These are a series of overlapping Quaternary-age basalt flows from multiple eruptive centers. This series is regionally termed the "Snake River Group", extending east from the study area across the entire eastern Snake River Plain and attaining thicknesses as much as 5,000 ft. (e.g. Whitehead, 1992). Geologists differ on the naming of individual units, and not all flows are present at all locations. In the study area, IGS mapping has identified, in descending order (getting older):

Basalt of McKinley Butte (Qmk);
Basalt of Notch Butte (Qnb), (Sand Springs Basalt (Qss) of Covington and Weaver (1990) around the town of Hagerman);
Basalt of Bacon Butte (younger) (Qbby);
Basalt of Bacon Butte (older) (Qbbo);
Basalt of Flat Top Butte (Qftb);
Basalt of Gooding Butte (Qgb); and
Madison Basalt (Qma).

In the study area, all these units are described as "fine grained basalt" (e.g. Kauffman et al., 2005). They create the extensive plateau east of the Hagerman rim. Individual basalts are named for their inferred eruption center (e.g. McKinley Butte, Gooding Butte), all of which are from 10 to 20 miles north, northeast, east, or southeast of the study area. Naming conventions vary, as each of these "basalts" consists of multiple, individual flows. In a detailed examination of core from a US Geological Survey borehole northeast of Wendell (plotted on Figure 1), for example, 25 "flow boundaries" were identified in the 400 ft. of Quaternary basalts penetrated (Whitehead and Lindholm, 1985).

The emplacement history of these basalts is a complex function of the locations of eruptive centers, the nature of the individual flows, and the topography upon which they flowed. The older flows that cover the plateau-area above the Hagerman Rim (i.e. Qma and Qgb on Figure 2) filled stream channels carved into the underlying Tertiary-age Glenns Ferry Fm. when it formed the land surface east of the present Hagerman Rim (discussed below, pp. 8-9)[1]. The somewhat younger Qftb flow mapped above Thousand Springs is interpreted as having been constrained by an "ancestral Snake River" channel immediately west of the present rim (Kauffman et al., 2005). The still younger Qnb flow appears to have flowed northwestward into the Hagerman Valley from the southeast and to have locally spilled over the present rim (e.g. 2.5 miles north of Rangen).

Along the Hagerman rim, the exposed basalt sequence is 50 - 100 ft. thick (e.g. at Rangen). At the Henslee well (3 miles east of the rim), the basalts are 240 ft. thick. At the USGS Wendell well (11 miles ENE), the basalts are 400 ft. thick. (See Fig. 1 for locations.)

West of the rim, Quaternary basalts are exposed immediately southwest of Rangen, beneath the Yahoo Clay along the scarp east of the National Fish Hatchery, and north and east of the town

[1]Such ancient, buried channels are called "paleo-channels".

of Hagerman. They are not present at all locations, however. In some places the Quaternary sediments immediately overlie the Tertiary-age deposits described below.

Groundwater Characteristics. "The largest and most productive aquifers in the Snake River Plain are composed of Quaternary basalts of the Snake River Group ... Aquifer tests and simulation indicate that transmissibility [transmissivity] of the upper 200 feet of the basalt aquifer in the eastern plain commonly ranges from about 100,000 to 1,000,000 feet squared per day." (Lindholm, 1996). These basalts comprise the "primary aquifer" as referenced in this report.

The Quaternary basalts are the source for nearly all the springs of significance in the study area – total Buhl to Lower Salmon Falls springs discharge averages 2500 cfs (Wylie, 2012a) – including both the tunnel and natural spring flow at Rangen (described in detail below).

Discharge from this aquifer produces springs where topography (e.g. the Hagerman rim, the Snake River canyon) intersects the Quaternary basalt water table, most commonly occurring at the contact between Quaternary basalts and underlying, dramatically less permeable Tertiary-age units. The details of these "contact springs" may be complicated by overlying landslide deposits obscuring contacts, but the basic relationship is the same: groundwater is discharged to the surface at local topographic low points where downward infiltration is inhibited by lower permeability materials.

Along the Hagerman Rim, the primary aquifer has been fully dissected by erosion. Although these deposits are 50-100 ft. thick, because they are drained by springs along their lower contact, the saturated thickness is substantially less than that. Saturated thickness increases eastward from the Rim springs, to 170 ft. at the Henslee and Wendell wells.

Regionally westward groundwater flow towards the rim terminates along the rim, either as discharge to the surface (e.g. at Rangen) or as a change-of-direction to flow toward the lower-elevation discharges along the Malad River (north) or in the Thousand Springs area (south). At the north end, the Hagerman Rim terminates at its intersection with the east-west trending Malad Gorge. At the south end of the rim, its topographic "step" simply attenuates, and by a point 1.5 miles southeast of Rangen, there is continuous outcrop of basalt from the eastern plateau area to the edge of the Snake River canyon (see Figure 2). Groundwater in the primary aquifer south of the termination of the Hagerman Rim continues southwestward to discharge in the Thousand Springs area.

Groundwater also discharges from the Quaternary basalts where they were dissected by erosion along the Snake River north of Hagerman. Covington and Weaver (1990) map an extensive group of springs below the Lower Salmon Falls Dam, with total flow estimated at 20 cfs. As with the springs along the Hagerman Rim, discharge commonly occurs at the contact with the underlying, Tertiary-age deposits. Additional discharge from the Quaternary basalts may occur upstream of the Lower Salmon Falls Dam, where these deposits extend to below-reservoir level.

While this basalt aquifer may behave in a general and predictable manner at a regional scale, the USGS studies point out that "locally, hydraulic characteristics of basalt and rate and direction of water movement vary widely within a short distance." (Whitehead, 1992; p. B23).

Geologists describing the core from the USGS Wendell borehole concluded, "Contacts between flows are commonly rubbly and have high porosities and hydraulic conductivities, which make interflow zones major avenues for horizontal movement of water" and "the basalt ranges from very vesicular with high hydraulic conductivity to crystalline with little or no hydraulic conductivity" (Whitehead and Lindholm, 1985).

A common source of greatly-enhanced basalt permeability occurs through the formation of "pillow basalts". Whitehead (1992; p. B15) explains the process: "Extremely rapid cooling, as in shallow water, causes steam explosions, and the cooled lava solidifies into a wide size range of generally rounded forms, or pillow lavas.", and describes mapping of "the north wall of the Snake River canyon between King Hill and Milner" that "verified that the largest springs issue at various altitudes from pillow lavas [filling] in ancestral Snake River canyons." (p. B26).

Detailed studies in the Quaternary basalt aquifer in the central Eastern Snake Plain Aquifer found "core-scale permeability of basalt varies by six orders of magnitude ..." (Welhan et al., 2002; p. 439). These authors also evaluated the impact of "fissure networks" on basalt permeability and concluded, "should such fracture networks prove to be important features of the eastern SRP [Snake River Plain] basalts, the high permeability and extreme hydraulic anisotropy[2] they would impart to the aquifer would explain such high-volume, localized spring discharges from the eastern SRP as are found at Thousand Springs." (p. 453).

At a regional scale, of course, local anisotropies tend to average out, but even so, the USGS Regional Aquifer-System Analysis (RASA) modeling used a "model calibrated" horizontal to vertical permeability ratio of 100 for basalt units (Garabedian, 1992; p. F44).

3. Tertiary Sediments

Underlying the Quaternary basalts (Snake River Group) in much of the study area are sediments primarily of Tertiary age. Although present beneath the study area east of the Snake River, these sediments are of greatest thickness and most extensive outcrop west of the river, part of a mixed volcanic and sedimentary series regionally termed the "Idaho Group"[3]. Within the study area, the Tertiary sediments are represented by:

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[2]"anisotropy - condition of having different properties in different directions" ("Dictionary of Geologic Terms", Doubleday, 1962)

[3]Over the larger area of the eastern Snake River Plain, the Idaho Group includes some deposits of Quaternary age (e.g. Whitehead, 1992), but IGS mapping in the study area places these deposits in the Tertiary Period.

Tuana Gravel (Tt) - "Well bedded and sorted pebble and cobble gravel interbedded with layers of sand and silt" (Kauffman et al., 2005).

Glens Ferry Formation (Tsgf) - "Poorly consolidated, bedded lake and stream deposits. In Hagerman Valley primarily flood plain lithofacies that include calcareous olive silt, dark clay, sand locally cemented, and fine pebble gravel." (Kauffman et al., 2005).

Across most of the study area, these sediments are present beneath the Quaternary basalts and this contact marks the bottom of the primary aquifer. In some areas, the Tertiary sediments were removed by erosion prior to deposition of Quaternary basalts (or were never deposited), and the lower contact of the primary aquifer is with the Tertiary basalt sequence described below.

Outcrops of Tertiary sediments on the east side of the Snake River are largely confined to the steep slopes beneath capping Quaternary basalts flows, where a mantle of basalt talus commonly obscures contact relationships. For example, Covington and Weaver (1990) map nearly all the slope along the Hagerman rim as Quaternary-age "talus", with exposed "Tg" (= Glenns Ferry Fm.) outcrop only along the Vader Grade. IGS mapping (Figure 2) presents nearly all this slope as Glenns Ferry Fm. ("Tsgf") outcrop.

The eastward termination of the Glenns Ferry Fm. is uncertain. The schematic cross-section presented by Whitehead (1992, Plate 3) suggests a roughly horizontal, tabular body of sediments between the Quaternary basalts and Tertiary basalts, extending eastward approximately 15 miles from the Hagerman rim, and terminating in some unknown geometry. Malde (1991; p. 258) concludes that "the Glenns Ferry Formation thins eastward and pinches out between Banbury Basalt and overlying basalt of the Snake River Plain about 20 km east of Hagerman". (The Banbury Basalt is of Tertiary age, discussed below. The "overlying basalt" is in the Quaternary basalt group described above.)

In some areas, the Tertiary sediments and basalts are interlayered. This is most common on the west side of the Snake River, where, adjacent to the present study area, the sediments of the Glens Ferry Formation dominate from river level to the upland surface (e.g. see the "Tsh" basalt units west of the river on Figure 2.) East of the Snake River, Kaufman et al. (2005) map Tertiary basalts overlying Glenns Ferry Fm. in a small exposure near the mouth of Malad Gorge. Farmer (undated; p. 69) suggests springs in the Thousand Springs area emerge at the top of the Tertiary basalts, one flow of which overlies an outcrop of sediments tentatively identified as Glenns Ferry Fm. Similarly, USGS investigators suggest sedimentary strata within the Tertiary basalt sequence are Glenns Ferry equivalents (e.g. Whitehead and Lindholm, 1985).

The Tuana Gravel (Tt) outcrops extensively west of the Snake River, capping the Glenns Ferry Fm. strata over most of the upland area above 3400 ft. elevation. East of the Snake River, Tuana Gravel outcrop is mapped only in a small patch atop the Glenns Ferry Fm. at the top of the Vader Grade (see Fig. 1 for location), at elevation 3230 ft. This is consistent with the interpretation of Othberg et al., 2005 that "the gravel was deposited by an ancestral Salmon Falls Creek [a west-side Snake tributary] that prograded braided-stream deposits across a high, nearly flat plain formed on the Glenns Ferry Formation" if the original Glenns Ferry Fm. were continuous across the present Snake River Canyon, i.e. sloping eastward through the present Hagerman rim. Link et al. (2002; p. 114) studied the emplacement of the Tuana Gravel with respect to the evolution of the Snake River drainage, and concluded, "The main stem of the Snake River need not have been present during any deposition at Hagerman".

Although of quite limited extent on the east side of the Snake River, the potential significance of this unit to my study is the conclusion of Farmer (2009; discussed further below) that the Tuana Gravel plays an important role in the Rangen groundwater discharge. Both the lithologic description and local expertise (Farmer, 2012) indicate this unit is locally highly permeable, with water-production potential akin to the overlying basalts. By virtue of its high permeability and only local occurrence, for purposes of hydrostratigraphic characterization, this gravel is combined with the overlying Quaternary basalts unit as part of the "primary aquifer". The following discussion of the groundwater characteristics of the Tertiary sediments addresses only the Glenns Ferry Fm.

Groundwater Characteristics. The groundwater-production and transmission potential of the Glenns Ferry Fm. is small. Although, well-driller logs note the presence of discernable groundwater (i.e. checking the "Y" [yes] in the "water" column of the standard IDWR "Driller's Report") in individual strata, they commonly drill on through to the underlying basalts even for the modest demands of domestic and stock use, suggesting generally low productivity.

The USGS exploration well northeast of Wendell ("Wendell Well" on Figure 1) penetrated a body of sediment identified as Glenns Ferry Fm.: 100 ft. of gravel and conglomerate and 100 ft. of clay, silt, and sand. The Glenns Ferry Fm. deposits were interpreted as "the confining layer" "that separates the two basalt units". Groundwater-level monitoring piezometers completed above and below these sedimentary layers monitored a consistent head[4] difference, approximately 64 ft. higher in the lower basalt unit, over a 3-year period (1982 - 1984). (Whitehead and Lindholm, 1985).

Closer to Rangen, the Henslee monitor well, interpreted by Farmer (2009) as having penetrated the Glenns Ferry Fm., found a 5 ft. head difference (again, higher in the deeper unit) across this sedimentary sequence. The role of the Glenns Ferry Fm. with respect to groundwater flow between the underlying and overlying basalts likely varies locally, but it consistently provides a much lower permeability in contrast with the highly-permeable, overlying Quaternary basalts in the study area.

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[4]"Head" is the fluid pressure in the aquifer, commonly expressed as the level to which groundwater will rise in a cased well. A substantial difference in head over a short vertical distance indicates the presence of confining layers which impede the equalization of head throughout an aquifer.

4. Tertiary Basalts

Underlying the Quaternary basalts and the Tertiary sediments (where present) in the study area is a thick sequence of basalts of Tertiary age forming the bulk of the regional "Idaho Group":

> Basalt of Shoestring Road (Tsh) - "Forms a thin layer 30-50 feet thick within the Glenns Ferry sediments on the west side of the Snake River" (Othberg et al., 2005).
>
> Basalt of Oster Lakes (Tos) - "Banbury Basalt, basalt of upper part" of Covington and Weaver, 1990 (Othberg et al., 2005).
>
> Older basalt flows, undivided (Tub) - also part of "Banbury Basalt, basalt of upper part" of Covington and Weaver, 1990; "includes fine-grained sediments either intercalated with or underlying the basalt near the mouth of Malad River" (Othberg et al., 2005).

These units underlie the entire study area, and extend eastward beneath the eastern Snake River Plain. In the study area, the Tertiary basalts outcrop only where erosion along the Snake and Malad Rivers have cut down through the Quaternary sediments, Quaternary basalts, and Tertiary sediments. The distribution and thickness of Tertiary volcanics beneath the broader eastern Snake River Plain are poorly understood. Where the Tertiary sedimentary strata were stripped away prior to emplacement of the Quaternary basalt flows, the upper contact of the Tertiary basalts marks the bottom of the primary aquifer.

<u>Groundwater Characteristics</u>. Although of similar origin, the lower (Tertiary) basalts are widely understood to have substantially lower permeability than the overlying, younger basalts (Quaternary), e.g. "The older volcanic rocks are typically much less transmissive than the Quaternary basalts", (Whitehead, 1992; p. B1). For a test hole in the central Eastern Snake Plain Aquifer, Whitehead (1992; p. B28) reports, "transmissivity of the Quaternary basalt was estimated to be 1,000 to 10,000 times greater than that of the Tertiary basalt".

As with the upper basalts, the Tertiary-age flows also exhibit significant anisotropy. There are confining units both above and within the Tertiary basalt sequence. For example, the USGS "Wendell" well referred to above also completed two piezometers within the Tertiary basalts - one at the top of the sequence, and one 416 ft. deeper, at the top of "sediments ... believed to be the middle member of the Banbury Basalt" (Whitehead and Lindholm, 1985; p. 17). In that case, a head difference of 93 ft. was observed, more than the head difference across the Glenns Ferry Fm. discussed above. The confining layer (within the Tertiary basalt sequence) is described as "clay-filled vesicular basalt, crystalline basalt, and clay" (Whitehead and Lindholm, 1985).

Although generally forming a low-permeability barrier, above which nearly all the large springs of the study area discharge, the Tertiary sediments and Tertiary basalts are not entirely unproductive of groundwater. At the USGS Wendell borehole, for example, "Eighty of the top 100 ft [of Tertiary basalts] is a porous cinder zone with high hydraulic conductivity." (Whitehead and Lindholm, 1985; p. 16). Whether due to poor permeability or to the abundant groundwater supply commonly available from shallower units, there are no high-volume wells completed in this lower aquifer in the study area (Farmer, 2012). Development of the Tertiary basalts has apparently been successful for domestic and stock wells along the Hagerman rim where the primary aquifer is unsaturated, forcing development into the underlying strata (e.g. Ramsey well, Anderson well; see Figure 4 for locations).

AQUIFER DEFINITION

This section evaluates how the hydrogeologic units described above have been grouped into identified "aquifer(s)" for the development of conceptual evaluations and numerical groundwater flow modeling. As explained above, my analysis concludes that the Quaternary basalts form the primary aquifer in the study area, but that the Tertiary sediments and basalts constitute a separate, lower aquifer within the regional groundwater framework.

Regional groundwater flow modeling of the eastern Snake River Plain has been undertaken by various groups over the last several decades. The USGS Regional Aquifer-System Analysis (RASA) investigations use the term, "Snake River Plain Regional Aquifer System", but the precise hydrostratigraphic delineation is uncertain. Whitehead, 1992; p. B19 refers to "a series of basalt flows and intercalated pyroclastic and sedimentary materials that underlie the Snake River Plain". However, the focus of attention is clearly on the younger basalts, e.g. Whitehead (1992) notes that the Quaternary basalts form "the most transmissive part of the aquifer system" (p. B19), and that "chiefly Quaternary basalt of the Snake River Group contain and yield exceptionally large volumes of water" (p. B22), and his summary of aquifer hydrology is titled "Hydraulic Characteristics of Quaternary Basalt and Alluvial Aquifers".

In terms of modeling groundwater flow within the aquifer, the regional RASA research divided the aquifer into 4 layers as arbitrary thickness slices. At the western edge, they maintained the 200 and 300-ft. thickness of the two uppermost model layers, regardless of lithology. Thus, in the present study area, the RASA modeling subsumed the uppermost Tertiary basalts, the Tertiary sediments, the Quaternary basalts, and the Quaternary sediments into a single layer, underlain by 300 ft. of additional Tertiary basalts (and interlayered sediments). (Garabedian, 1992; p. F38 and Figure 23).

The documentation for the Enhanced Snake Plain Aquifer Model (ESPAM), also a regional-scale model, refers generally to the "eastern Snake River Plain aquifer", but provides no specific vertical delineation. For groundwater modeling, an arbitrary elevation of 2000 ft. was adopted for the base of the effective aquifer, although "the active portion of the aquifer often is thought to be limited to the upper several hundred feet of saturated thickness" (Cosgrove et al., 2006; p. 13).

The ESPAM modeling (versions 1 and 2) treats the entire aquifer as a single layer, representing all four of the sequences described above only in terms of their impacts on average, cell-by-cell hydrologic properties[5].

Ralston (2008; p. 3), working in the present study area, discards all deposits beneath the Quaternary basalts in concluding, “The Snake Plain aquifer in the general vicinity of the Thousand Springs to Malad reach is hosted by the Quaternary basalt units with thin sedimentary units. The effective base of the aquifer is the contact between the Quaternary basalt units and the underlying Tertiary sedimentary and/or basalt units. Almost all of the springs within the Thousand Springs to Malad reach are located along the contact between the Quaternary basalt units and the underlying Tertiary sedimentary and/or basalt units.”

Farmer (2009), also working at the scale of the present study area, echos the concept of “the upper Quaternary basalt flows that host the Eastern Snake Plain Aquifer” (Farmer, p. 36), but suggests there are underlying aquifers as well. He proposes “a three-layer geologic model ... [as] the foundation for the hydrostratigraphic model” (Farmer, p. 17): 1) Quaternary basalt; 2) Glens Ferry Fm.; and 3) Tertiary basalt, i.e. sequences 2, 3, and 4 as described above (pp. 4-11); see Figure 5 for Farmer’s schematic cross-section. He goes on (p. 36), “The GFF [Glenns Ferry Fm.] likely forms a wedge of clastic sediments eastward from Rangen towards Wendell and may create vertically divergent groundwater flow paths with a deep path flowing through basalts underlying the GFF.” and refers to “a deep aquifer system beneath the Glenns Ferry Formation that is not being used” (Farmer, p. 33).

Delineations of the regional aquifer west of the Hagerman rim also vary. The RASA and ESPAM 1 models carried the regional aquifer west to the Snake River, but Whitehead (1992; Plate 3) terminates the Quaternary basalt at the rim. (West of the rim, the thickness of the Quaternary basalts is described as, “Generally none. If present, of small areal extent and less than 100 ft. thick.”) ESPAM 2 and 2.1 terminate the aquifer along or just west of the Hagerman rim, consistent with the conclusions of Bendixen (1995) and Ralston (2008) that the basalts west of the rim have no hydrologic connection with the regional aquifer. (For example, “The available data indicate that water producing zones (aquifers) in the area between the Plateau rim [Hagerman Rim] and the Snake River are not part of the Snake Plain aquifer, regardless of the age of the basalt units.” (Ralston, 2008; p. 5).) Farmer (2009) concluded that those basalts are somewhat connected, not via direct east-to-west groundwater flow, but via a “ramp” down which groundwater flows from the south end (i.e. northward from the Thousand Springs area). IDWR well records do not suggest there is a significant aquifer present in this area (west of the rim and north of Rangen), i.e. there are no irrigation wells, and the highest listed production rate is only 85 gpm (for a domestic well use).

[5]One ESPAM2.1 model cell is 1 mile by 1 mile by 4,000 ft. thick.

GROUNDWATER FLOW

At the regional scale, groundwater in the Eastern Snake Plain Aquifer is recharged with surface and groundwater inflow from the north and by precipitation and surface-water irrigation infiltration across the expansive outcrop surface. Groundwater flow is generally westward, as presented on regional potentiometric surface maps, e.g. Figure 6.

At the scale of the present study area, Figure 7 presents a more detailed view. This contouring is of November, 2011 synoptic measurements of groundwater levels including the present study area, collected by IDWR (contoured by Farmer and Blew, 2012 as their "Figure 14"). With the exception of a few wells right along the rim, these data are from the Quaternary basalt aquifer. Flow toward the Hagerman rim from east and northeast is demonstrated, which of course is required by the copious discharge from the aquifer to the many springs along the Snake River. But Farmer and Blew conclude there are "at least six groundwater divides" in this reach, separating the generalized eastward groundwater flow to converge on specific discharge areas (see groundwater flow arrows[6]).

BASE OF THE PRIMARY AQUIFER

Division of the deposits of the study area into an upper, "primary" aquifer and a "lower" aquifer, requires delineation of the boundary between the two. This section of the report begins with an explanation of the hydrogeologic importance of that delineation, then addresses the boundary for each of several portions of the Rangen study area (Malad Gorge, Hagerman Rim, Hagerman Valley, Magic Springs / Thousand Springs, and East of Rim).

As described above, there are many hydraulic boundaries within the larger stratigraphic sequences present beneath the study area. Vertical flow barriers of unknown lateral extent exist within individual basalt flows and between flows. Fine-grained sedimentary deposits within and between basalt sequences are also likely present at many geographic scales, adding further to the complexity of groundwater flow. However, there is one, major, regional hydrogeologic boundary of widely recognized importance at the base of the primary aquifer (Quaternary basalts):

> "Large springs in the Snake River canyon between Milner and King Hill [locations which span the study area] issue at the contact between the highly transmissive pillow lava and the less transmissive underlying rocks" (Whitehead, 1992; p. B1)

> "the altitude of north-side springs are controlled by several factors: (1) altitude of the contact between relatively impermeable Banbury Basalt and basalt of the Snake River

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[6]Groundwater flow directions on this and other figures in this report are inferred based on perpendicularity to equal-head contours. In basalt aquifers, this generalization is more appropriate over larger areas than at very local scales.

Group, (2) location of lake clays, and (3) location of relatively impermeable Idaho Group (Glenns Ferry Formation) sedimentary rocks." (Garabedian, 1992; p. F17)

> "Therefore, in the Thousand Springs area, sedimentary rocks constitute the base of the Quaternary basalt aquifer. The steeper water-table gradient in this part of the Snake River Plain is attributed to lower transmissivity caused by thinning of the basalt aquifer" (Whitehead, 1992; p. B27)

> "The topography of the geologic contact between the Quaternary basalt units and the underlying Tertiary sedimentary and/or basalt units along the plateau rim is an important controlling factor for ground-water flow and spring discharge characteristics in the Thousand Springs to Malad reach." (Ralston, 2008; p. 5)

> "The topography of the bottom of the Quaternary basalt is the dominant control for the locations and amounts of water discharged from springs and the sensitivity of the springs to changes in ground-water levels." (Ralston, 2008; p. 6).

> "the Rangen Spring (and probably other springs north from Rangen up to Malad Gorge) has a strong component of paleo-topographic lows controlling flow characteristics" (Farmer, 2009; p. 18).

> "Highly permeable pillow lavas and the interconnection of ancestral canyons make the basaltic aquifer along the river reach from Kimberly to Bliss highly transmissive." (Garabedian, 1992; p. F18)

The terms "paleo-topography" and "ancestral canyons" in these statements refer to the shape of the land surface prior to emplacement of the Quaternary basalts. As these basalts, in liquid form, spread across the landscape, they filled in the existing stream channels and valleys and solidified to create a new topography. The drainage network subsequently established on that new surface guided the deposition of later basalt eruptions and gradually the primary aquifer was built up across the eastern Snake River Plain to produce the present surface topography. Thus, there are many inter-flow surfaces beneath the present land surface - as between the cards in a deck - but the surface at the bottom of the "deck", where the Quaternary basalts overly the lower-permeability Tertiary deposits is the surface of interest here.

The lower boundary of the primary aquifer controls the occurrence of major springs in the study area. It is also important for its impact on the saturated thickness of the primary aquifer, i.e. the thickness through which groundwater flows and through which any impacts to groundwater flow must be transmitted. The saturated thickness is the difference between the groundwater level and the lower boundary of the aquifer.

Over the great majority of the aquifer, saturated thickness is likely quite large, vastly more than the few feet or even tens of feet of water level impacts due to changes in recharge or groundwater extractions. In such circumstances, precise delineation of the bottom of the aquifer may be of little significance. Where the saturated thickness is relatively small, however, as it is along the spring discharges of the Hagerman rim, including at Rangen, seasonal and long-term changes in water level may be a significant fraction of saturated thickness. As stated by Ralston (2008, p. 7), "The saturated thickness of the aquifer is small near the Plateau Rim. Lowered groundwater levels result in not only decreased hydraulic head for the springs but also significantly decreased transmissivity." Thus, delineation of the base of the primary aquifer is particularly significant along the Hagerman Rim.

Finally, the elevation of the base of the primary aquifer is important in creating horizontal boundaries to groundwater flow where the base of the aquifer intersects the land surface. This occurs where the aquifer is severed by the Hagerman Rim, the Snake River, and by a section of the Malad River.

Figure 8 presents a schematic contour map of the bottom surface of the primary aquifer. The figure is based on concepts developed by previous investigators (e.g. Farmer, various dates; Ralston, 2008) and the depositional history of the Tertiary sediments discussed above (pp. 7-9), controlled to mapped outcrops, well logs[7], and inferences based on the location of springs. The dots on Figure 8 present the control points. Contouring distant from control points and in areas with only "less-than" control points is hypothetical, presenting an interpretation consistent with the available data, but more conceptual than precise. With the exception of the Rangen area, I have not attempted to resolve the geometry of each spring system along the Hagerman Rim, but expect that considerable detail could be added through careful review of outcrops, springs, and local well logs.

The Figure 8 horizon marks the top of either the Glenns Ferry Fm. or of the Tertiary basalt sequence where Glenns Ferry Fm. deposits are either absent or occur within the Tertiary basalt sequence. For purposes of this investigation, the Tuana Gravel is included with the primary aquifer, despite the geologic age difference, due to the sporadic occurrence and inferred high permeability of the gravel unit. From a hydrostratigraphic perspective, the effective aquifer is defined by the hydrologically-connected body of relatively high-permeability material, bounded on the bottom by the strong permeability contrast with underlying materials (Glenns Ferry Fm. and Tertiary basalts).

Lateral boundaries of the primary aquifer, i.e. the exposed contact with the underlying deposits, are indicated by the red line in Figure 8. At many locations, that contact is obscured by the veneer of Quaternary sediments.

The following paragraphs discuss the base of the primary aquifer for specific portions of the study area.

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[7]The logs for relatively deep wells in the contoured area were reviewed to find both contact elevations and, absent encountering the Quaternary:Tertiary contact, elevations below which that contact is assumed to occur (i.e. the elevation of the bottom of the well).

Malad Gorge

Both Othberg et al. (2005) and Covington and Weaver (1990) map a small outcrop of Glenns Ferry Fm. and Tertiary basalt near the mouth of the gorge. At this point, the primary aquifer is severed by the Malad River. Erosion has carved the gorge entirely through the Quaternary basalt flows to expose the underlying, much-lower-permeability, lower aquifer. Hydrologic continuity within the primary aquifer is likely established upstream (east) of the spring area, where there is substantial, saturated Quaternary basalt thickness above the Glenns Ferry Fm. contact.

Along the river upstream from the Tertiary basalt/Tertiary sediments outcrops at the mouth of the gorge, prolific springs issue from Quaternary basalt flows, at elevations from 2850 to 3090 ft. (Covington and Weaver, 1990). In a schematic north-south cross-section through this reach Farmer and Blew (2009; Figure 7, reproduced here as "Figure 9") suggest springs emerging at river level are a function of a Glenns Ferry Fm. floor to the canyon, i.e. the primary aquifer is draining to the level of the Glenns Ferry Fm. at this point.

In east-west cross-section, detailed examination of groundwater levels associated with dye tracer studies led Farmer and Blew (2012; p. 8) to conclude, "The contour lines show a trough-like depression in the water table with the same long axis orientation of northwest/southeast as the tracer test flow path .... The location of this water table depression fits near where Malde (1971) mapped it. If the ancient canyon exists here, and has highly permeable pillow rubble zones at depth, then in effect the subsurface mega-scale feature is acting like a drain (Stearns, 1936) that captures the Eastern Snake Plain Aquifer water and routes it down the ancient canyon towards the Malad Gorge." Thus, the Quaternary basalt:Tertiary basalt contact dips eastward from the mouth of the gorge, but then rises to the east further upstream. Well logs adjacent to the canyon upstream of the springs (around I-80) report sediments interpreted as Glenns Ferry Fm. at elevations around 3100 ft., marking the northeast bank of the suggested north-south paleo-channel (e.g. see the "2900" contour on Fig. 8).

Hagerman Rim

Covington and Weaver (1990) map the west-facing slope below this topographic rim as simply, "Landslide deposit", with the exception of an outcrop of Glenns Ferry Fm. at the Vader Grade, ½ mile northwest of Rangen. Kaufman et al. (2005) and Othberg et al. (2005) map most of this slope as Glenns Ferry Fm. outcrop, and provide a Quaternary basalt:Glenns Ferry Fm. contact from just south of the Malad Gorge (Glenns Ferry Fm. top at 3125 ft. elevation) through the Vader Grade (3210 ft.) and on to approximately 1 mile southeast of Rangen (3180 ft.). This contact forms a broad arch in north-south profile.

At a finer scale, this arch is cut by notches (interpreted as roughly east-west paleo-channels eroded into the Glenns Ferry Fm. surface), which serve as outlet points along the west edge of the Quaternary basalt aquifer that covers the plateau and fills the paleo-channels. Data from the Rangen area mark the top of the Glenns Ferry Fm. at 3210 ft. elevation on the Vader Grade outcrop, 3400 ft. northwest of the Curren Tunnel (Kaufman, 2005); at 3159 ft. elevation in the

Rangen Monitor Well 600 ft. east of the tunnel (Farmer, 2009), and at 3100 ft. (Farmer, 2009) where the springs below the Curren Tunnel discharge. Thus, the local relief on the base of the primary aquifer at Rangen is on the order of 100 ft.

Farmer (2009; Figure 24) suggests that the Curren Tunnel, at elevation 3145 ft., may mark the actual base of the Quaternary basalts, with the larger, lower groundwater discharges (at 3100 ft. elevation) issuing from underlying, high-permeability layers of the Tuana Gravel. If so, the Tuana deposits serve as part of the primary aquifer despite their Tertiary age, with groundwater discharge controlled by the occurrence of underlying, low-permeability units of the Glenns Ferry Fm. proper.

The 3210 ft. elevation for the top of the Glenns Ferry Fm. cited above from outcrop mapping is based on the location of the Glenns Ferry Fm.:Tuana Gravel contact, i.e. grouping the Tuana Gravel with the overlying basalts. Well logs in the area are interpreted similarly (see Figure 4 for locations):

Richardson well: 3161 ft. - contact between "crevas w/ cinders" and "clay"
Prisbrey well: 3166 ft. - contact between "sand & gravel" and "clay"
Anderson well: 3189 ft. - contact between "basalt gray" and "clay"
Ramsey well: 3157 ft. - contact between "cinders" and "clay"
Rangen Monitor Well: 3100 ft. - contact between "gravel" and "clay & gravel"/"clay sand"
Hosman well: 3168 ft. - contact between "basalt grey" and "clay"
Kelley well: 3098 ft. - contact between "sand" and "clay"
Waters well: 3138 ft. - contact between "basalt grey" and "clay"

The saturated thickness of the primary aquifer is 170 ft. at the Henslee well, 3 miles east of the rim. But comparing the bottom elevations with the groundwater elevations along the rim, e.g. 3155 ft. in the Rangen Monitor Well (Farmer, 2009), demonstrates that the saturated thickness of the primary aquifer is zero at many locations. Farmer (undated, p. 82) makes this point for the Quaternary basalt:Glenns Ferry Fm. contact outcrop at the Veenstra Dairy (1 mile south of Rangen), where the 3162 ft. elevation of the contact leaves the primary aquifer unsaturated.

Saturation is maintained along the rim only where the elevation of the base of the primary aquifer is relatively low, at the "notches" in the underlying Glenns Ferry Fm. through which aquifer discharge takes place. Eastward from the rim, the saturated thickness of the primary aquifer increases substantially, as the groundwater level gets higher in elevation (Fig. 7) and the base of the aquifer gets lower (Fig. 8).

Based on his 30 years of local well-drilling experience, Wendell driller Larry Nielson (2012) recommends staying back from the rim (east) to avoid dry holes and sand problems; "closer to the rim, your chances of a big well are slimmer", "a half a mile can make a big difference".

Hagerman Valley

West of the Hagerman rim, the top of the Glenns Ferry Fm. is substantially lower than along the rim. This reflects the complex erosional history of the present Snake River gorge and, perhaps, downdropping of parts of the valley along rim-parallel faults (e.g. a "ramp fault" above the National Fish Hatchery suggested by Farmer (e.g. undated, p. 66) and the Kauffman et al., 2005 conclusion that, "The stratigraphic relationship [of the Tuana Gravel] at Vader Grade is similar to that at the top of Snake River bluffs to the west where the contact is about 3,400 feet in elevation, suggesting the section is downdropped to the east. Evidence from well drillers' logs in the Tuttle quadrangle support that conclusion."

In any case, the Quaternary basalt aquifer is severed along the rim, creating a series of springs along its exposed lower contact. Quaternary basalt flows overlying the Glenns Ferry Fm. within the Hagerman valley (i.e. below the rim) have the potential for hydrological continuity with the larger Eastern Snake Plain Aquifer only south of the middle of Sec. 5 (T8S, R14E), i.e. at the head of Farmer's "ramp" structure (e.g. Farmer and Blew, 2012), (see Figure 1 for location). Farmer (2009) suggests that "Groundwater is flowing down this ramp structure through a pillow zone and contact between Quaternary basalt flows."

Younger (post-Quaternary basalts) sediments obscure the Quaternary basalt:Glenns Ferry Fm. contact through much of this area. Minimum elevations around 2850 ft. are provided by mapped Glenns Ferry Fm. outcrops along the Snake River between Lower Salmon Falls and the Malad Gorge (Covington and Weaver, 1990), and by mapped Tertiary basalt outcrops at 2950 ft. elevation 2 miles south of Hagerman (Kaufman, 2005). A Quaternary basalt:Glenns Ferry Fm. contact is mapped at 3020 ft. in the middle of Sec. 6 (T8S, R14E), at the north end of the Hagerman National Fish Hatchery (Kaufman, 2005). For this contact surface to remain buried beneath the younger sediments, a northward dip is required.

Magic Springs / Thousand Springs

Covington and Weaver (1990, 1991) map only a thin band of landslide deposits between outcrops of the Quaternary basalts and the underlying Tertiary basalts in this area, i.e. a contact elevation of approximately 3000 ft. Kaufman et al. (2005) mapping indicates that the Glenns Ferry Fm. is locally absent south of the middle of Sec. 5 (T8S, R14E), i.e. the Eastern Snake Plain Aquifer terminates at the major spring line on top of the Tertiary basalts. Spring elevations in this reach are around 2980 ft., emerging "at the top of the Banbury Basalt" (Tertiary basalt) (Covington and Weaver, 1990).

East of Rim

As described above, the Quaternary basalt:Glenns Ferry Fm. contact appears to dip eastward from near the mouth of the Malad Gorge, then to rise beneath the upstream portion of the gorge. The eastward dip appears to be maintained to the south, i.e. east from along the Hagerman rim.

Farmer (2009) provides cross sections for the Rangen area indicating a locally eastward dip, on which he identifies the top of the Glenns Ferry Fm. at 3028 ft. elevation – 80 ft. lower than on the Vader Grade – in the “Henslee” well, 3 miles east of Rangen.

Wells sufficiently deep to hit the Glenns Ferry Fm. (or Tertiary basalts) east of the Hagerman rim are relatively rare due to the widespread productivity of the overlying Quaternary basalts (i.e. there is little reason to explore for deeper groundwater). Thus, there are few data with which to profile the base of the primary aquifer.

The most detailed stratigraphy available is from a hole cored to a depth of 1123 ft., drilled by the USGS northeast of Wendell in support of their RASA work. Sedimentary rocks were encountered between 403 and 590 ft. in depth: “The 187-ft thick interval of low electrical resistivity material that underlies the basalt consists of sediments that grade downward from gravel to clay. Correlation with other drill holes and comparison with outcrops near the Snake River suggest that the sediments are part of the Tertiary and Quaternary Glenns Ferry Formation.” (Whitehead and Lindholm, 1985; p. 16). The elevation of the top of this sedimentary sequence is 3197 ft., 169 ft. higher than at the “Henslee” well and thus requiring a relatively low area between the Wendell well and the Rangen rim, similar to that suggested by Farmer and Blew (2012) for the Malad area.

The southeastward extension of the paleo-channel that intersects the Malad Gorge (see Figure 8) is based on the Quaternary:Tertiary contact in the USGS “Wendell” well (Whitehead and Lindholm, 1985), the Henslee well (Farmer, 2009), and along the Hagerman rim (Idaho Geological Survey mapping). Logs for wells indicated with a “?” symbol on Figure 8 do not provide clear indication of the contact at the contoured elevation; whether due to the absence of a significant thickness of contact-identifying sedimentary layers or due to errors in this interpretation of the contact surface, is beyond the scope of this investigation.

In addition to the USGS “Wendell” well, examination of drillers’ logs for the area east of Rangen finds a group of wells 7 miles ESE of Wendell (southwest of Jerome; T8S, R16E, Secs. 21, 28, 33) that encountered from 95 to 174 feet of fine-grained sediment (e.g. “clay & sand stripe”, “yellow clay”, “clay sticky”, “clay”), with upper-contact elevations between 3304 and 3376 ft. (depths around 200 ft.). Wells within two miles north and northwest failed to report significant thicknesses of sedimentary deposits, despite bottom-hole elevations around 3200 ft. elevation, indicating the sediments either represent a local high spot on the base of the primary aquifer or a discrete body of sediments within the widespread series of basalt flows. In either case, this area appears to represent a barrier to groundwater flow in the primary aquifer, as the saturated interval above the fine-grained sediment sequence is minimal to zero, i.e. there may be no effective Quaternary basalt aquifer at these locations.

RANGEN GROUNDWATER DISCHARGE

This section presents a focused discussion of the details of the specific groundwater discharges supplying the Rangen facilities. Like the discussion of the study area hydrogeology above, the objective is to develop a foundation from which to examine the fidelity of the ESPAM2.1 groundwater flow model to the actual conditions at Rangen. The two groundwater discharges at Rangen – the Curren Tunnel and the "lower springs" are described, followed by evaluation of the groundwater flow system they reflect and conditions in the supplying aquifer.

Figure 10 presents a topographic profile of the groundwater discharge at the Rangen complex; Figure 11 shows the area photographically.

The rim of the plateau immediately above the Rangen complex is at approximate elevation 3220 ft., then rises gradually to the east (e.g. 3250 ft. elevation 1 mile away). The rim and the plateau to the east consist entirely of basalt flows, with the tiny exception of a small outcrop of Glenns Ferry Fm. and Tuana Gravel on the plateau at the top of the Vader Grade (see Figure 2).

Pillow basalts are well exposed in outcrops immediately below the rim. Below an elevation of approximately 3170 ft., continuous outcrop is uncommon as rubble has accumulated on the less-steep slopes. Also, as seen in Figure 11, vegetation further obscures outcrop relationships.

CURREN TUNNEL

There are various groundwater discharge points feeding the Rangen complex. Highest in elevation is the Curren Tunnel. This tunnel was bored into the hillside beneath the rim. The tunnel opening is approximately 75 ft. west of the rim and approximately 70 ft. below the rim elevation. The tunnel begins in a deposit of large basalt boulders, immediately downslope from conspicuous outcrops of pillow basalts. At the outlet, the tunnel is lined with 6-ft. diameter corrugated steel pipe. This pipe extends into the hillside for approximately 50 ft. (visual inspection and IDWR, 1993), beyond which the tunnel extends as an open rock excavation (see Figure 11). Groundwater enters the tunnel from the aquifer at unknown (probably numerous) points and flows by gravity to discharge at the tunnel mouth.

The history and construction details of the Curren Tunnel are unclear. The earliest water right attributed to the tunnel has an 1884 priority date. Testimony by Lonny Tate (2012; pp. 14, 60, 61) states that the tunnel is "maybe 300 foot" long, at a fairly constant elevation, and includes a fork about 3/4 of the way to the end. Flow is described as somewhat greater from the east [south] fork. Dan Maxwell has also been inside the tunnel. He described the length of the tunnel as "oh, 100 feet maybe", but also remembers the fork described by Tate (deposition testimony 2012, p. 9).

Assuming groundwater does not enter the tunnel through the steel culvert lining, the first opportunity for collection of groundwater is at the end of the lining. Given the slope of the hillside above the tunnel entrance, this groundwater-entry point is at least 40 ft. below the land surface, and the effective "depth" of the tunnel increases with greater penetration into the hillside. As the tunnel proceeds eastward beneath the plateau rim, it is approximately 70 ft. beneath the ground surface (see Figure 10).

The earliest water rights on production from the tunnel are for irrigation (e.g. Candy, Crandelmeier), with an 1884 priority. These rights irrigate land to the south and west of the tunnel which, for gravity irrigation, require delivery of water at an elevation of at least 3130 ft. (e.g. the Candy right in the NE1/4 SE 1/4 Sec. 31, T7S, R14E; see Fig. 4 for location of this area). Thus, although there are natural springs at a lower elevation (described below) there was obvious value in intersecting the groundwater table at as high an elevation as possible, to allow irrigation of the target lands by gravity flow.

There are small seeps on the hillside just north of the tunnel entrance, suggesting there may have been a natural groundwater discharge at the site of the tunnel, although these seeps may be a function of irrigation runoff from the adjacent rim (see Figure 11). An article in the December 30, 1962 Twin Falls Times News suggests the source of the Rangen groundwater supply as "man-made springs", created when "early pioneers in search of irrigation water drilled a hole into the cliff and struck water" (emphasis added). The source of this report is unclear (and it was clearly long after tunnel construction), but it describes an excavation to develop groundwater in the absence of an existing spring. It is unclear if the tunnel sought to develop additional groundwater at a site of existing discharge or was excavated into a dry hillside in hopes of intersecting the groundwater table as the tunnel penetrated into the aquifer.

Whether the 50 ft. of lining was necessary to ensure tunnel stability, or reflects the distance to the first significant groundwater flow (or flow increase), is also unknown. It is clear, however, that the tunnel would have substantially increased the flow of groundwater from the aquifer at this point, both by greatly increasing the surface area through which groundwater escapes the aquifer, and by penetrating into the higher aquifer water levels east of the rim (i.e. increasing the available drawdown[8]). And the tunnel is certainly instrumental in maintaining the discharge of groundwater at this point in times of declining aquifer water levels (i.e. groundwater might not discharge in the absence of tunnel excavation).

The Curren Tunnel is a horizontal, flowing well. Just as a vertical well is constructed to provide access to groundwater below the water table, allowing the removal of water to create a gradient toward the well, a horizontal well creates drawdown in the aquifer by virtue of penetrating a sloping water table. Discharge is a function of the difference between the hydraulic head at the point(s) where groundwater enters the well and the head in the surrounding aquifer. The greater that difference, whether created by pumping water from the well, relieving the pressure in an artesian aquifer, or excavating a horizontal well to a point further below the aquifer water table,

[8]The difference between the total depth of a well and the water level in the surrounding aquifer is the "available drawdown", i.e. how far down the water level can be drawn to induce flow into the well.

the greater the discharge. The advantage of a flowing well, whether vertical or horizontal, is that groundwater can be extracted from the aquifer without use of a pump.

To provide quantitative analysis of the potential impact of the construction of a horizontal well like the Curren Tunnel, a small MODFLOW-based groundwater model was developed by Dwivedi and Clark (2012). The aquifer at the tunnel was idealized as a rectangular prism, 606 ft. long (the approximate distance between the tunnel outlet and the Rangen Monitor Well), 408 ft. wide (representing the paleo-channel filled with pillow basalts and Tuana Gravel), and 60 ft. deep (the difference in elevation between the outlet of the lower springs at Rangen and groundwater level in the Rangen Monitor Well). The aquifer to the east is represented by a constant head boundary at one end of the aquifer; the tunnel is represented by a 250-ft. long horizontal line of constant-head cells extending back into the aquifer from the west end (see Figure 12). The elevation difference between the constant head boundary and the drain discharge is 10 ft. The aquifer transmissivity was adjusted to produce a steady-state flow rate of 26 cfs from the tunnel. When the tunnel was reduced to a single constant-head cell to represent a pre-tunnel natural spring at the location of the tunnel outlet, the flow was reduced to 6.7 cfs. Under this schematic-level modeling, the impact of construction of a drainage tunnel was to increase flow by 19 cfs, a factor of 3.

Of course, this illustrative model provided no alternative outlet for groundwater. For the Curren Tunnel, the pre-construction discharge may have been zero, i.e. the entire production is a function of the creation of the tunnel as a high-level groundwater discharge facility. To the extent aquifer management decisions, calculations of impacts as percentages of discharge, etc. distinguish natural springs from constructed wells, the Curren Tunnel may appropriately be considered a well.

The Rangen Monitor Well is located 588 ft. east of the outlet of the Curren Tunnel (Farmer, 2009). The outlet elevation of the Curren Tunnel has been variously reported as 3138 ft. (Covington and Weaver, 1990), 3145 ft. (Farmer, 2009) and 3150 ft. (IDWR, 2011). The water level elevation in the well has varied between 3153 and 3158 ft. over the 2008 - 2012 period of record. Thus, the aquifer water level may vary between as little as 3 and 8 ft. above the tunnel outlet. That this small difference is sufficient to produce the observed flows is testimony to the utility of tunnel construction and of the permeability of the aquifer, but also indicates the potential vulnerability of tunnel production to small changes in aquifer water levels. The greater fluctuations in flow from the tunnel as compared with the fluctuations in the lower springs (discussed below, p. 23) are likely the result of this tenuous intersection of the groundwater table.

As with a vertical well, the production capacity of a horizontal well like the Curren Tunnel is limited by the available drawdown (< 8 ft.). Although the tunnel is 70 ft. below the ground surface, it is only slightly below the surrounding water level in the aquifer. With only a small head difference between the tunnel outlet and the water table in the host aquifer, the tunnel is akin to a vertical well that barely penetrates the saturated portion of the aquifer. Such a "shallow" well is poorly constructed with respect to maintaining production if aquifer water levels drop, as may happen in response to reduced aquifer recharge (e.g. a decrease in precipitation or irrigation canal seepage) or increased aquifer discharge (e.g. development of the aquifer by other groundwater users). By way of comparison, wells constructed in the primary aquifer immediately east of Rangen have available drawdown of 69 ft. (Tate), 105 ft. (Gibson), and 170 ft. (F. Henslee) (see Figure 4 for locations). The location and construction of the Curren Tunnel render its discharge highly vulnerable to relatively small changes in the water levels in the supplying aquifer.

Had the original intent for the Curren Tunnel been as a year-round supply of water to hatchery facilities at Rangen rather than gravity irrigation of crops on the surrounding uplands, construction of the tunnel at the elevation of the lower springs would likely have provided more water and been far less vulnerable to impacts of fluctuations in regional groundwater levels.

LOWER SPRINGS

There is a small area of seeps north of the tunnel at similar elevation to the tunnel, but natural discharge is predominantly downslope from the tunnel. The geologic conditions of the main springs are not entirely clear, as downslope of the tunnel, vegetation and talus mantle the hillside, obscuring bedrock outcrop relationships. Substantial discharge emerges from areas of angular basalt cobbles and boulders, with and without associated soils and vegetation. Nace et al. (1958; p. 54) describe the “Curran Spring” as, “Water emerges from tunnel dug into brecciated, highly permeable basalt, and from talus slope below tunnel.” Farmer (2009; p. 28) describes “a large discharge area” he calls the “lower spring zone”, at an approximate elevation of 3100 ft., and relates an employee report that approximately 2/3 of the total flow of the system originates from these springs.

Discharge from the Curren Tunnel and the Lower Springs is collected through a complex of collection boxes, pipes and open channels to aggregate to the full water supply of the Rangen facilities.

SITE GEOLOGY

An understanding of the relationship between Rangen groundwater discharges and water levels in the supplying aquifer is necessary to assess the response of the former to changes in the latter. Farmer (2009; Figures 20 and 24) offers a conceptual model of the Rangen system. Those perpendicular-to-the-cliff and parallel-to-the-cliff cross-sections are reproduced here as Figures 5 and 13. In this interpretation, the basic control on groundwater discharge is the strong permeability contrast between the primary aquifer and the underlying Glenns Ferry Fm. In detail, Farmer places the tunnel at the bottom of a paleo-channel eroded into underlying sediments and filled with Quaternary pillow basalts. Groundwater infiltrates from the bottom of this channel into permeable strata of the Tuana Gravel, and/or other post-channel-erosion gravel deposits, to emerge as the “lower spring zone” at the top of the laterally extensive clay-dominated layers of the Glenns Ferry Fm.

Well logs for the area are consistent with this interpretation of a paleo-channel eroded into the Glenns Ferry Fm. The Rangen Monitor Well (see Figure 4 for location) encountered the Quaternary basalt:sediment contact at 3159 ft., i.e. 10-15 ft. above the observed Quaternary basalts at the Curren Tunnel, but did not encounter consistent clay strata, i.e. the Tuana Gravel:Glenns Ferry Fm. contact, until elevation 3100 ft. Further north, that contact is mapped in outcrop, at elevation 3210 ft. and was encountered in a nearby well ("Ramsey"; Farmer, 2009; Figure 14) at elevation 3157 ft. There was clearly substantial relief on the Glenns Ferry Fm. surface upon which the primary aquifer was emplaced, whether as a gravel[9] or pillow-basalt deposit or some combination of the two.

Others, e.g. Covington and Weaver (1990, Fig. 3), have suggested that differing spring elevations along the Hagerman Rim are a function of groundwater emerging from a thick blanket of talus, beneath which the elevation of the controlling basalt:Glenns Ferry Fm. contact is obscure. Under this interpretation, the differing elevation of the Curren Tunnel and Lower Springs would be a function of differing pathways through the slope-manteling talus deposits. However, Kaufman et al. (2005) map most of Covington and Weaver's (1990) slope-mantling "landslide deposits", including at Rangen, as Glenns Ferry Fm. outcrop, placing the various springs at the Quaternary basalt:Glenns Ferry Fm. contact (Figure 2) and rejecting the Covington and Weaver interpretation.

Farmer (2009) also rejects a multiple-pathways-through-the-talus interpretation, based on the relatively thin talus associated with the clear Glenns Ferry outcrops on the Vader Grade, and his observations of outcrops of what he interprets as bedrock sediments at the Rangen Lower Springs. His interpretation explains the differing discharge elevations with a two-step permeability contrast: the tunnel flows originate at the Quaternary basalts:sediment contact, and the lower spring flows originate at a gravel:clay contact within the underlying sediments.

Hydrologically, this two-step distinction may be of little significance, as a complex basalt flow likely contains within itself a high degree of permeability contrast and groundwater channelization. Whether due to lithologic differences (pillow basalt vs. underlying gravels) or simply heterogeneity within the same lithology (pillow basalt), the steeper gradient between the wider aquifer and the point of discharge favors greater flow from the lower spring than from the tunnel.

FLOW DATA

The hydrogeologic model presented in the previous section is consistent with the measured flow data for the Rangen system. Flow data for the Rangen system have been developed in various ways over the past 30 years, varying from automated flow gaging at the Curren Tunnel by IDWR to ad hoc measurements at various weirs and raceways by Rangen personnel. (See Brendecke,

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[9]Farmer (2009, p. 28) suggests this gravel may be either the Tuana Gravel or "Quaternary age (Qg) gravels eroded from the Tuana".

2012 for detailed review of Rangen discharge data.) Figure 14 presents reported flow measurements/estimates for the period since IDWR began discrete monitoring of the Curren Tunnel in 1993. Qualitatively, these data are consistent with a straightforward model of aquifer head, gradients, and discharge, with two distinct discharge pathways:

> In the 1990s, flow from the tunnel and the springs are of comparable magnitude, despite the lower discharge elevation (i.e. higher gradient) of the springs. This requires a higher effective aquifer permeability for the tunnel, e.g. due to its much larger area open to the aquifer and its penetration into the hill reducing the effective distance to the background aquifer.
>
> Both spring and tunnel discharge declined with the onset of the drought of the 2000s, although the tunnel was affected more strongly than the springs. This is consistent with the springs' lower elevation, in that a unit change in aquifer water level creates a proportionately larger change in gradient for the tunnel.
>
> Similarly, the higher elevation of the tunnel will result in larger fluctuations in discharge from the tunnel as fluctuations in aquifer water level impact the gradient that drives water from the aquifer to the tunnel more than they impact the gradient to the lower springs.

At a more detailed level, these flow data demonstrate another potentially important aspect of the system: the inadequacy of a simple hydraulic model of flow as a linear response to changes in head in the common aquifer. For example, at points "A", "B", and "C" on Figure 14, tunnel and spring flows variously rise together, one flow rises while the other falls, and one flow rises while the other remains unchanged. A more complex hydraulic model and/or a substantial degree of error in these flow data is indicated. The issue of uncertainty in the relationship between aquifer water levels and groundwater discharges is further addressed below.

GROUNDWATER GRADIENTS

Groundwater flow is controlled by groundwater gradients, i.e. the difference in hydraulic head between two points; "water runs downhill". While recognizing that, in a groundwater system, "downhill" can describe both horizontal flow (within a layer) and vertical flow (between layers), and that gradients in a confined aquifer can be upward, the Rangen discharges are assumed to generally result from unconfined flow in the primary, Quaternary-basalt aquifer[10]. The geometry and saturated thickness of the primary aquifer in the study area were discussed above. Here, I

[10]"The aquifer in basalt of the Snake River Group as a whole behaves as an unconfined system." (Whitehead, 1992; p. B29).

look at the groundwater elevation data and the indicated groundwater flow directions[11] and rates for the Rangen system specifically.

As noted above (p. 13), the contouring of Figure 7 (after Farmer and Blew, 2012) depicts the variations from simple, east-to-west groundwater flow in the aquifer to a more complex pattern as flow approaches discharge points along the Hagerman Rim. This depiction is based on a simple, automated contouring of the input data, however, and careful examination of the Rangen area finds that groundwater flow under the head distribution of Figure 7 would be away from, rather than into the Rangen discharge points. Rangen is perched on a potentiometric ridgeline in this interpretation (see flow arrows on Figure 7). Because that is clearly not the case (or there would be relatively little Rangen flow), the actual situation is obviously more complicated.

Similarly, the contouring of Figure 7 includes a closed contour approximately 1 mile northeast of Rangen. This represents a depression in the potentiometric surface, an unlikely occurrence in a prolific aquifer outside the active irrigation season. Hydrographs for two IDWR-monitored wells in this area - the "33BBB" and "29CDC"[12] wells - are provided as Figure 15. (See Figure 4 for locations.) The westernmost of these two wells (29CDC) consistently reports the higher groundwater elevation of the two, demonstrating that groundwater flow is not simply east-to-west through this area. Local groundwater flow from west-to-east is demonstrated here, and the creation of a "sink" in this vicinity is unlikely, i.e. the contouring of Figure 7 is incorrect with respect to the Rangen area.

Figure 16 presents a more detailed examination of groundwater levels in the Rangen area. First, water-level data from wells that are not completed in the primary aquifer (or are completed in portions of the aquifer that are not hydraulically connected with the aquifer that supplies the Rangen discharges) are removed from the Farmer and Blew (2012) dataset supporting Figure 7. These are wells located at T8S, R14E, Sec. 5bbb; T8S, R14E, Sec. 5bba ("Waters"); and T7S, R14E, Sec. 31adc.

Second, the November, 2011 dataset is augmented by other late 2000s water levels measured in October or November[13], the season of highest groundwater levels. These points are measurements from wells at (see Figure 4 for locations):

T7S, R14E, Sec. 28DCB1 - measurement taken 11/29/2007
T7S, R14E, Sec. 29CDC1 - measurement taken 10/20/2011

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[11]In strongly anisotropic permeability distributions, as are likely present at local scales in a basalt aquifer, groundwater flow may be oblique to equipotential contours. Absent sufficient data to suggest the patterns of such anisotropy, conventional, perpendicular-to-equipotential-contours flow is assumed here.

[12]This well is Well No. 989 used in the calibration of ESPAM2.1.

[13]Data from: http://www.idwr.idaho.gov/hydro.online/gwl/default.html

T7S, R14E, Sec. 33BBB1 - measurement taken 12/8/2011

Third, the contouring of Figure 16 is guided by an understanding of the physical system: 1) the simple presence of major groundwater discharge at Rangen requires a local convergence of groundwater flow; 2) my interpretation of the configuration of the base of the primary aquifer (Figure 8) includes a locally-thicker aquifer in a paleo-channel extending eastward from Rangen; and 3) consideration of the emplacement of the lava flows creating the aquifer suggests such a channel as a likely place for high-permeability pillow basalts. In short, a groundwater "channel" as shown on Figure 16 is a reasonable interpretation of the groundwater flow system feeding the Rangen discharges.

Although data density in the area is insufficient to delineate local gradients in detail, the contouring of Figure 16 offers an interpretation that is more consistent with the available data than previous mapping. Under this interpretation, a zone of high transmissivity, e.g. coincident with the increased aquifer thickness and pillow-basalt deposition of a paleo-channel, drains a portion of the regional aquifer to discharge at Rangen. A groundwater divide to the south distinguishes the local Rangen system from the Thousand Springs area. A groundwater divide to the north distinguishes the local Rangen system from rim springs between Rangen and the Malad River.

Groundwater gradients also determine the discharge rates of springs and drainage tunnels. Given an opportunity for discharge (e.g. a well, a drainage tunnel, a low spot in the exposed contact with an underlying formation), discharge rate is a function of the gradient (the difference in elevation per unit of distance) between the aquifer and the discharge point. Because the elevation of the discharge points – the Curren Tunnel and the springs – and the distance between the discharge and any reference point in the aquifer are fixed, the gradient is controlled by the only variable quantity in this relationship: the water level in the surrounding aquifer. Higher aquifer water levels produce higher discharge rates. (Because the Curren Tunnel is relatively high relative to the water level in the supplying aquifer, only relatively small gradients into the tunnel are possible.)

Figure 17 presents the relationship between the water level in the aquifer at the IDWR-monitored well in T7S, R14E, Sec. 33BBB1 and the estimated monthly flows from the Rangen groundwater discharges. While the expected general association of higher aquifer water levels with greater discharge is obvious, the scatter on the plot is remarkable. For example, a water level elevation of 3169.5 ft. has corresponded with Rangen flows anywhere from 18 to 50 cfs. Similarly, the same system discharge of 29 cfs has corresponded with groundwater elevations varying by 5 ft. By way of comparison, in the ESPAM2.1 model cell containing the 33BBB1 well, the change in water level predicted to result from the curtailment of all post-1962 priority wells across the Eastern Snake Plain Aquifer, is also 6 ft. (Brendecke, 2012).

Some interference with the direct relationship between aquifer water levels and groundwater discharge might be expected over the 1.1 miles between the 7S 14E 33BBB1 monitored well and Rangen, particularly during the irrigation season, and additional scatter might be expected from the use of averaged monthly data. However, a similar ambiguity is apparent in much more well-controlled data from the “Rangen Monitor Well”, compiled in Figure 18. This well was constructed by IDWR in 2008. It is the nearest groundwater monitoring point to the Rangen discharges. The well is 588 ft. east of the outlet of the Curren Tunnel (Farmer, 2008) . The well is a dedicated monitoring well and there are no other wells (producing or monitoring) between this monitor well and the Rangen facilities. There is one small sprinkler-irrigated field between the monitor well and the rim above Rangen, and a small irrigation tailwater ditch. Thus, there is very limited opportunity for significant interference with the relationship between aquifer water levels and aquifer discharge. Furthermore, there are frequent measurements available for this well (albeit over a limited period of record), which can be rigorously paired with daily flow measurements from the Curren Tunnel to minimize time-related discrepancies. (System-wide Rangen flows are only available as average monthly estimates.)

Figure 18 shows the expected general correspondence between higher aquifer water levels (i.e. higher gradients) and greater flow from the aquifer, via the tunnel in this case. As with Figure 17, however, the relationship is inconsistent in detail. A groundwater elevation of 3156 ft. in the Rangen Monitor well corresponded with Curren Tunnel flows varying between 3.6 and 7.5 cfs; the range in values approaches 100% of the average flow. Similarly, groundwater elevations varying by 2.5 ft. have been measured at the same measured flow of 5.7 cfs.

Because accurate predictions of the impact of water-level changes in the aquifer on groundwater discharge depend on an accurate understanding of the relationship between the two, Figures 17 and 18 represent considerable uncertainty in such predictions.

GROUNDWATER DEVELOPMENT OPPORTUNITY

As noted above, the Curren Tunnel is far from an ideal facility for the production of groundwater due to its small available drawdown and the resulting sensitivity to small changes in aquifer water levels. A grant application filed by Rangen to investigate additional horizontal well drilling to enhance their water supply recognized the importance of available drawdown, recommending targeting “an elevation below the Curren Tunnel”, suggesting that such “a horizontal well could provide substantial increase in flow”, and characterizing the proposal as a “well deepening” (Rangen, Inc., 2004).

Another alternative is the construction of a vertical well or wells into the very productive aquifer that supplies the Rangen discharge. In the Rangen-to-Wendell area, approximately 50% of the 40+ irrigation wells for which yields are listed in the IDWR database[14] report yields in excess of 750 gpm. The aquifer is sufficiently productive that few wells penetrate to great depth. For this area, the average irrigation well is 150 ft. deep, and the average depth-to-water in these wells is 100 ft. The average available drawdown is 50 - 60 ft. This is substantially less than the full

[14]http://www.idwr.idaho.gov/ftp/gisdata/Spatial/Wells/WellConstruction/WellConstruction.zip

saturated thickness of the primary aquifer (e.g. 170 ft. at the F. Henslee well, Fig. 4), indicating that additional production likely could be realized from deeper wells. By way of comparison, the available drawdown for the Curren Tunnel (based on average depths to water in the Rangen Monitor well, and using Farmer's (2009) discharge elevation of 3145 ft.) is only 10 ft. Based on the IDWR (2011) discharge elevation of 3150 ft., the available drawdown averages only 5 ft.

Within 2-1/2 miles of Rangen, east of the rim, there are 19 permitted irrigation wells. These wells are plotted, along with reported depth and yield on Figure 19. The highest reported yield in this group is 4500 gpm, from an irrigation well approximately 0.6 mile northeast of Rangen. The average permit yield (for those listing a yield) is 2500 gpm. Test data are reported for few wells in this area, but four of these irrigation wells include some quantitative indication of aquifer productivity:

production (gpm)	duration (min)	dia (in)	drawdown (ft)	indicated T[15] (ft^2/day)	Owner
4000	300	16	15	54,000	F. Henslee
4500	60	16	1.25	800,000	T. Gibson
3800	180	20	"None"	>800,000[16]	P.H. Hess
2817	240	20	13	40,000	P.H. Hess

Local driller Larry Nielson (2012) reports a group of wells 8 miles southest of Wendell that are less than 100 ft. deep, with a 70-ft. static water level, yet produce 3200 gpm.

Although highly-productive wells appear to be common in the area, the variations in pump-test responses compiled here demonstrate the expected inhomogeniety of this complex aquifer. (The occurrence of domestic wells in the area for which 40 and 54 ft. of drawdown are reported demonstrates the same point.)

Regional groundwater flow modeling (e.g. ESPAM2.1) assigned somewhat higher transmissivities, i.e. between 800,000 and 1,500,000 ft^2/day, to the area between Rangen and Wendell; Mundorf et al. (1964) estimated a value of 700,000 ft^2/day for analysis of wellfield production, based on aquifer tests and flow net analysis. These values are based on the entire productive thickness of the aquifer, but that productivity is concentrated in the uppermost layers. Mundorf et al. (1964) report the results of 9 pump tests in the Eastern Snake Plain Aquifer in Gooding County (the County including Rangen and Wendell), which produced an average realized specific capacity of 900 gpm per ft. of drawdown. That study estimated a maximum drawdown for a row of fifty, 2250 gpm wells (i.e. 250 cfs total) between Wendell and Rangen. Drawdown was only 10.5 ft. for the mid-point of the wellfield, if pumped for 122 days each year, for 50 years.

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[15]Transmissivities calculated from Theis Equation with assumed S = 0.10.

[16]Assume drawdown < 1 ft. to be reported as "none".

Comparison of Figures 8 and 16 indicates a saturated thickness of approximately 100-150 ft. for much of the area immediately east of Rangen. In this setting, the drawdowns projected for even the aggressive development discussed in the previous paragraph certainly do not produce unreasonable pumping levels.

Figure 20 provides one of the longer groundwater-level records for the area. Although the generally lower levels associated with the 2000s drought is evident, this hydrograph demonstrates that the aquifer is not in long-term decline, i.e. that groundwater withdrawals are not significantly exceeding normal rates of recharge, and that seasonal fluctuations in groundwater levels would not present a significant impediment to additional development.

Construction of vertical wells on the order of 200 - 250 ft. deep at favorable locations would insulate the Rangen water supply from the impacts of the relatively small variations in groundwater levels experienced in the primary aquifer. Moving the point of diversion for this groundwater extraction from the tunnel to vertical wells would not be expected to significantly alter the quality or temperature of the groundwater, since production would be from the same aquifer as currently supplies both the Curren Tunnel and the lower springs.

GROUNDWATER MODELING OF THE EASTERN SNAKE PLAIN AQUIFER

This section examines the representation of the Eastern Snake Plain Aquifer by the ESPAM2.1 groundwater flow model with respect to the detailed examination of the hydrogeology of the Rangen discharge area developed in the previous sections. (More detailed discussions of the history of groundwater modeling of the Eastern Snake Plain Aquifer and the development of the ESPAM2.1 are provided in Brendecke (2012), who was also the source for all ESPAM2.1 output values cited herein.)

ESPAM2.1 represents the aquifer as a series of “cells”, each of which is one mile by one mile in plan view, and 4,000 ft. thick. The aquifer is represented as a single layer. Figure 21 presents approximately the western quarter of the ESPAM2.1 model area. Vertical lines show the location of individual ESPAM2.1 columns along this model row (Row 42, the row containing the Rangen discharge). Aquifer properties within each cell – transmissivity and storativity – are the same throughout that cell and are held constant through time.

The inset on Figure 21 represents the present report, which focuses on the Rangen study area to investigate how well the ESPAM2.1 generalizations capture important aspects of the hydrogeology in this specific area of aquifer discharge. Even at the scale of this figure, it is obvious that considerable local detail is lost in the ESPAM model structure.

Figures 22, 23, and 25 provide three cross-sections within the study area, along the specified ESPAM2.1 model rows, south of, north of, and at Rangen. (See Fig. 1 for the lines of section.) Topographic profiles and geologic contacts (in black) are from USGS topographic maps and IGS geologic maps, respectively. Subsurface interpretations are schematic, controlled to outcrops and well-log formation tops where available. Groundwater level profiles (in blue) are based on observed spring elevations and groundwater levels in monitoring wells. Superimposed on these cross sections (in red) are the ESPAM2.1 columns (numbered across the top), cell-by-cell ESPAM2.1 groundwater elevations (from the "steady-state" model run developed to initialize annual calculations[17]) and the ESPAM2.1 modeled elevations for springs (drains) and general head boundaries (GHB).

Figure 22 is the simplest of the three cross sections. The measured water level and the modeled water levels are in reasonable conformity in the eastern (right-hand) portion of the figure. The westward flow of groundwater terminates along the Snake River canyon, both in the model and in reality. Groundwater leaves the model domain, in column 12, via springs at elevations 3092 and 2970 ft., and via a general head boundary provided to simulate groundwater flow directly into the Snake River at modeled elevation 2877 ft. The "3092" and "2970" used by ESPAM2.1 come from surveying by HDR (IDWR, 2011) of the highest and lowest spring discharges in this one-mile-wide model cell[18].

The ESPAM water level and drain elevations for column 12 are presented to one decimal place in order to show that a small gradient from the aquifer to the spring is modeled. Model calibration assigned an extraordinary drain conductance of 300,000,000 ft^2/day (190 times the average of all other drains) in order to simulate the spring flow at this location.

Figure 22 uses a value of 3050 ft. for the actual groundwater discharge elevation in this line of section, based on the inferred location of the geologic contact between the Quaternary and Tertiary deposits (Gillerman et al., 2005), which is understood to control the location of these springs (e.g. Covington and Weaver, 1991[19]). Because ESPAM2.1 explicitly includes neither the surface topography of the Snake River canyon, nor the geologic contact controlling the Thousand Springs, basically, it models this area as a 1 mi^2 bucket, filled with water to elevation 3092 ft., with three holes in the side to represent a range of spring elevations and the Snake River.

The line of section presented in Figure 23 is complicated by groundwater discharges along both the Malad and Snake Rivers. Figure 24 presents the ESPAM2.1 grid and Covington and Weaver (1990) springs in plan view. In ESPAM2.1, all springs within a single model cell are simulated as a "drain" (or "drains") in the center of that 1-mile-by-1-mile cell (the red dots on

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[17]This dataset was chosen to reflect the general, "average" conditions modeled. Limited examination of transient model calculations for individual months does not find sufficient variation to significantly affect the conclusions presented here.

[18]IDWR (2011) notes that the "3092" value actually comes from the adjacent cell (row 45), "but since it obtains water from the same hydrogeologic feature as Thousand Springs and Minnie Miller Springs the ESHMC has chosen to model it as if it were in cell 1045012."

[19]"springs emerge at top of Banbury Basalt"

Fig. 24). Each drain is assigned a single elevation to represent all associated springs, and the springflows are aggregated to that point.

The large difference in ESPAM2.1 drain elevations in column 14 was necessitated by the model's one-mile cell size encompassing springs near river level (2730 ft. on Fig. 23; #73 on Fig. 24) along the Snake River within the canyon in the northern part of the cell, and also springs issuing from talus slopes under the Hagerman Rim (2975 ft.; #65) in the southeast corner of the cell. It is doubtful that there is significant real hydrologic connection between these disparate locations, but ESPAM2.1 can only treat all groundwater discharges within a model cell as occurring at the same point (in plan view) and from the same, continuous aquifer.

Similarly, the springs at #68 (elevation 2750 ft.[20]), #69 (elevation 2765 ft.), #70 (elevation 2750 ft.), #71 (elevation 2740 ft.), and #72 (elevation 2740 ft.) are not explicitly modeled by ESPAM2.1. (Much of the flow at #68, #69, and #70 falls outside the active ESPAM2.1 model grid.)

The two discrete ESPAM2.1 drain elevations in column 15 (Fig. 23) span the discharge elevations for a nearly continuous string of large springs along the Malad River between elevations 2860 ft. (#75; 2850-2860 ft.) and 2990 ft. (#52; 2975-2990 ft.). The Figure 23 line of section intersects the river at approximately 2900 ft. These high-discharge springs continue upstream along the Malad River into ESPAM2.1 model column 16. With a modeled discharge elevation of 3010 ft. This ESPAM2.1 "drain" corresponds with mapped springs #53, which extend upstream from elevation 3010 ft. to elevation 3090 ft.

The 3040 ft. ESPAM2.1 drain in column 16 corresponds with a discrete spring (#51) located north of the river. The steady-state ESPAM2.1 groundwater elevation for model cell 36-16 is 3015 ft. This water level in the aquifer would leave the ">10 cfs" (Covington and Weaver, 1990; #51) ESPAM2.1 drain at 3040 ft. dry[21], and would provide no discharge corresponding (in elevation) to the continuous string of mapped springs along the 0.75 miles of river between elevations 3015 ft. and 3090 ft. (#53).

The striking divergence of the actual and modeled water tables in this area (the red and blue lines on Figure 23), and of the actual and modeled elevations and locations of the springs (Figure 24), are largely a function of applying a relatively coarse model grid to this area of complex topography and groundwater flow patterns. While ESPAM2.1 may usefully simulate the overall discharge of groundwater from the generalized aquifer in this area in terms of aggregate volumes and wide elevation ranges, the Malad River area illustrates the uncertainty with which simulation of individual discharges at specific elevations must be viewed.

[20]Spring elevations are from Covington and Weaver, 1990.

[21]ESPAM2.1 assigns a conductance of 1 ft^2/day to this drain, precluding significant discharge in any case.

Figure 25, for the Rangen area, is the most complicated of the three cross sections developed here. As with Figure 22, there is a general conformity between modeled and measured (or inferred) groundwater elevations in the eastern (right hand) portion of the section, but that conformity breaks down in the critical area of groundwater discharge in model columns 12, 13, and 14. As interpreted here, there are three, and possibly four local groundwater systems:

1. The discharges from the primary aquifer at elevations 3150 ft.[22] (Curren Tunnel) and 3100 ft. (lower springs), which are modeled by ESPAM2.1 with a single drain elevation, in a model cell with no internal layering.

2. The discharge from a local groundwater system developed within the Quaternary sediments at elevation 3045 ft., i.e. the Crowsnest gravel draining from the contact with the underlying Yahoo Clay (Covington and Weaver, 1990; spring #26), which is modeled by ESPAM2.1 as simply another discharge point for the regional aquifer.

3. The discharge from Quaternary basalts at elevation 2958 ft., well below the Hagerman Rim and not immediately connected with the primary aquifer east of the rim, which is modeled by ESPAM2.1 as simply another discharge point for the regional aquifer.

4. Whatever discharge occurs through the lower-permeability Tertiary deposits directly to the Snake River, which is modeled by ESPAM2.1 using a General Head Boundary (GHB) in model column 12. (The ESPAM2.1 active grid does not extend to the Snake River.)

As on Figures 22 and 23, all of these disparate features are modeled as elevation-controlled discharge points from the same, thick, interconnected, regional aquifer. In the case of flow system no. 1, ESPAM2.1 uses a single elevation - 3138 ft. - to model both upper and lower discharges.

Figure 26 presents the potentiometric surface generated from ESPAM2.1 groundwater level output for the study area for November, 2007[23]. Regional westward flow is indicated, broadly diverging along the western edge of the model toward major discharge points representing the

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[22]A 3150 ft. elevation for the Curren Tunnel is diagramed based on HDR surveying (IDWR, 2011). Farmer (2008, 2009) reported an elevation of 3145, but the IDWR spreadsheet received in association with Farmer and Blew (2012) ("Mass Meas. all data (except #1101 & 1103) with springs.XLS") cites an elevation of 3149.83 ft., suggesting an updated understanding.

[23]ESPAM2.1 cell-by-cell groundwater head values were placed at the grid cell centers and contoured using SURFER, without adjustment. The ESPAM2.1 November dataset closest in time to that of Figure 7 was chosen for comparability; November water levels are typically the seasonal maxima, outside the short-term, local fluctuations due to irrigation-season recharge and discharge activity.

Malad Gorge and Thousand Springs. Comparison with either Figure 7 – a first-approximation contouring of the actual water table in the study area after Farmer and Blew (2012) – or Figure 16 – my more detailed examination of groundwater gradients in the immediate Rangen area – demonstrates the level of generalization to which the ESPAM2.1 model design is constrained. Missing from the ESPAM2.1 representation are the multiple groundwater divides noted by Farmer and Blew (2012; p. 11) and the local convergence of groundwater flow necessary to create the Rangen discharge.

The following sections provide additional comparisons between specific features of ESPAM2.1 and what is known or can reasonably be interpreted regarding the study area hydrogeology.

AQUIFER TRANSMISSIVITY

The ease with which groundwater flows within an aquifer is controlled by the permeability of the aquifer material and the saturated thickness of the aquifer. Higher permeability material and more material through which to flow generate more groundwater flow at any given gradient. The permeability multiplied by the thickness is the transmissivity.

At the regional scale, the RASA modelers observed, "The steep gradient near the Snake River is due to thinning of the basalt aquifer and reduction in transmissivity" (Garbedian, 1992, p. F29), and in the ESPAM1.1 documentation, Cosgrove et al. (2006; pp. 16, 17) note that "Steep hydraulic gradients are apparent near the margins of the plain due to tributary valley inflow and lower transmissivity relative to the center of the plain." and that, "Steep gradients also are apparent near the Kimberly to King Hill discharge area due to convergence of flow lines and probable aquifer thinning."

Referring specifically to springs along the Hagerman Rim, Ralston (2008) states, "The lower aquifer transmissivity is associated with smaller spring discharge with a greater sensitivity to changes in the regional water table." and "The saturated thickness and thus the transmissivity of the aquifer are greater in the Thousand Springs area and the Malad River canyon than anywhere in the Thousand Springs to Malad reach."

Farmer (2009, p. 41) makes the case that, "The transmissivity of the aquifer at the Curren Tunnel will be more responsive [to changes in aquifer water levels] than further east because the saturated thickness is less near Rangen".

Consideration of Figures 8 (base of the primary aquifer) and 16 (groundwater levels) demonstrates the pronounced decrease in saturated thickness of the primary aquifer from east to west as the Hagerman Rim is approached. Absent a change in aquifer permeability, the transmissivity of the aquifer will decrease accordingly.

No explicit "aquifer thinning" is possible in the ESPAM2.1 structure, nor can the calibration-assigned transmissivity be responsive to temporal changes in water levels. Transmissivities are constant values. The model tacitly includes an effective aquifer thickness in its assignment of transmissivities, e.g. a lower modeled transmissivity could reflect a lower permeability and/or a smaller effective aquifer thickness. The ESPAM1.1 documentation argues, "Neither the hydraulic conductivity nor the saturated thickness must be individually well understood." (IDWR, 2012; p. 23).

However, the ESPAM2.1 transmissivity distribution shows no decrease in aquifer transmissivity along the western edge of the model for either reason (thickness or permeability). Model transmissivities are highly variable (e.g. values from 0.6 million ft^2/day to 36 million ft^2/day within three model cells from Rangen), but there is no reflection of decreased transmissivity at the western edge of the aquifer in the study area[24]. ESPAM2.1 transmissivities are actually higher along the Hagerman Rim cells (average 11 million ft^2/day) than in the aquifer 3 miles to the east (average 2.3 million ft^2/day), and higher than at Thousand Springs (0.7 - 1.1 million ft^2/day) or Malad Gorge (0.2 million ft^2/day).

In the Rangen area specifically, the model cell (42-13) containing the Rangen discharges has an ESPAM2.1-assigned transmissivity of 1.6 million ft^2/day. The cell immediately to the northwest (41-13) has T = 4.3 million ft^2/day. The cell immediately northeast (42-14) has T = 1.5 million ft^2/day. Yet in much of the northwest model cell, the primary aquifer is either absent (west of the rim) or dry (e.g. at the Ramsey and Anderson wells; see Figure 4). In the model cell northeast of Rangen, the primary aquifer is thicker than in the Rangen cell and the water level is higher, so the saturated thickness is certainly higher, yet the ESPAM2.1 transmissivity is slightly lower.

Although of less immediate importance with respect to Rangen flows, the ESPAM2.1 transmissivities also fail to reflect areas of locally small (or absent) saturated thickness in the primary aquifer across the plateau area east of the rim, e.g. as identified southwest of Jerome (p. 19).

The ESPAM2.1-assigned transmissivity distribution is not well matched with the hydrogeology in the Rangen area.

AQUIFER ANISOTROPY AND MODEL LAYERS

As described above, the geologic deposits of the Rangen area are far from homogeneous (the same at all locations) or isotropic (the same in all directions). The Quaternary and Tertiary basalt sequences are composed of multiple flows, with multiple zones within each flow. While layer-like in aggregate, individual flows are of limited horizontal extent and can vary widely in

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[24]The ESPAM2 documentation (IDWR, 2012; p. 87) includes the statement, "The map of the calibrated model transmissivity (Figure 100) shows that estimated transmissivity values tend to be lower along the margins of the plain and higher towards the center. ... these features in the calibrated transmissivity distribution are consistent with my current understanding of the aquifer.", but this is only generally correct, on a regional scale. Cell-by-cell values in the Rangen study area were examined for the present investigation.

thickness in response to the topography of the surface upon which they were emplaced. Sedimentary units are also layered at a regional scale, but in detail include lenses and stringers of varying lithology, with poorly understood geometries (and permeabilities) in the subsurface.

While such variations in aquifer characteristics are unlikely to impact regional flow modeling and associated regional-scale modeling conclusions, as aquifer inconsistencies tend to "even out" over large distances, the potential for local anisotropy is a major source of uncertainty with respect to modeling individual groundwater discharge points. Consideration of the mixed nature of the primary aquifer at Rangen (basalt, pillow basalts, gravel, sand) and of the ambiguous relationship between aquifer water levels and groundwater discharge (p. 27), indicates Rangen as a location where a more detailed model would better support local-scale conclusions.

ESPAM2.1 provides very little accommodation for aquifer anisotropy and inhomogeneity at a scale potentially important to individual groundwater discharge points such as Rangen.

The most pervasive anisotropy in the study area is, of course, the difference between the primary aquifer hosted by the Quaternary basalts, and the underlying units. This difference controls the location of the majority of the natural discharge from the aquifer in the Rangen area. The most common method for accommodation of such model-scale differences in hydrogeologic characteristics is by discriminating separate model layers. The USGS RASA modeling divided the aquifer into four layers, the uppermost of which was considered "unconfined" (Garabedian, 1992), meaning transmissivity was allowed to vary over time as the saturated thickness changes in response to changes in withdrawals and recharge.

Farmer (2009) did not develop a groundwater flow model, but his three-layer conceptualization was proposed to capture the locally important differences between the upper basalts, the Glenns Ferry Fm. sediments, and the lower basalts (see Figure 5). Relatively few data are available with which to quantify geometric or hydrologic distinctions between Farmer's Layers 2 and 3 (Glenns Ferry Fm. and Tertiary basalts), but the "Base of The Primary Aquifer" section above, provides a study-area delineation of his Layer 1:Layer 2 contact.

ESPAM2.1 is constructed with only one model layer. All variations between and within the four sequences described in the "Stratigraphy" section of this report are consolidated into singular values of transmissivity and storativity for each model cell.

The absence of aquifer layering in ESPAM2.1 precludes model representation of:

- the important geologic contact at the base of the Quaternary basalts that is responsible for nearly all large springs in the Milner to King Hill reach of the Snake River, including the groundwater discharges at Rangen;

- the paleo-topography widely understood to control the location of springs along the Hagerman Rim, including the groundwater discharges at Rangen; and

- the changes in aquifer transmissivity that accompany changes in aquifer water levels in the thin, western edge of the primary aquifer.

GRID SIZE

Another basic element of the ESPAM2.1 structure is grid size. While the 1 square mile cells of ESPAM2.1 may be adequate to represent aquifer conditions over the vast expanse of the Eastern Snake Plain Aquifer to the east, the aquifer discharges along the Hagerman rim are understood to be controlled by paleo-topographic features on a finer scale. At Rangen, for example, the bottom of the primary aquifer varies from 3100 ft. elevation at the lower spring to 3189 ft. at the Anderson well, a distance of 0.7 mile. As outlined above, this difference is instrumental in creating and controlling the observed discharge. Farmer and Blew (2012; p. 11) suggest that "if a numerical flow and transport computer model honors the field data then the computer grid cell size needs to be at least ¼ mile in size for several miles away from the spring area." Koreny et al. (2006) also suggested that the ESPAM "model grid in the reach below Milner is too coarse for representation of individual springs".

The grid spacing for ESPAM2.1 precludes realistically modeling potentially important details of the hydrogeology along the Hagerman Rim, including the groundwater discharges at Rangen.

AQUIFER DISCONTINUITY

Another important aspect of the upper, most productive portion of the Eastern Snake Plain Aquifer that is lost in a single-layer model is the severing of that layer along the Hagerman rim. The springs along the rim stand witness to the termination of the primary aquifer as its water table intersects the ground surface and downward migration is greatly restricted by the lower permeability of the underlying deposits.

ESPAM2.1 represents the rim springs using "drain" cells, for which a specified elevation and conductance control the discharge from a model cell that, in most cases, remains saturated well above the discharge point (e.g. Figs. 22, 23, and 25). Like a straw into a sandbox full of water, the "spring" does not mark the end of the aquifer, but simply draws off a flow of water, allowing the remaining groundwater to proceed as dictated by surrounding gradients. In this sense, the Rangen discharge is modeled like a well with a fixed "pumping" water level, completed in a laterally continuous aquifer.

This is illustrated by ESPAM2.1 water levels and groundwater flow in the cell containing the Rangen discharge (42-13) and the model cell immediately to the southwest (42-12). The actual groundwater flow passing westward beneath Rangen is obviously zero in the primary aquifer, and is likely relatively small in the underlying Glenns Ferry Fm. and Tertiary basalt sequences. Yet the steady-state ESPAM2.1 groundwater flow westward from the Rangen is 367 cfs[25].

As noted on Figure 25, the ESPAM2.1 estimation of substantial flow through the rim produces a modeled groundwater elevation in the adjacent cell to the southwest (42-12) of 3125 ft., despite the ground surface being well below that elevation in all but the cell's far east corner (see Fig. 4). For much of this cell, the modeled groundwater elevation is more than 170 ft. above the ground surface.

This aberration cascades through the immediate area of the model, as ESPAM2.1 water levels in the cells between Rangen and Thousand Springs, i.e. along column 12, define a gradient creating southeastward groundwater flow. This is 180º opposed to the flow direction cited by both Farmer (2011, p. 17) and Ralston (2008)[26] based on review of local hydrogeology and water level measurements, which present flow to the northwest. In the three model cells running NW from the Thousand Springs area (44,43,42-12) modeled groundwater elevations create a southeastward gradient of approximately 15 ft./mi.

In the Malad Gorge area, similar discrepancies are modeled (see Figures 23 and 26). Groundwater flow from the ESPAM2.1 model cell at the mouth of the gorge (36-14) and from the cells immediately southeast (37-14) and northwest (35-14) is to the northeast, i.e. away from the Snake river and in "under" the rim. Mapping by Othberg et al. (2005) suggests there is little or no Quaternary basalt in the cell at the mouth of the gorge, and the underlying Tertiary basalts are dissected by the Snake River down to an elevation of 2720 ft. The ground surface for nearly the entire cell (36-14) is below 2900 ft. elevation, yet this cell has a modeled groundwater elevation of 3106 ft.

As noted in the discussion of study area hydrogeology (p. 16, Figure 9), the gorge has been interpreted as dissecting the Quaternary basalt aquifer in the lower springs area of the Malad Gorge. The river has cut down to an elevation below 2900 ft. in this reach, creating a ceiling to groundwater flow in the productive aquifer. However, the groundwater model produces a groundwater elevation of 3073 ft. in this area (cell 36-15, Figs. 23, 26). This provides 150 - 200 ft. of saturated aquifer <u>across</u> the Malad Gorge, through which modeled groundwater impacts can be communicated. If the aquifer is severed by the gorge, however, any impacts to groundwater levels on the north side can only be communicated to the south side via the continuously saturated portions of the primary aquifer further east, or through the lower aquifer, which is deeply exposed by erosion (and thus drained) in the adjacent channel of the Snake River.

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[25]Were this correct, mitigation of impacts to the Rangen flows could be a simple matter of intercepting a portion of the passing groundwater flow.

[26]"This suggests ground-water flow is from south to north in the area between the plateau rim and the Snake River." (p. 5)

The configuration of ESPAM2.1 precludes modeling the important impacts of aquifer-severing topography in the Rangen area.

RANGEN "DRAIN" MODELING

In ESPAM2.1, groundwater discharge at Rangen is modeled using a single "drain" cell. A drain cell is a standard feature of the MODFLOW code used by ESPAM2.1. The mathematical representation of a drain is the linear equation:

A) Discharge = Conductance * (aquifer water elevation - drain elevation)

with the condition that once the aquifer water elevation falls to or below the drain elevation, i.e. the groundwater gradient from the aquifer to the "drain" decreases to zero, discharge is set to zero (McDonald and Harbaugh, 1988; p. 9-3). Discharge is a linear function of gradient; a graph of the gradient (elevation difference) vs. discharge will be a straight line, with the slope defined by the conductance term. ("Linear" in this context means that twice the elevation difference produces twice the flow, half the elevation difference produces half the flow, and so forth. Discharge is assumed to be predictable based solely on a given elevation difference and a constant conductance, and discharge is directly proportional to that elevation difference.)

In ESPAM1.1, both the drain elevation and the conductance of the Rangen cell were adjusted to approximate the historical flows in aggregate with other springs in the reach. In ESPAM2.1, the reported elevation for the "Rangen Spring" from Covington and Weaver (1990) was used to represent the total Rangen discharge with a fixed value (IDWR, 2012; p. 29) and the combined Rangen discharge became a single calibration objective. Thus, the aquifer water elevation is determined by the ESPAM2.1 model integration of all inputs and outputs across the model domain; the drain elevation and drain flows are directly observed; and the "conductance" term is adjusted to provide an acceptable level of reconciliation of modeled and measured flows through the model calibration process.

This modeling approach presents two problems:

1. In reality, there appear to be at least two outlet elevations. Figure 14 presented the bimodal discharge response for the Rangen system, i.e. the Curren Tunnel and the lower spring have reacted differently to changes in water level in the supplying aquifer. ESPAM2.1 provides only one response function for the Rangen system, with a single discharge elevation. Currently (the 2000s) the majority of the overall Rangen discharge occurs at an elevation of approximately 3100 ft., rather than the 3138 ft. assigned by ESPAM2.1.

The conductance term assigned by ESPAM2.1 to the Rangen drain is 419,036 ft^2/day. The average conductance value for other springs in the Thousand Springs to Malad reach is 32,209 ft^2/day. Presumably, the relatively high Rangen conductance was necessary to produce the target flow with the relatively small head difference between the drain and the surrounding aquifer (1 to 10 ft.). A more realistic elevation for the bulk of the Rangen discharges would certainly change the calibrated conductance value, and would likely generate collateral changes in other model parameters and results. Recognition of the lower-elevation discharge of the Rangen system would generate a subdued response to small changes in aquifer water levels as are predicted to occur were groundwater pumping curtailed in the supplying aquifer.

Figure 27 presents ESPAM2.1 simulation of the water levels in the model cell containing the Rangen discharges, highlighting the 3150 ft. elevation (IDWR, 2011) of the Curren Tunnel discharge for comparison. As modeled, there would have been no discharge from the Curren Tunnel for the 88% of the time (1980 - 2008) that the aquifer water level was below the tunnel.

This problem was encountered by IDWR (Wylie, 2012b) in their modeling of the "1900 Validation Scenario". The ESPAM2.1 simulation of the 1900 aquifer water level in the Rangen cell was only 3136 ft., leaving the overall Rangen (both tunnel and springs) discharge at zero, even though the ESPAM2.1 modeled discharge elevation is 3138 ft.

A similar discrepancy was discussed above (p. 32) in relation to a spring in ESPAM2.1 cell 36-16, for which ESPAM2.1 provides no flow, despite a reported discharge of ">10 cfs".

Koreny et al. (2006), concluded "further refinement is needed" (in ESPAM1.1) including the use of "multiple drains to represent multiple springs within a model cell" because "in reality, each model cell may contain numerous springs" which "makes the cumulative discharge behavior nonlinear because the springs at higher elevations will see larger flow declines than springs at lower elevations for the same head decline in the aquifer".

Again, while ESPAM2.1 may satisfactorily route aquifer recharge and discharge at the scale of the 150-mile wide aquifer, its ability to duplicate the details of individual cell flows and to predict the impacts on those flows of changes in the regional aquifer, is compromised by its generalization of potentially important local details.

2. The relationship between aquifer water levels and Rangen discharge does not appear to be a simple, linear function. (See discussion above, pp. 27-28.) Farmer (2009; pp. 40-41) noted that a "non-linear relationship may exist" between aquifer water levels and discharge at Rangen, analogizing the "U" shape of the paleo-channel at Rangen to a "V-notched weir", which has a strongly non-linear depth-to-flow response. Figure 17 is essentially the same graph presented to the Sept. 21, 2009 ESHMC meeting by Jim Brannon of Leonard Rice Engineers, with the accompanying statement, "hydrographs are indicating some hydrogeologic controls that exhibit faster responses than regional scale aquifer head controls".

ESPAM2.1 is structurally incapable of modeling the relationships shown on Figures 17 and 18. Figure 28, for example, presents the data of Figure 18, expressed as deviations from an ideal, linear model as required by ESPAM2.1[27]. The average error in the predicted discharge is 20% of the average discharge, and deviations as large as 50% are not uncommon. Because Figure 28 uses well-measured, paired daily data (e.g. rather than monthly averages), and because the monitor well and discharge points are in near proximity, the relationship presented should be well controlled with respect to data-collection and location based errors.

While the flow patterns reported for the Rangen groundwater discharges appear to conform qualitatively with a straightforward model of aquifer gradients, a more careful examination finds additional complexity that calls into question the ability of ESPAM2.1 modeling to confidently predict the impact of changes in aquifer levels on groundwater discharge at this location.

ELEVATION UNCERTAINTIES

The ESPAM1.1 documentation states that, "It was agreed that the true elevations of the drains are unknown", and modeled elevations were arbitrarily set to 30 ft. lower than the model-predicted water level elevation in the host model cell to keep cells from going dry (Cosgrove et al., 2006; p. 108). For ESPAM2.1, this conclusion was reversed, and the Rangen discharge was modeled with a single, fixed elevation, at 3138 ft.

In 2011, HDR surveyed spring elevations for the development of ESPAM2.1 (IDWR, 2011). Their Nov. 9, 2011 value for the "Currant Tunnel-Portal" was 3150 ft., with a stated vertical accuracy of "less than plus/minus 2 ft.". In reference to the HDR survey, however, IDWR (2011) states, "the cell containing Curren Spring, has only one drain with an assigned elevation of 3138 feet from Covington and Weaver. The HDR survey did visit Curren Spring, but surveyed the "Tunnel Portal" which is not the low elevation of the spring. I visited Curren Spring and believe that significant water discharges from the below the tunnel. Therefore I recommend that the ESHMC continue using the 3,138-foot elevation." Recognizing that a single elevation did not properly reflect the Rangen discharge, IDWR apparently opted for a value an arbitrary 12 ft. lower as something of a compromise.

The "3138" value is cited by Covington and Weaver (1990) for the "developed" "Rangen Spring". Farmer (2008; pp. 3,4; 3.6-ft. elevation accuracy) cites, "where it discharges from the Curren Tunnel is 3145 feet".

With an ESPAM2.1 water level elevation for the Rangen cell (42-13) of 3144 ft. (the steady-state model value), the "correct" elevation for the tunnel (either the HDR or Farmer elevation) produces no flow at all. Similarly, based on the average groundwater-level elevation reported by Farmer (2009) for the Rangen Monitor Well (3155 ft.), 588 ft. to the east of the tunnel outlet, the groundwater gradient between the well and the outlet of the Curren Tunnel is (3155-3145)/588 =

[27]The linear function used here is a "best fit" (least-squares) to the data of Figure 18; ESPAM2.1 explicitly models neither the Curren Tunnel discharge nor the Rangen Monitor Well aquifer levels.

0.0170. Substituting the HDR-reported elevation for the tunnel (3150 ft.) reduces the gradient to 0.0085; use of the Covington and Weaver (and ESPAM2.1) elevation (3138 ft.) increases the gradient to 0.0289. In an ideal aquifer, discharge is a linear function of gradient. The implied discharge rates for these three gradients would vary by a factor of 3.4.

On one hand, as long as ESPAM2.1 uses an internally consistent set of elevations for groundwater levels and discharge points, gradients and flows may still be correct. On the other hand, with small changes in gradient creating large changes in flow, the importance of accurate elevations and the ambiguity of model calibration targets adds to the uncertainty of model results.

Elevation uncertainties and calibration of ESPAM2.1 to a Rangen discharge elevation understood to uniquely represent neither the Curren Tunnel nor the lower spring compromise the ability of ESPAM2.1 to achieve a credible calibration and to accurately predict the impacts of small changes in aquifer water levels at this location.

SNAKE RIVER GAINS

At the west edge of the study area, ESPAM2.1 is ambivalent on the nature of the effective aquifer. While the model domain was reduced from that of ESPAM1.1 to exclude connection to the Snake River through the Hagerman valley, under the Ralston (2008) interpretation that the Eastern Snake Plain Aquifer terminates at the rim and does not extend beneath the Hagerman valley to the Snake River (IDWR, 2009; p. 9), this design decision was effectively reversed by the inclusion of a series of general head boundaries (GHB) representing flow from the western terminus of the aquifer into the Snake River[28].

In the development of the ESPAM2 groundwater model, the measured gains in flow between the Buhl and Lower Salmon Falls streamflow gages were found to significantly exceed the measured/estimated flow of the springs tributary to this reach. From the 1980 - 2008 average estimated river gain of 3370 cfs, 2463 cfs of spring inflow were subtracted to conclude the average groundwater inflow directly to the river channel averages 907 cfs (Wylie, 2012a).

The 907 cfs of unaccounted-for groundwater discharges to the Buhl-to-Lower-Salmon-Falls reach were further disaggregated for the ESPAM2 modeling: subtraction of 494 cfs average measured just from the Thousand and Magic Springs model cells[29], and 63 cfs measured from the Blue Heart model cell specifically (Wylie, 2012a); left a 350 cfs average to spread across the

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[28]Flow to the Snake River is not explicit in the model, but the elevations of the general head boundaries and the calibration targets for these flows were developed based on the elevations and unaccounted-for underflow into the Snake River (Wylie, 2012a).

[29]The values calculated from upstream and downstream gaging ranged from 224 to 765 cfs.

remaining 14 model cells of the reach. The GHBs in model rows 37 - 41 are assigned identical elevations and conductances, and their ESPAM2.1-modeled discharges are nearly constant, all between 29 and 31 cfs. The row 42 GHB was given the same conductance, but a slightly higher elevation (reflecting the higher level of the river behind the Upper Salmon Falls Dam). ESPAM2.1-modeled discharge for that cell is nearly constant at 22 cfs.

Thus, for the 6 model cells along the Hagerman Rim, ESPAM models 174 cfs of groundwater inflow into the Snake River in addition to the output of the observable springs.

For most of the Buhl-to-Lower Salmon Falls reach, the Snake River channel has been eroded into Tertiary deposits (Kauffman et al., 2005; Othberg et al., 2005; Gillerman et al., 2005), suggesting the "non-spring" gaged gains are evidence of groundwater flow within deposits below the primary aquifer. Whether these gains are the result of groundwater flow into the channel from the Tertiary deposits, however, is confounded by the occurrence of over-the-rim basalt flows of the Quaternary aquifer and outcrop-obscuring talus at various locations. At Blue Heart Springs, geologic mapping suggests groundwater flow may be through the primary (Quaternary) aquifer. At Thousand / Magic Springs, a small area of Quaternary basalts are mapped down to river level, but for the most part, the Snake River channel is bounded by exposed Tertiary deposits. Covington and Weaver (1990; springs #68 - #72) map a series of springs at river level just upstream of the Lower Salmon Falls gage, with a total estimated flow of approximately 20 cfs, identified with the upper contact of the Tertiary basalts (i.e. springs issuing from the Quaternary units)[30].

Wylie (2012a; p. 5) states that "the underflow targets [for ESPAM calibration] will be average underflow for the model period (1980 - 2008)". Thus, a constant, average value is used to represent these flows in ESPAM2.1, despite the fact that the total gains through this reach have declined over the period, and include seasonal fluctuations of 700 cfs.

In summary, the geographic distribution, source aquifer, and seasonal variations for 900 cfs of groundwater flow, over a 21-mile reach of the Snake River including most of the study area for the present report, are poorly understood and grossly reflected in the ESPAM2.1 flows. At an average of 907 cfs, these flows constitutes 27%[31] of the total groundwater discharge through the reach. Calibration of ESPAM2.1 to this large component of groundwater discharge is thus subject to substantial uncertainty with respect to the local transmissivities and groundwater gradients produced by that calibration.

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[30] The status of these springs is unclear, as they fall outside the ESPAM2.1 model, but contribute to the "springs" portion of total reach gains above the Lower Salmon Falls gage.

[31] 907 / 3370 = 27% (Wylie, 2012a)

CALIBRATION COMPARISONS

The calibration of ESPAM2.1 is dealt with in detail by Brendecke (2012). In this section, select examples are drawn from the ESPAM2.1 reporting to illustrate discrepancies related to the issues discussed above. While groundwater flow models are rarely able to duplicate every variation in aquifer behavior, consistent errors in the same direction indicate a systematic failure to capture relevant characteristics of the groundwater system. ("Differences between simulated and measured head and spring discharge also indicate areas where model refinement is needed." (Garabedian, 1992; p. F31).)

Figure 29 compares the ESPAM2.1-modeled aquifer water levels with the calibration well closest to Rangen, PEST #989[32]. The modeled levels are consistently around 22 ft. lower than the measured levels at this point in the aquifer. Groundwater flow to the Rangen "drain" is controlled by the difference in water level between the aquifer and the "drain" elevation. (This difference is the groundwater "gradient".) Because ESPAM2.1 underestimates this gradient, it must overestimate the aquifer transmissivity and/or drain conductance value by a compensating amount to simulate the observed Rangen discharge. Higher transmissivities and conductance values make groundwater discharge from a cell more sensitive to changes in aquifer water levels, e.g. as are projected to occur as a result of groundwater pumping curtailment.

Figure 30 compares the ESPAM2.1-modeled discharge at Rangen with the reported estimates of actual flow for the 2000s[30]. Over this period: 1) the model consistently overpredicts the flow; 2) modeled seasonal fluctuations generally exceed those observed; and 3) ESPAM2.1 consistently predicts the month of lowest flow 3 months earlier than it actually occurs.

The general overprediction of Rangen flows suggests local ESPAM2.1 transmissivities are too high, the drain conductance assigned to the Rangen discharge is too high, modeled aquifer water levels are too high, the assigned drain elevation is too low, or some combination of these factors.

Potential reasons for ESPAM2.1's overprediction of annual fluctuations include incorrect elevations, incorrect modeling of a multiple-elevation discharge, incorrect aquifer storage properties, and incorrect modeling of aquifer recharge and/or discharge (e.g. recharge from surface irrigation operations, precipitation recharge, groundwater irrigation extractions).

Errors in the timing of the annual cycle of discharge may be generated by many of these same factors. Rogers (2012) has analyzed the relationship between seasonal flow fluctuations and the operation of the Rangen fish-rearing facilities. He evaluated the relationship between annual cycles in the water demands of Rangen fish production and annual cycles in the availability of groundwater discharge. A "bottleneck" in the Rangen operation occurs when demands are high and supplies are low. A multi-month difference in the timing of seasonal low flows may have a

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[32]From IDWR spreadsheet, "ESPAM2_ESPAM21.XLS"

significant effect on the assessment of the impacts to Rangen of the curtailment scenarios generated using ESPAM2.1.

Figure 31 compares the ESPAM2.1-modeled discharge for the Buhl-to-Lower Salmon Falls reach of the Snake River (which includes the Rangen discharge) with the reported estimates of actual flow for the 2000s[30]. Over this period, the model consistently overpredicts the flow, by 170 cfs on average. Also, the model produces a seasonal range of flows generally less than 100 cfs, compared with measured seasonal fluctuations in excess of 300 cfs. During the 1980s, ESPAM2.1 consistently underestimates these flows, suggesting the calibration to constant monthly values has compromised its ability to address either long-term or seasonal discharge relationships.

Figure 32 presents ESPAM2.1-modeled discharge through the GHBs for the Magic and Thousand Springs model cells (43-12 and 44-12), and includes the specific measurements from which the ESPAM2.1 treatment of reach gains in this reach was developed (Wylie, 2012a). As above, the very generalized nature of ESPAM2.1 treatment of this component of the groundwater balance is obvious.

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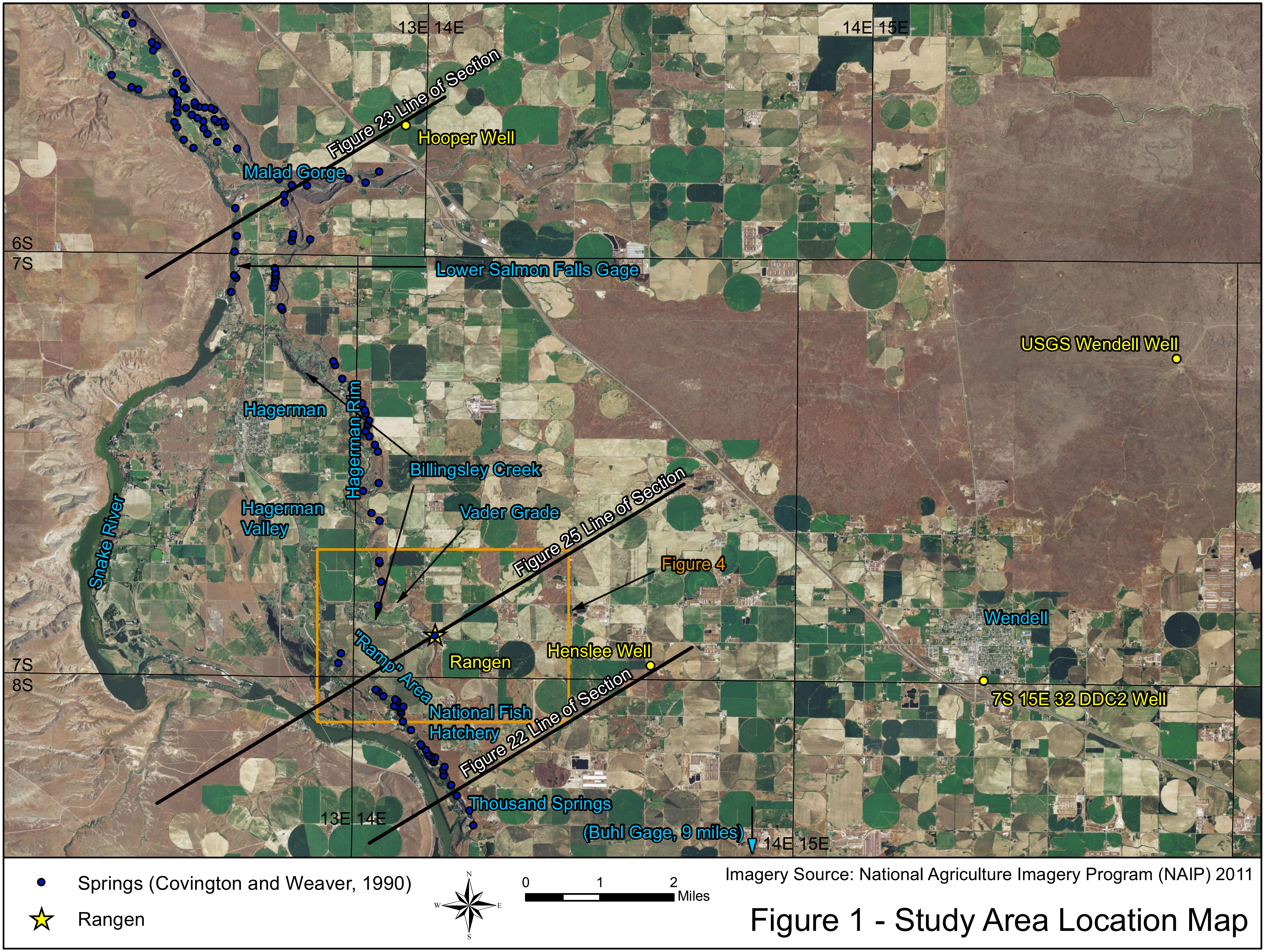
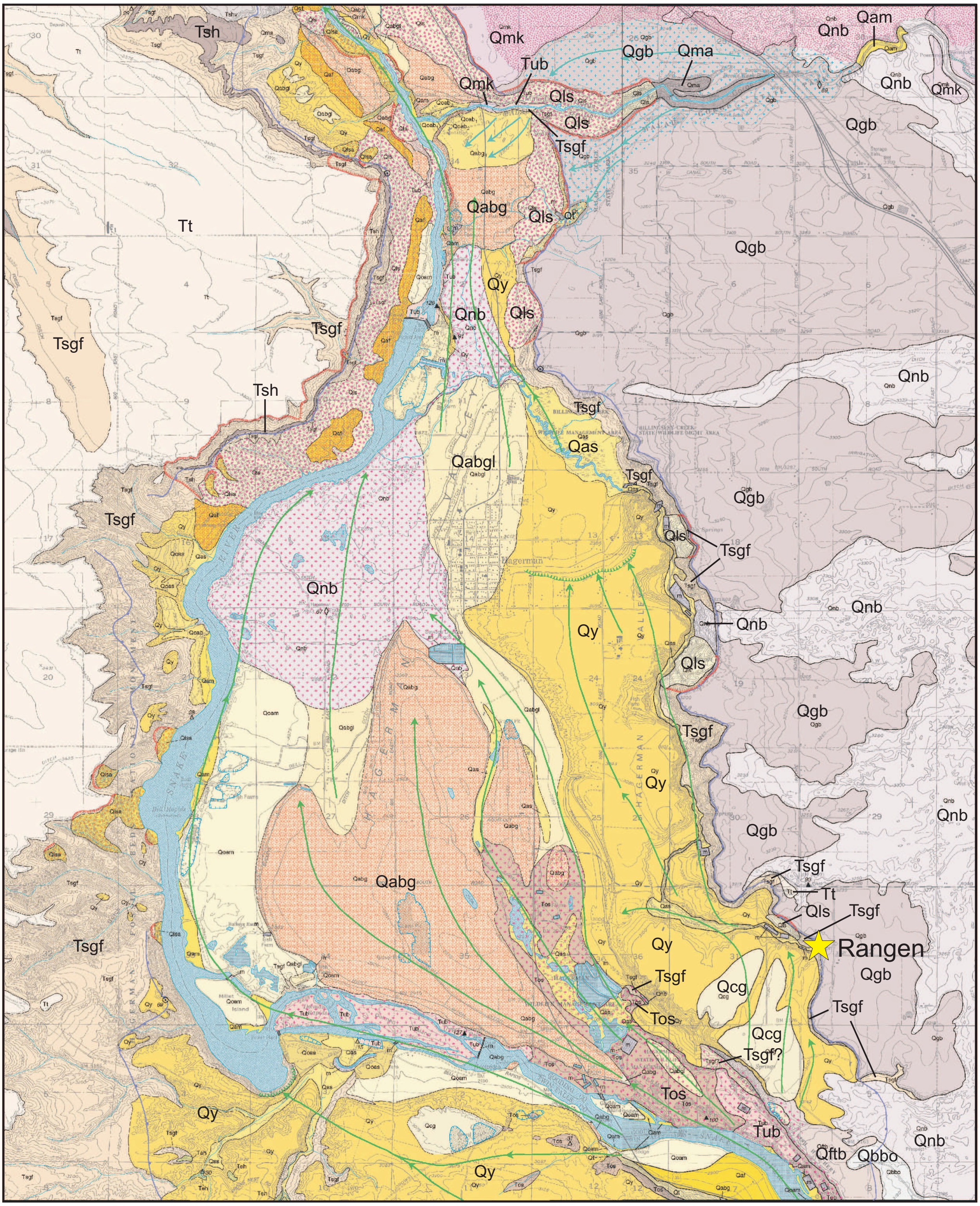


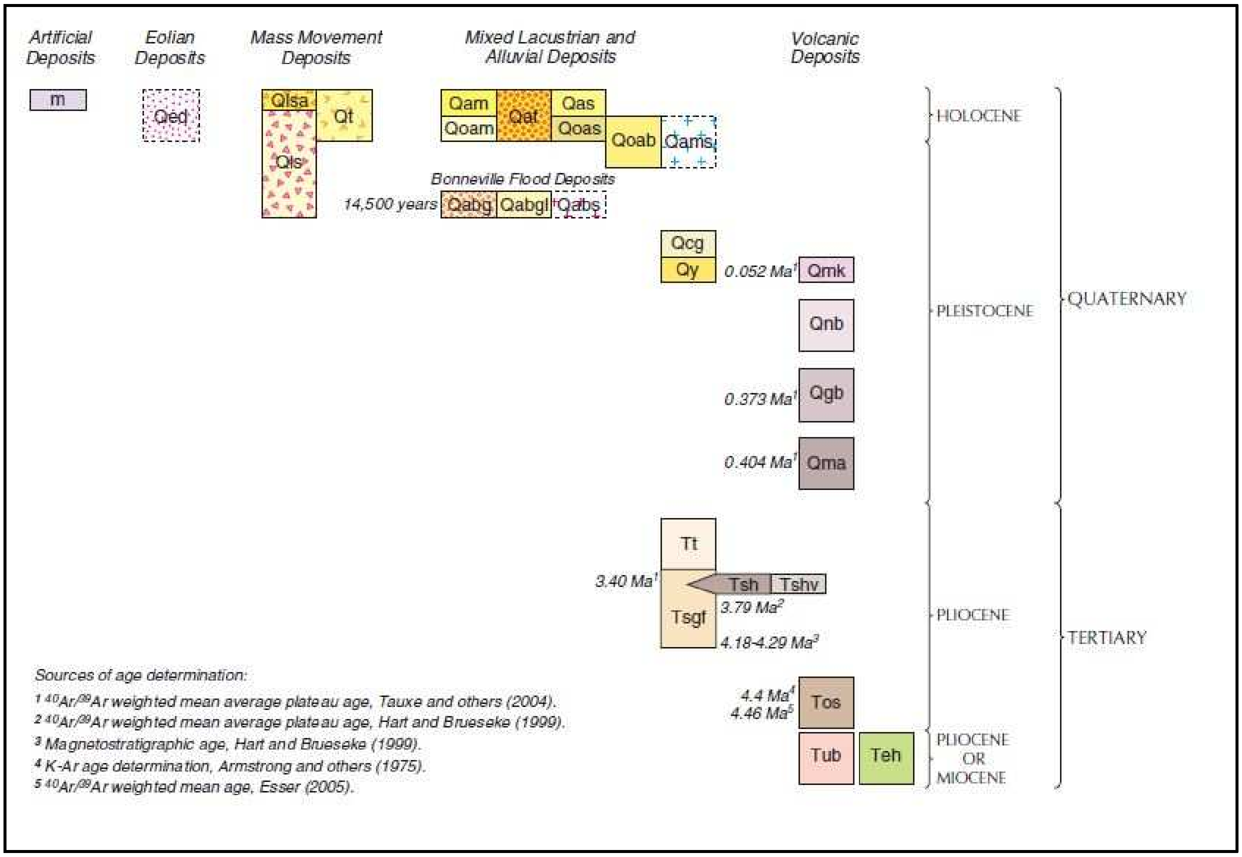
Imagery Source: National Agriculture Imagery Program (NAIP) 2011

Figure 1 - Study Area Location Map



Source: Othberg et al., 2005 and Kauffman et al., 2005

Figure 2 - Study Area Geology



Source: Kaufman et al., 2005

Figure 3 - Stratigraphic Summary and General Lithology

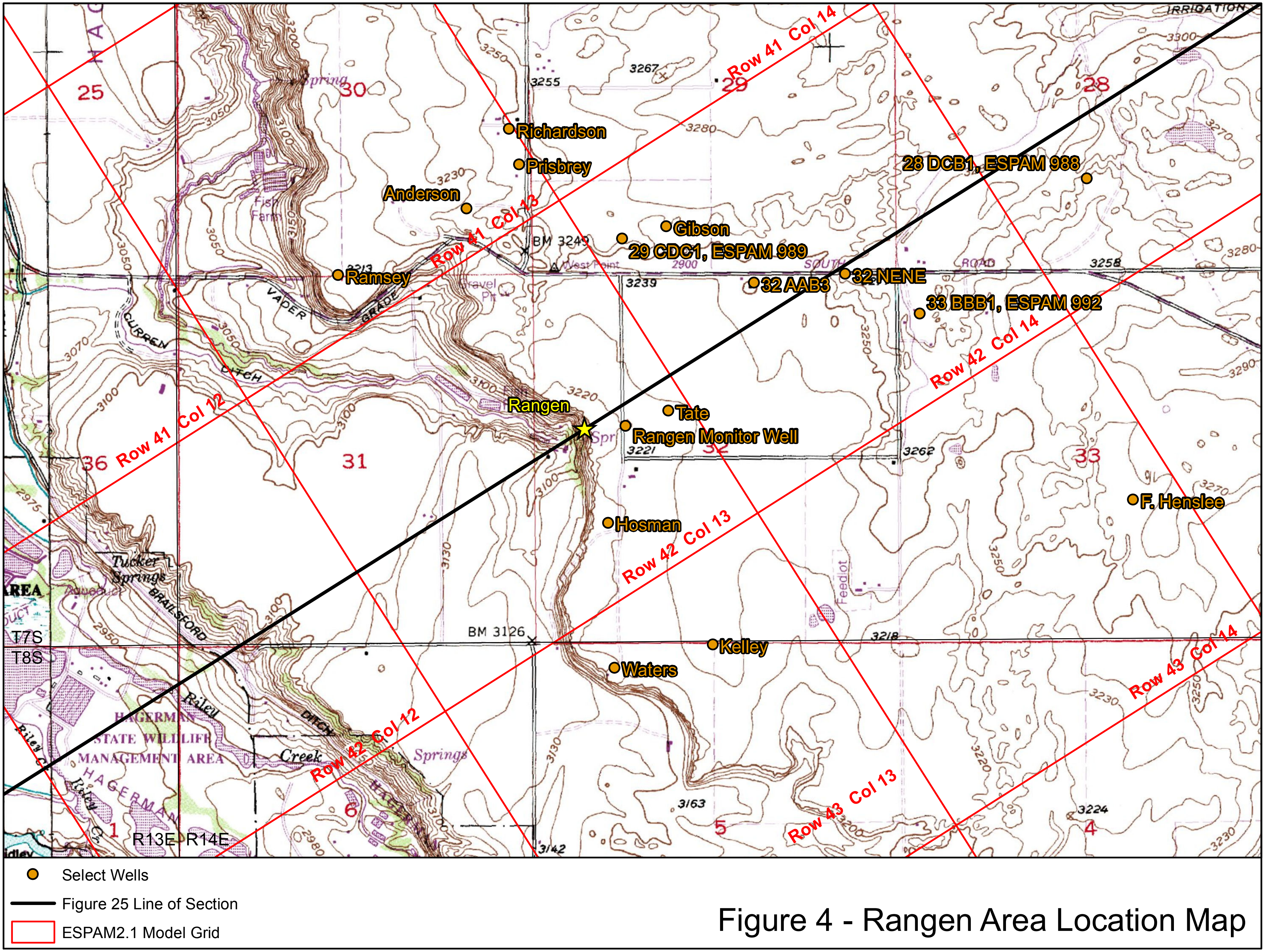


Figure 4 - Rangen Area Location Map

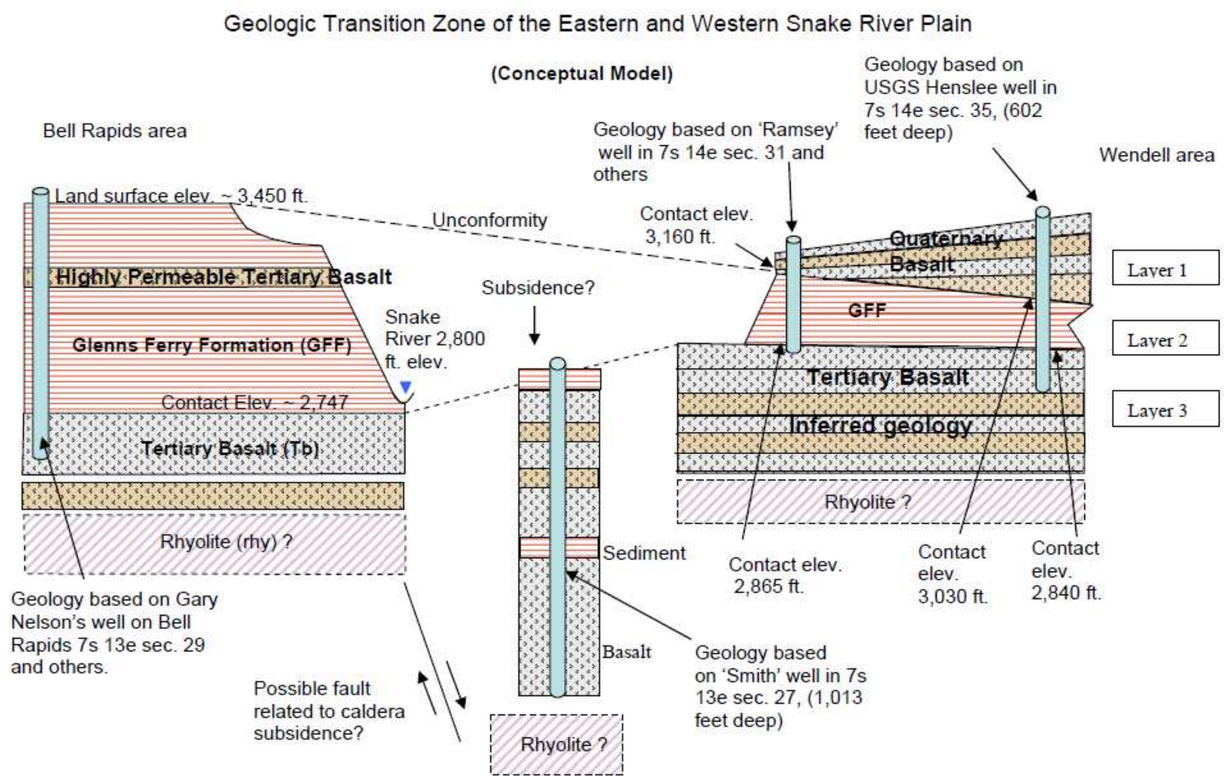


Figure 9. Conceptual 3-layer model of east Hagerman Valley (not to scale). The Tb/rhy contact may not have been horizontal and the Qb/GFF contact is erosional.

Source: Farmer, 2009; Fig. 9

Figure 5 - Rangen Conceptual Model

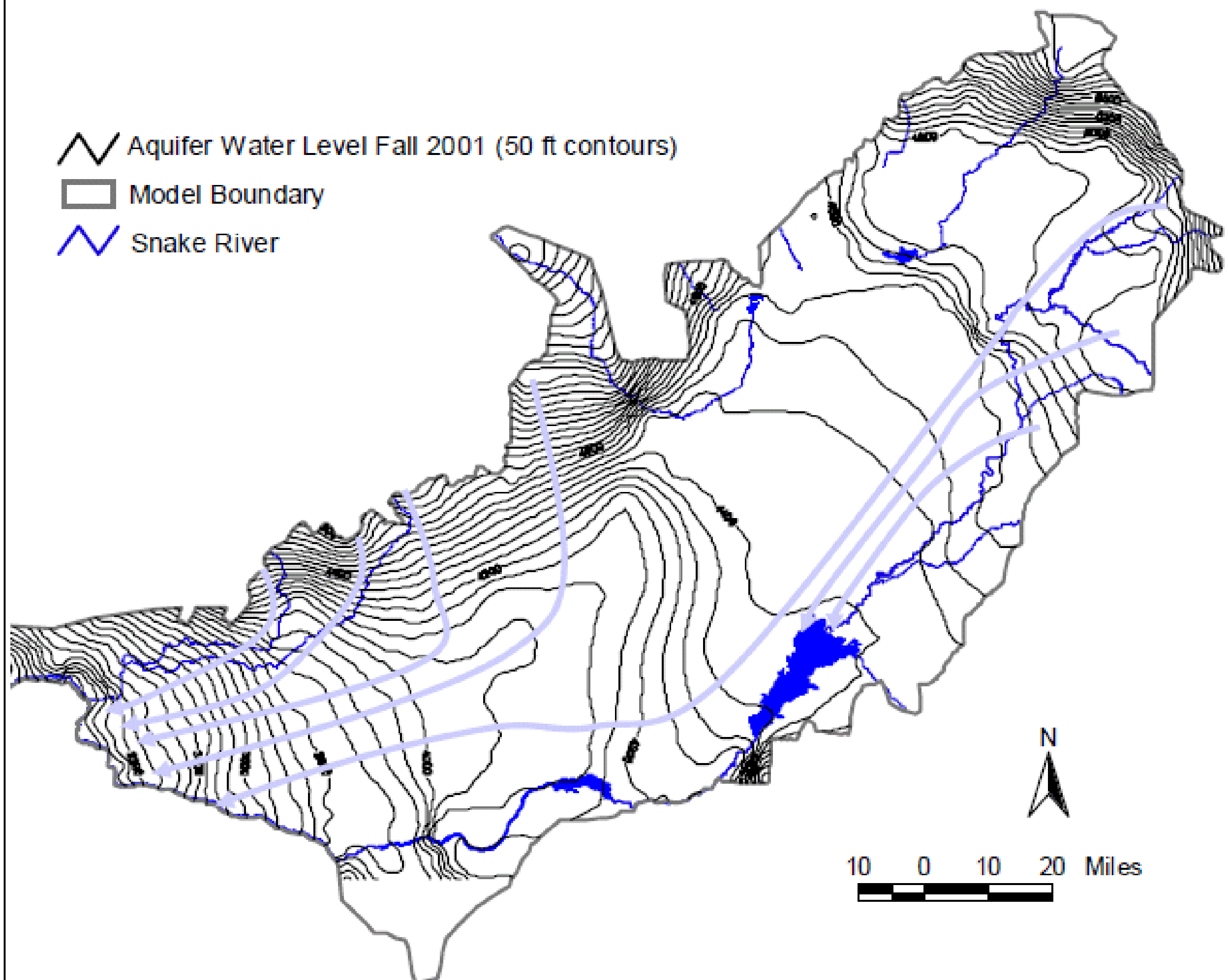
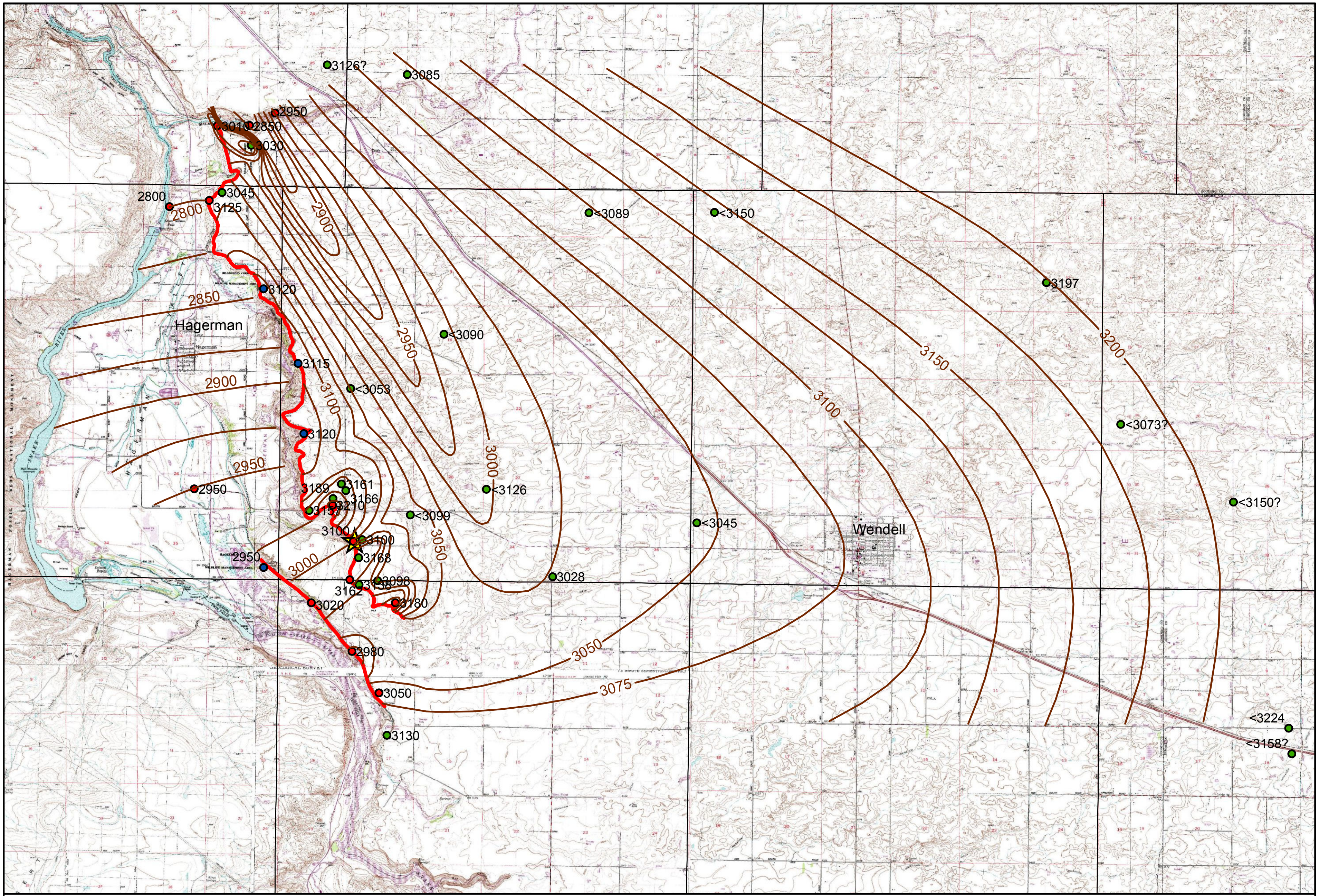


Figure 10. Contours of the Fall, 2001potentiometric surface of the Snake River Plain Aquifer and estimated aquifer flow lines.

Source: Cosgrove et al., 2006

Figure 6 - Potentiometric Surface for the Eastern Snake Plain Aquifer



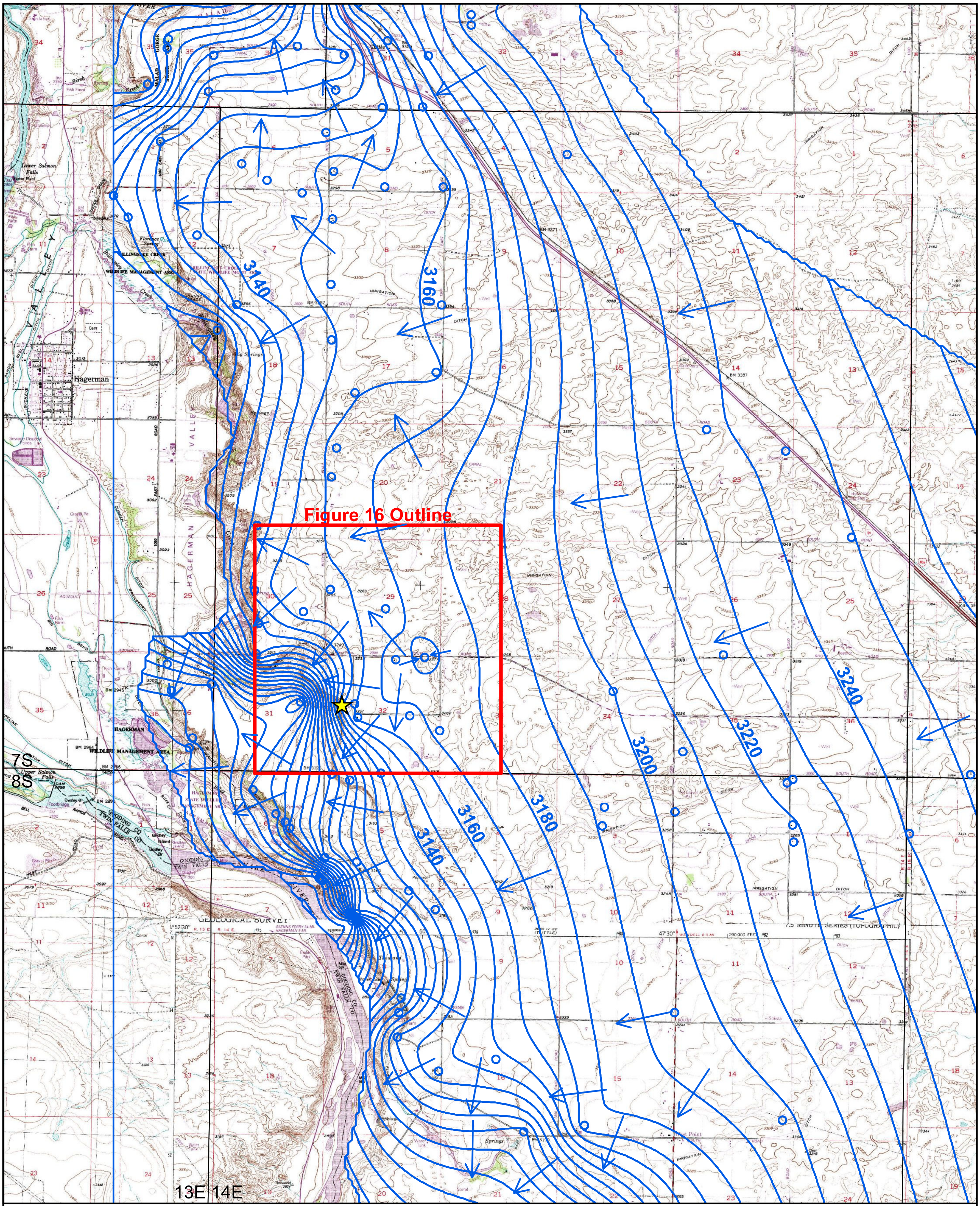
Primary Aquifer Base Contact Points

- Springs (Covington and Weaver, 1990)
- Outcrops (Othberg et al., 2005 and Kauffman et al., 2005)
- Well Logs (IDWR Files)

☆ Rangen

— Exposed Base of Primary Aquifer

Figure 8 - Schematic Contouring of Base of Primary Aquifer

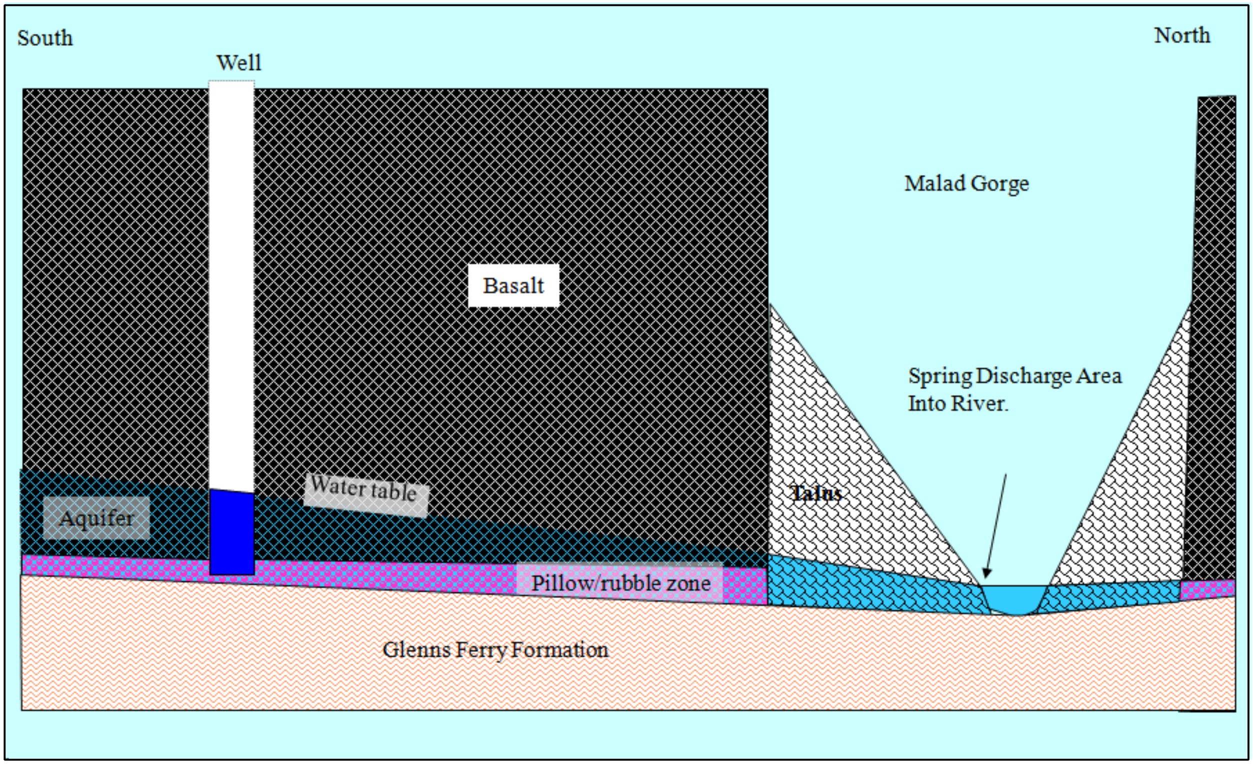


Flow Lines

Rangen

Data points and contouring from Farmer and Blew (2012)
(Shapefile: Nov. 2011 WT map (10ft.) contours CLIPPED, found at http://www.idwr.idaho.gov/Browse/WaterMngmt/
Rangen Delivery Call/Rangen Spring Hydrology Discussion/%237/Mass Measurement/2011 Nov. Mass Meas/)

Figure 7 - Study Area Potentiometric Surface Nov. 2011



Source: Farmer and Blew (Sept. 2009; Fig. 7)

Figure 9 - Malad Gorge Schematic
Geologic Cross-Section

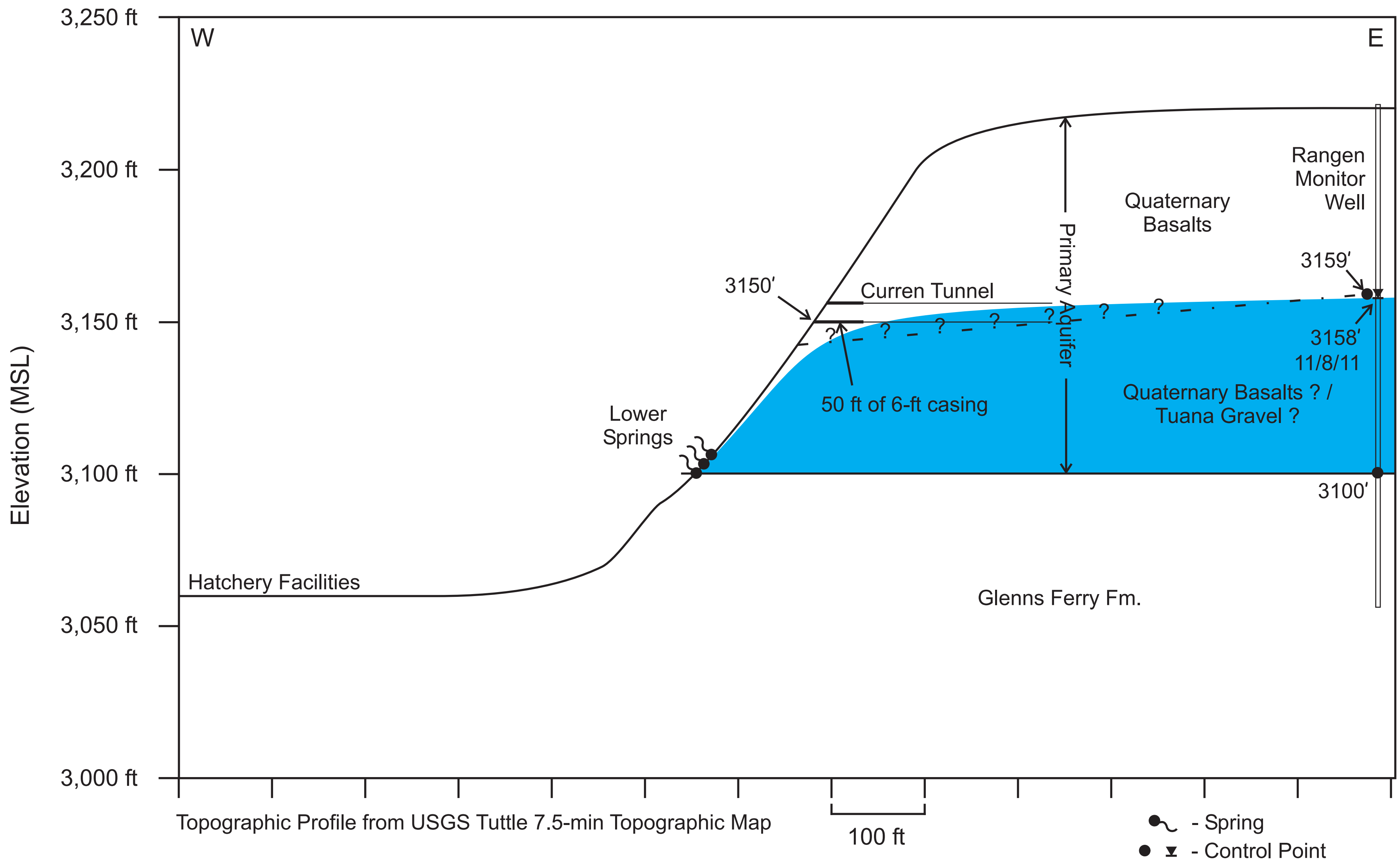
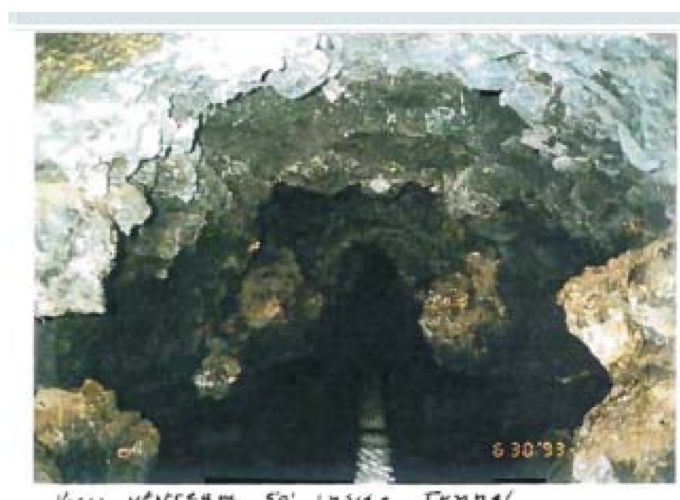


Figure 10 - Rangen Groundwater Discharge Profile

Imagery Source: GoogleEarth 9/21/11

source: IDWR (1993)

Entrance to Curren Tunnel



source: IDWR (1993)

Curren Tunnel Beyond Lining

Figure 11 - Rangen Groundwater Discharge

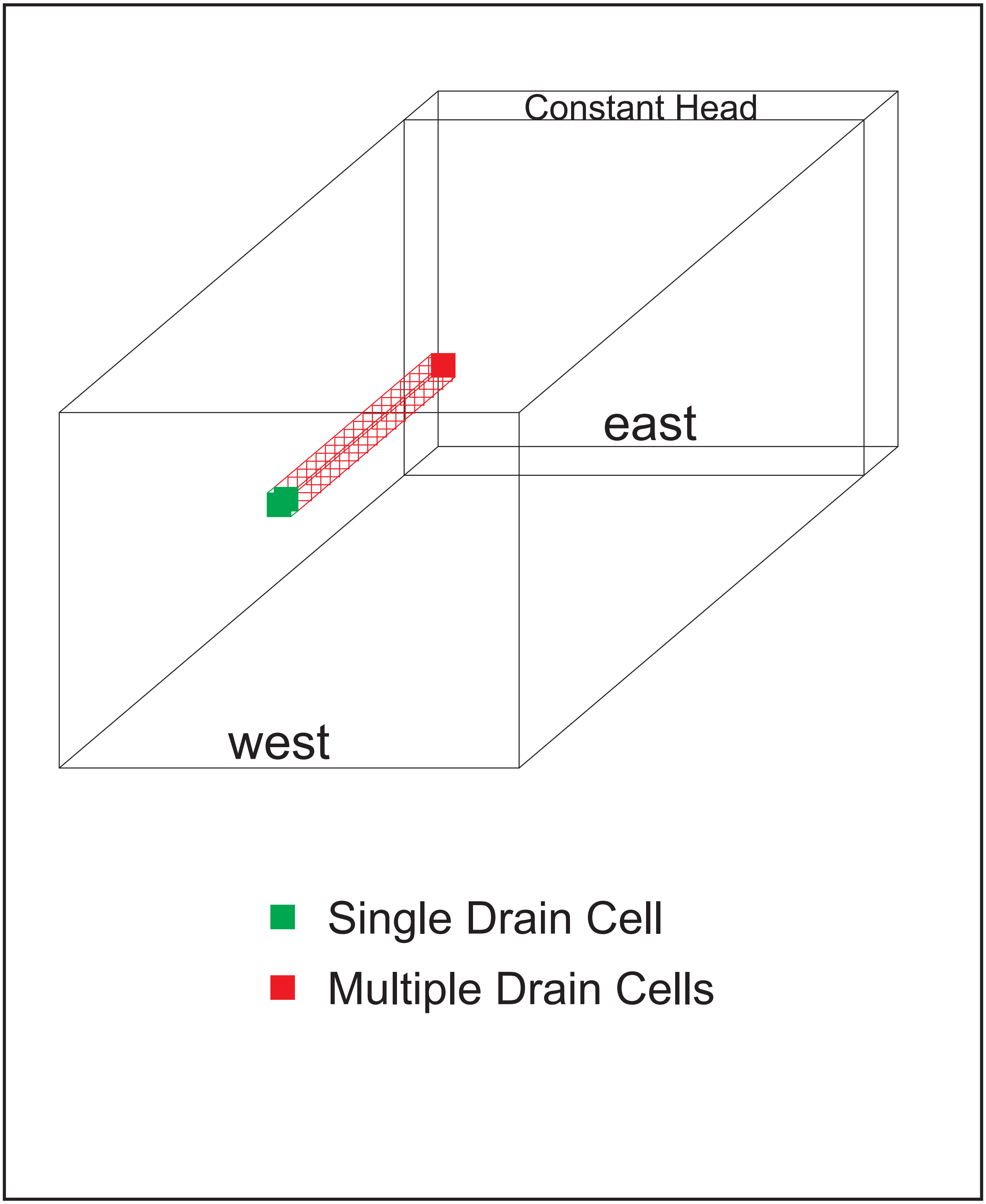


Figure 12 - Drainage Tunnel Groundwater Model Schematic

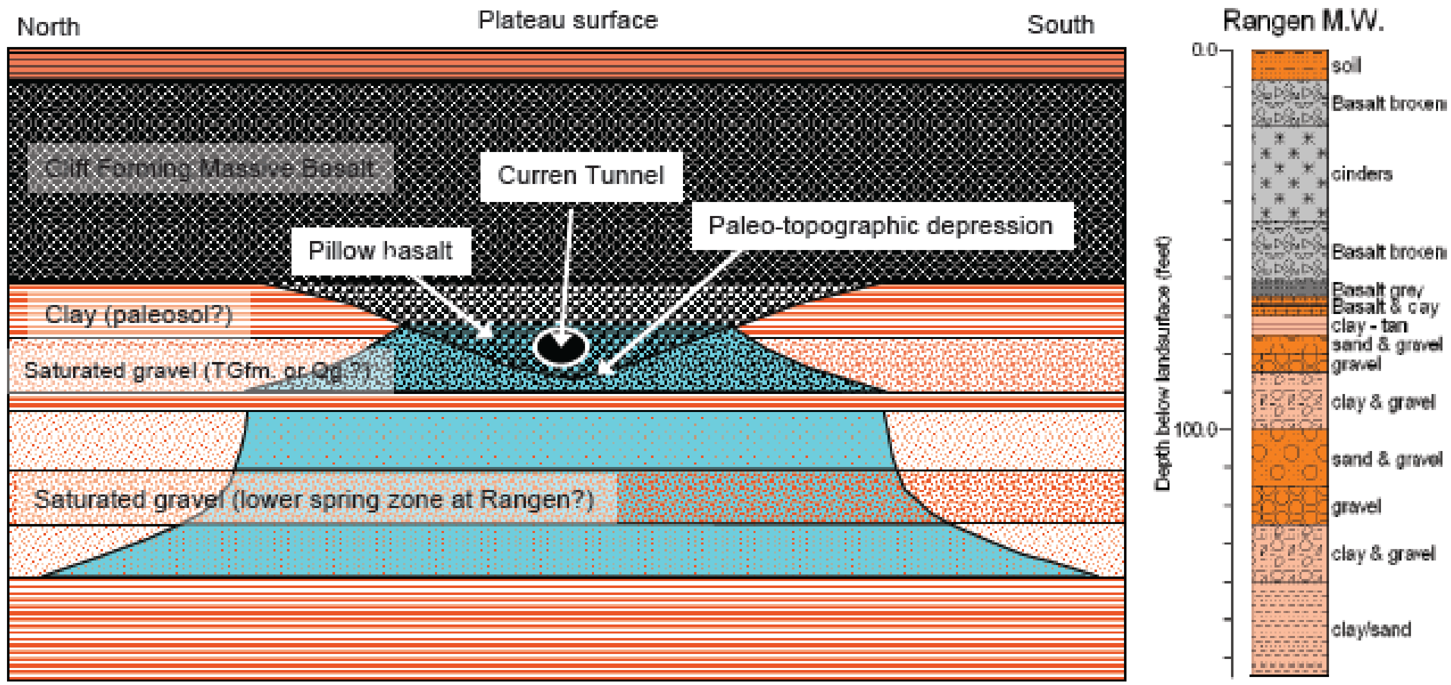


Figure 24. Conceptual hydrostratigraphic model for the Rangen spring area showing the paleo-topographic depression filled with pillow basalts and underlying sediments transporting groundwater.

Source: Farmer (2009)

Figure 13 - Rangen Groundwater Discharge Cross-Section

Figure 14 - Rangen Discharge 1993 - 2009

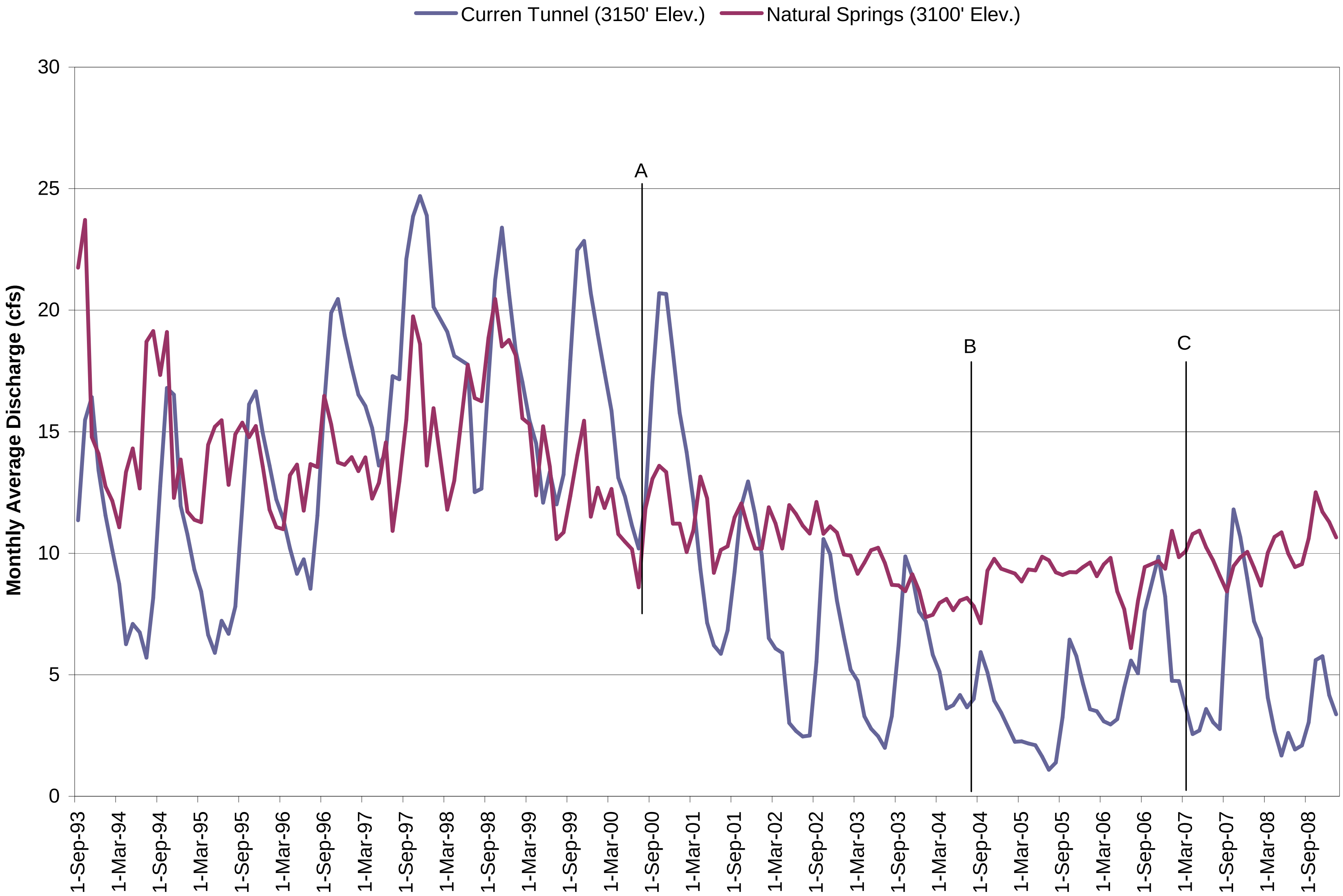
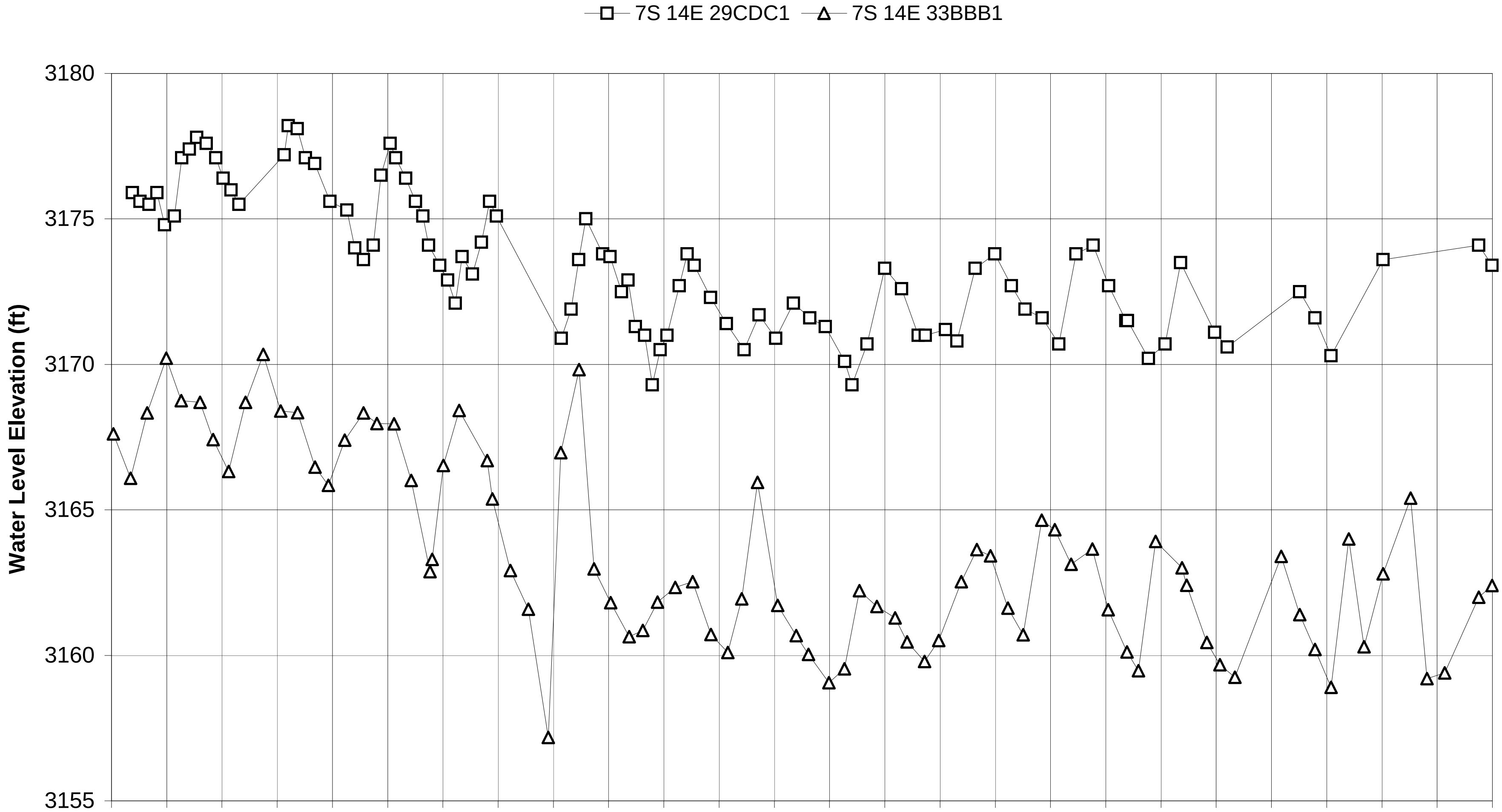
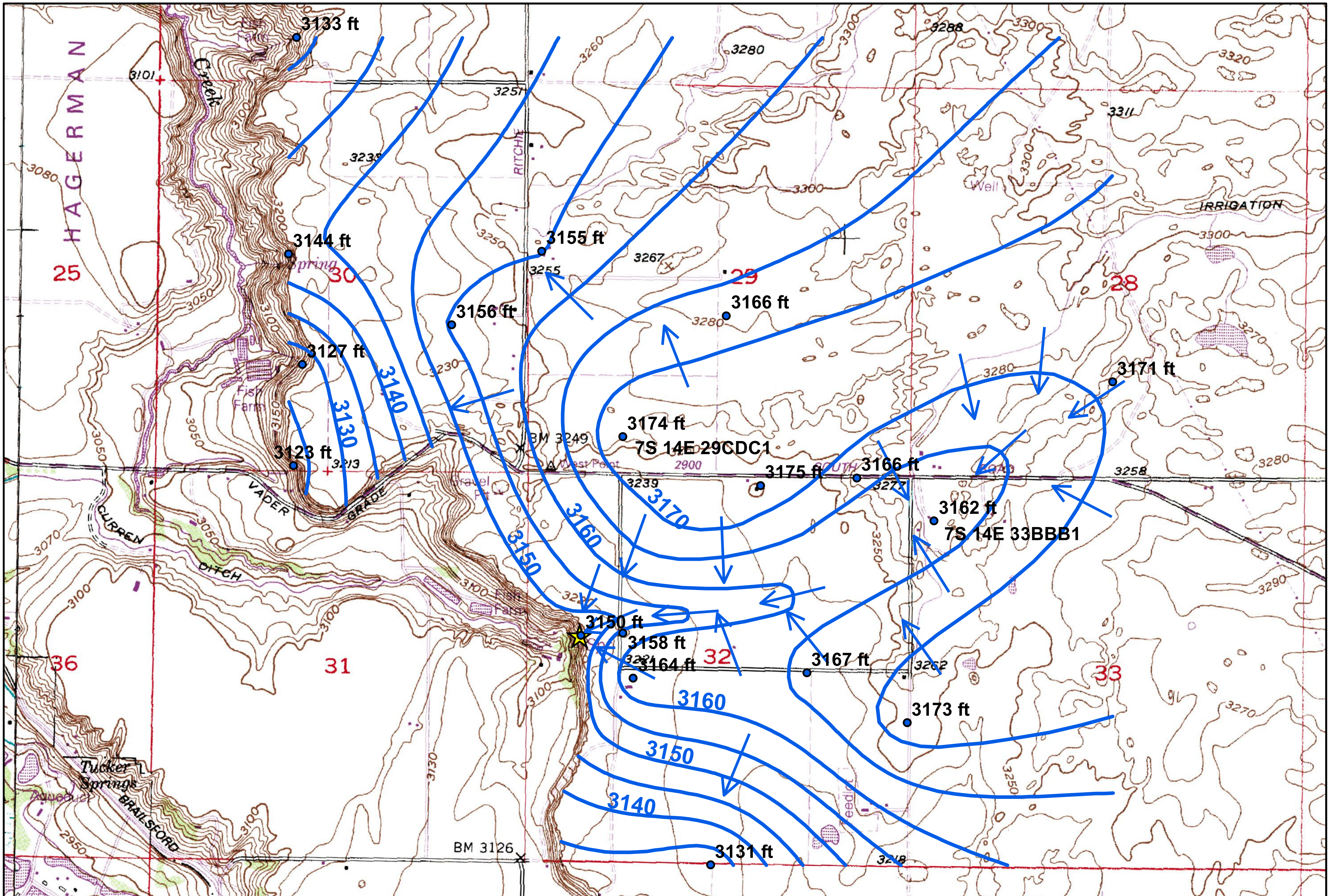


Figure 15 - Rangen Area Groundwater Elevations





Flow Lines

Contour Control Points

Rangen

Figure 16 - Rangen Area Groundwater Level Schematic

Figure 17 - Rangen System Discharge and Aquifer Water Level Elevation
8/6/1985 - 5/4/2009; Well 7S 14E 33 BBB1

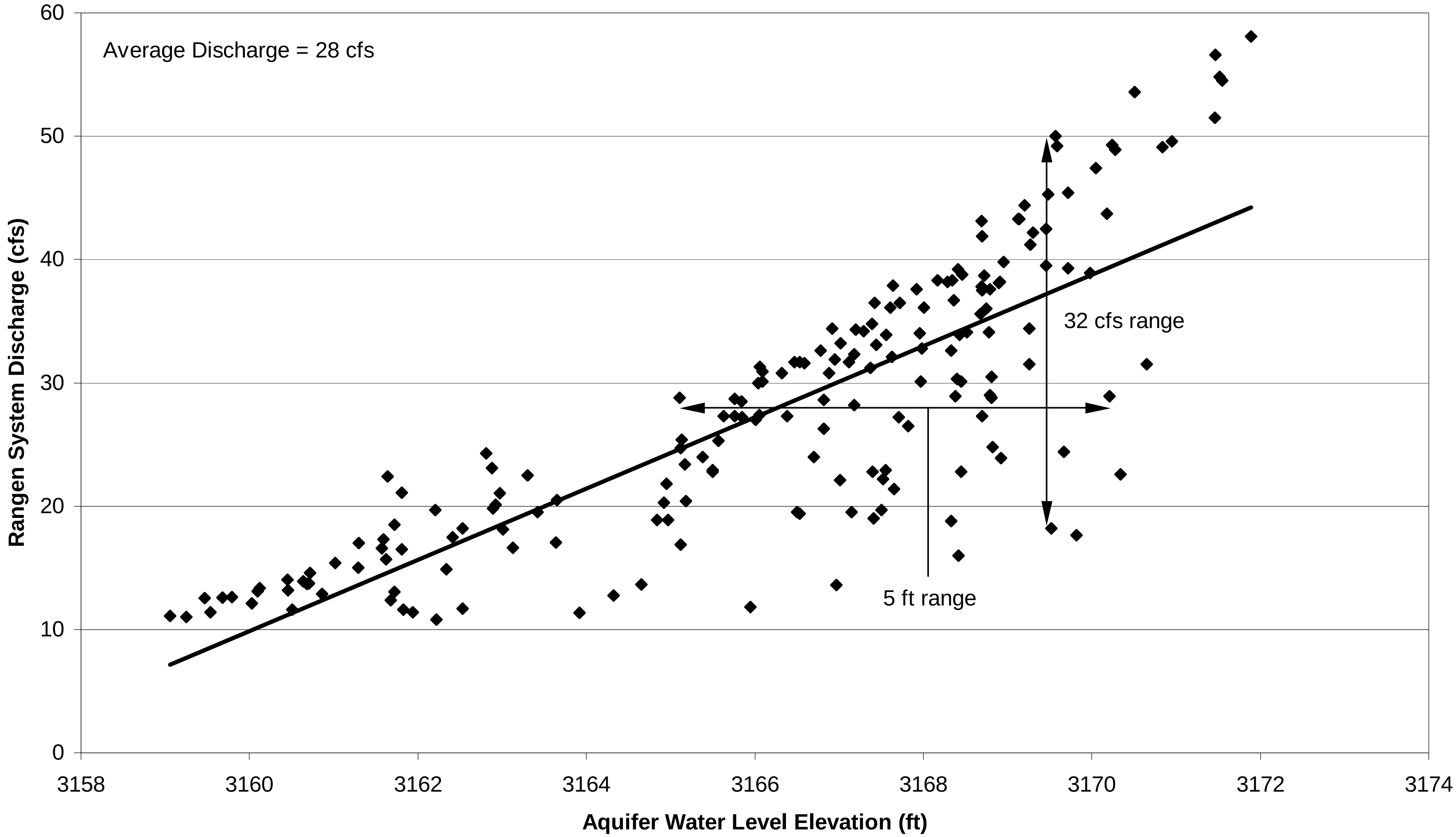
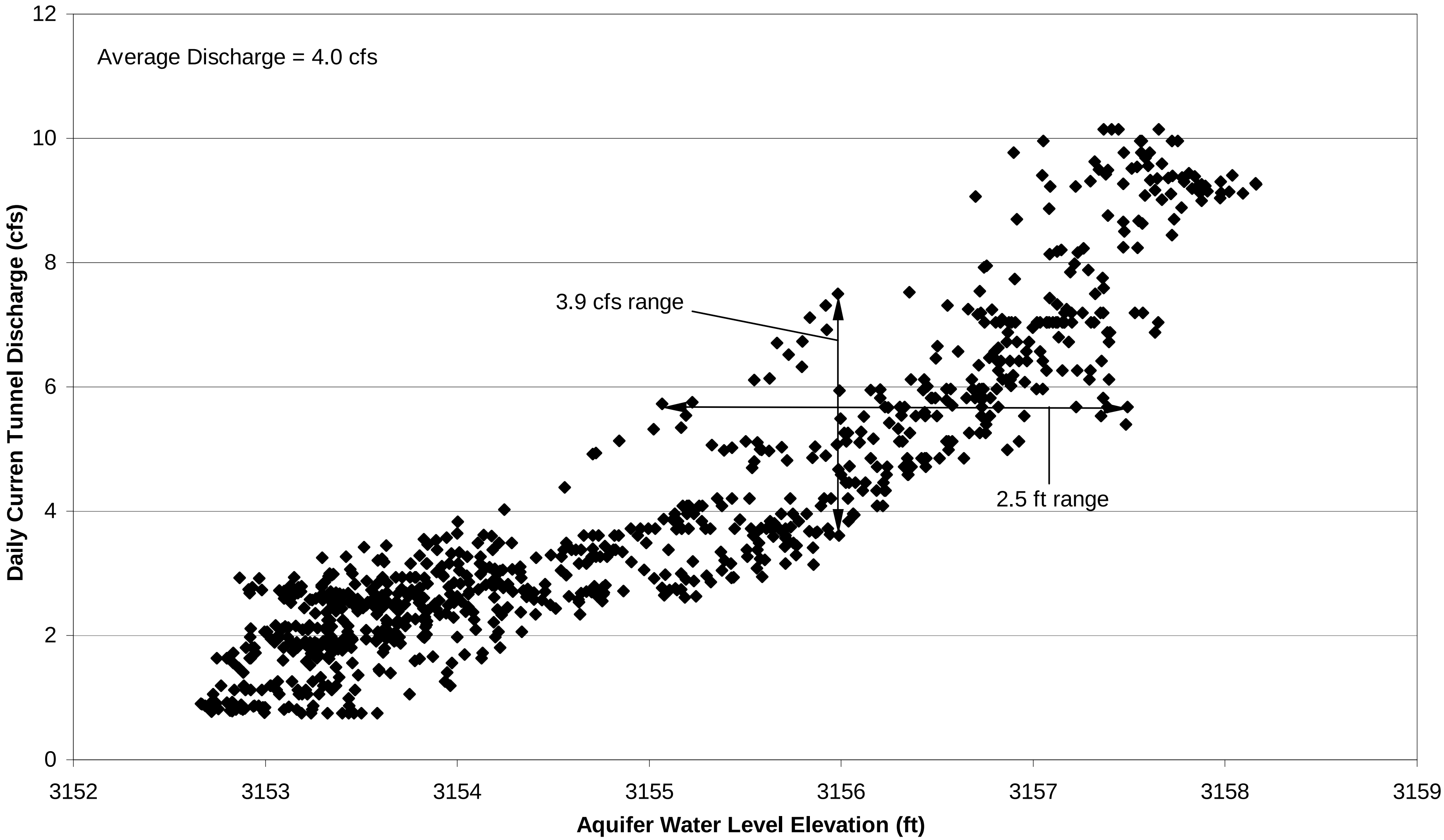
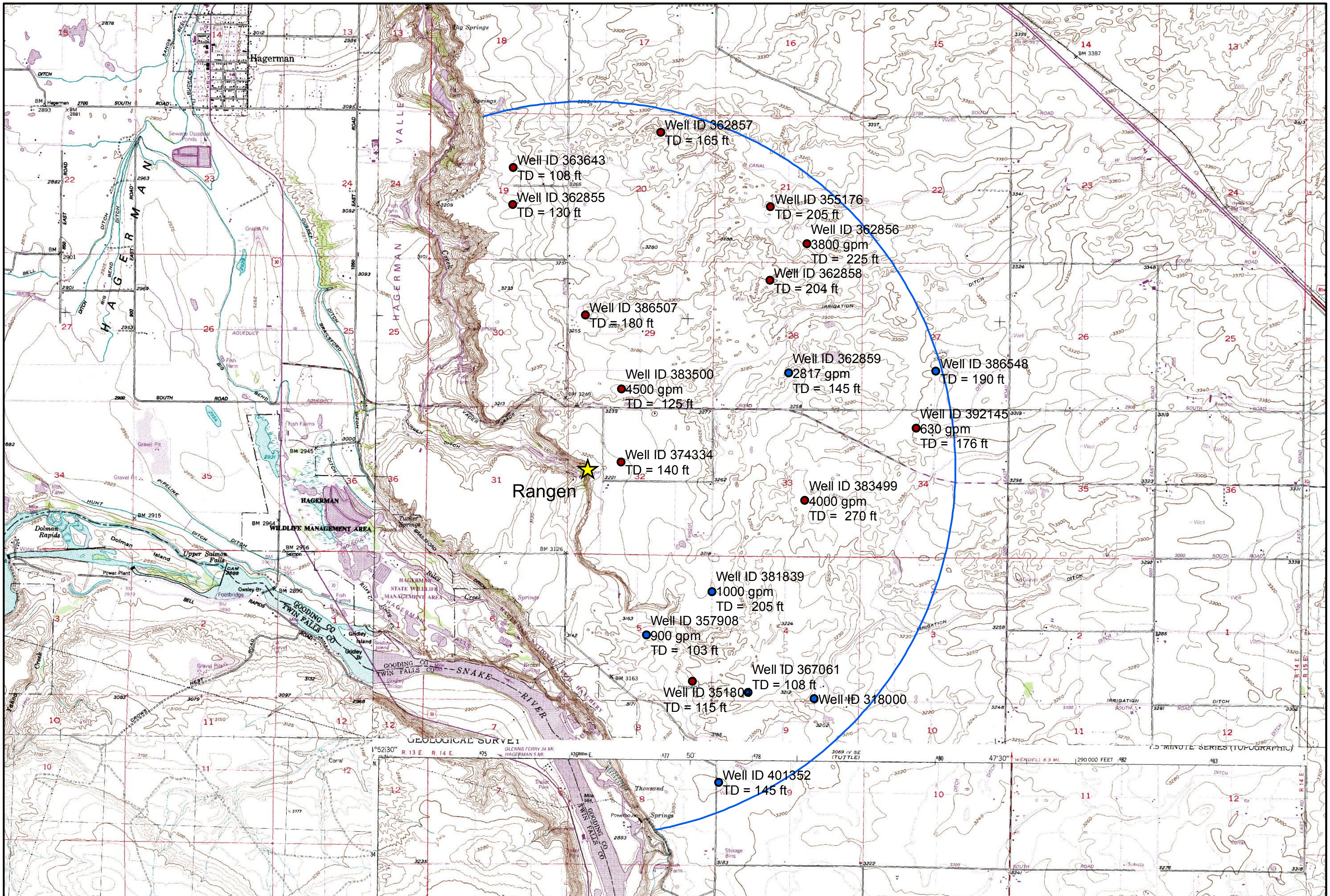


Figure 18 - Curren Tunnel Discharge and Aquifer Water Level Elevation
8/6/2008 - 1/31/2012; Rangen Monitor Well 7S 14E 32 SENW





Irrigation Wells

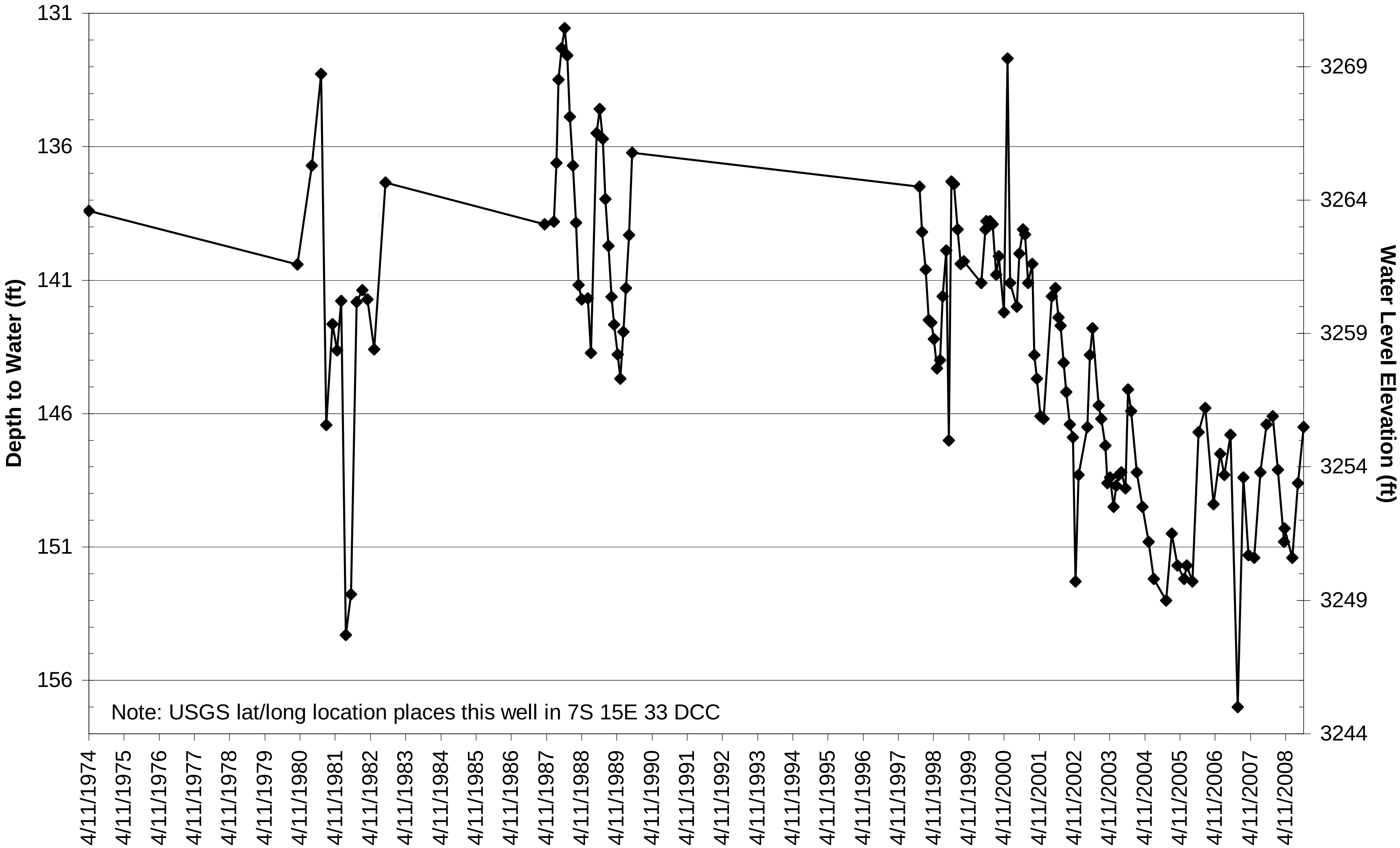
- GPS/Air Photo Location
- Qtr-Qtr Location

Source: http://www.idwr.idaho.gov/ftp/gisdata/Spatial/Wells/WellConstruction/WellConstruction.zip

Area within 2 1/2 miles of Rangen, east of the rim.

Figure 19 - Rangen Area Irrigation Wells

Figure 20 - IDWR Well Number 7S 15E 32 DDC2



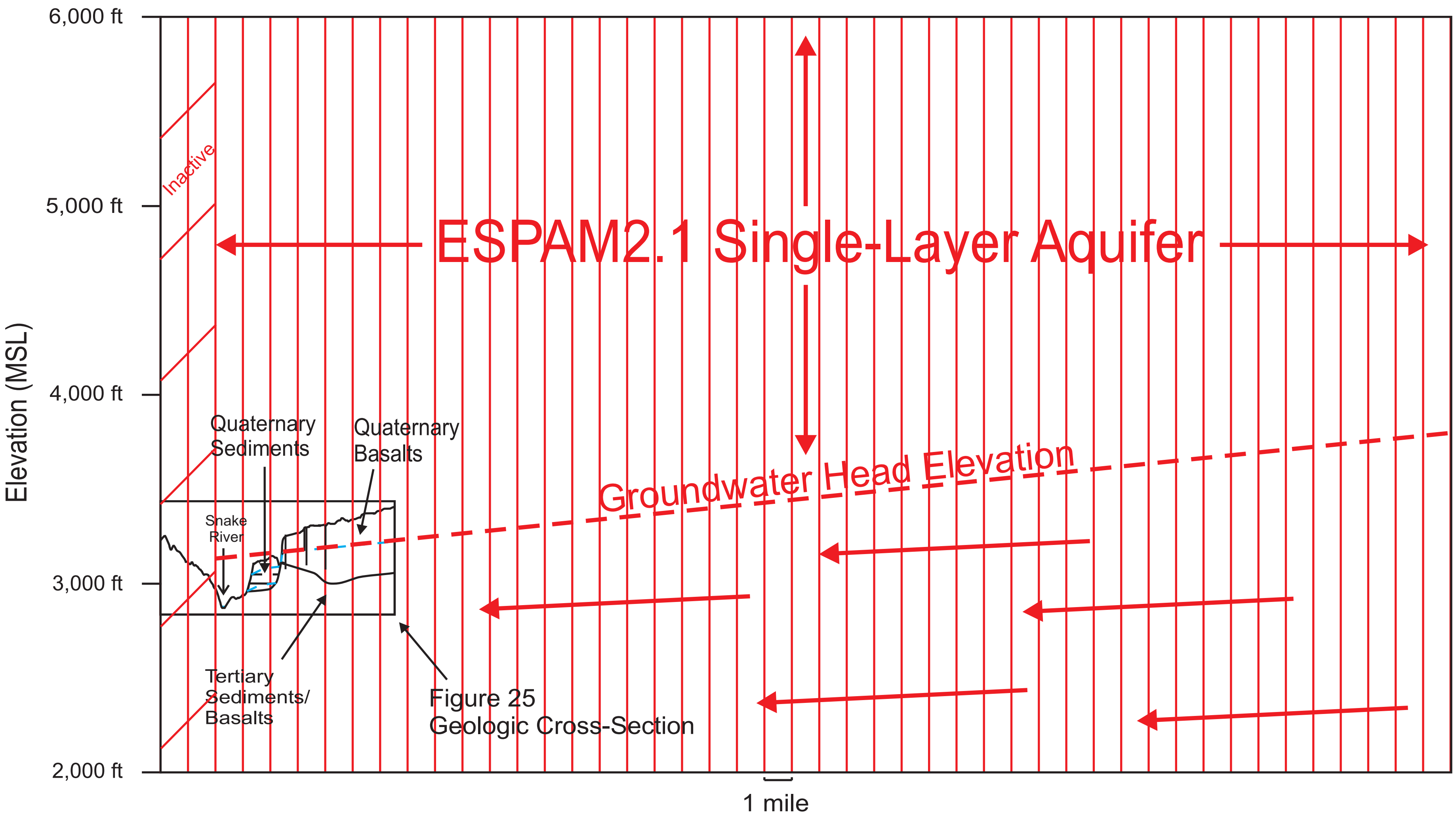


Figure 21 - ESPAM2.1 Row 42 Cross-Section with Rangen Inset

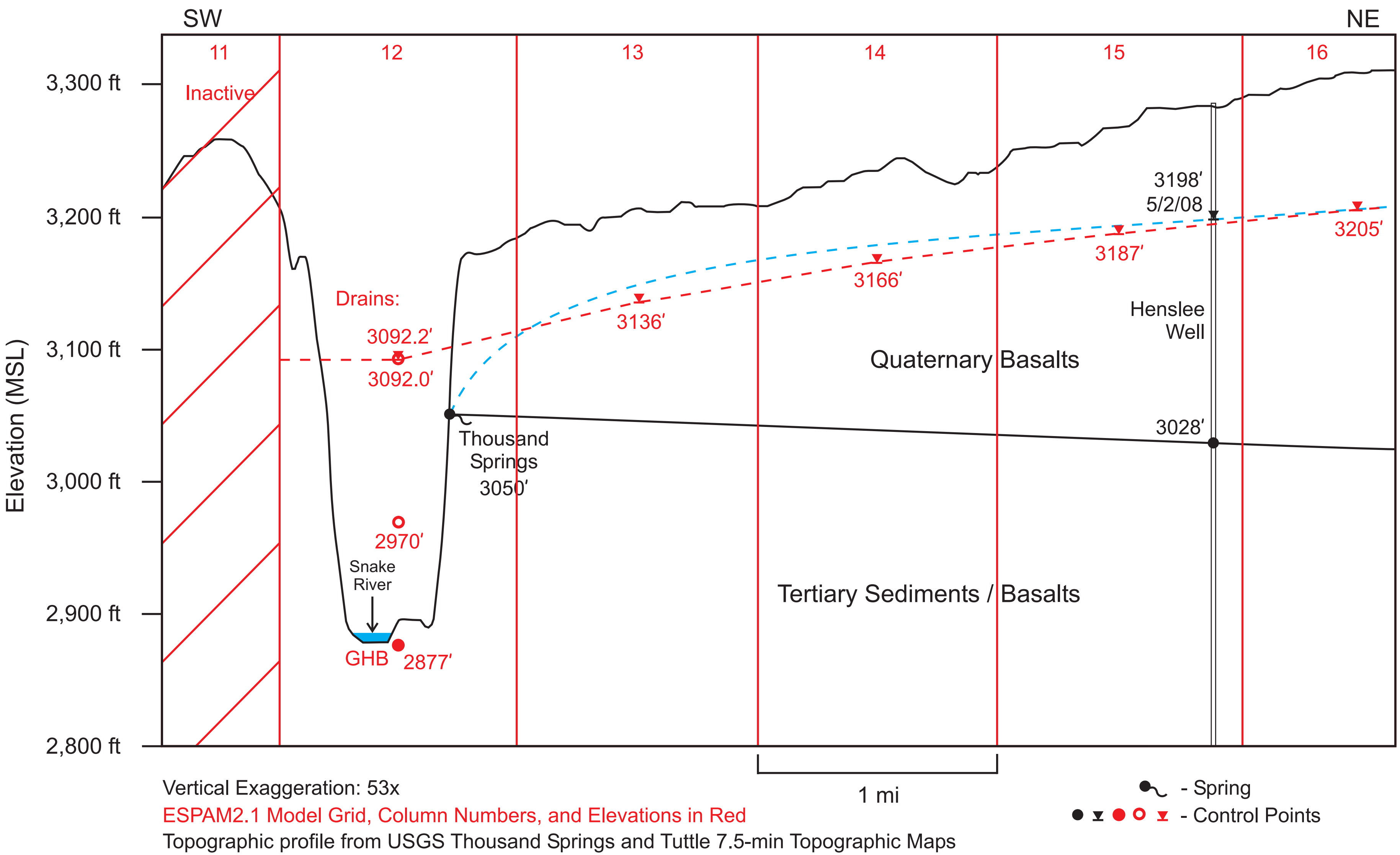


Figure 22 - ESPAM2.1 Row 44 Schematic Profile and Model Overlay

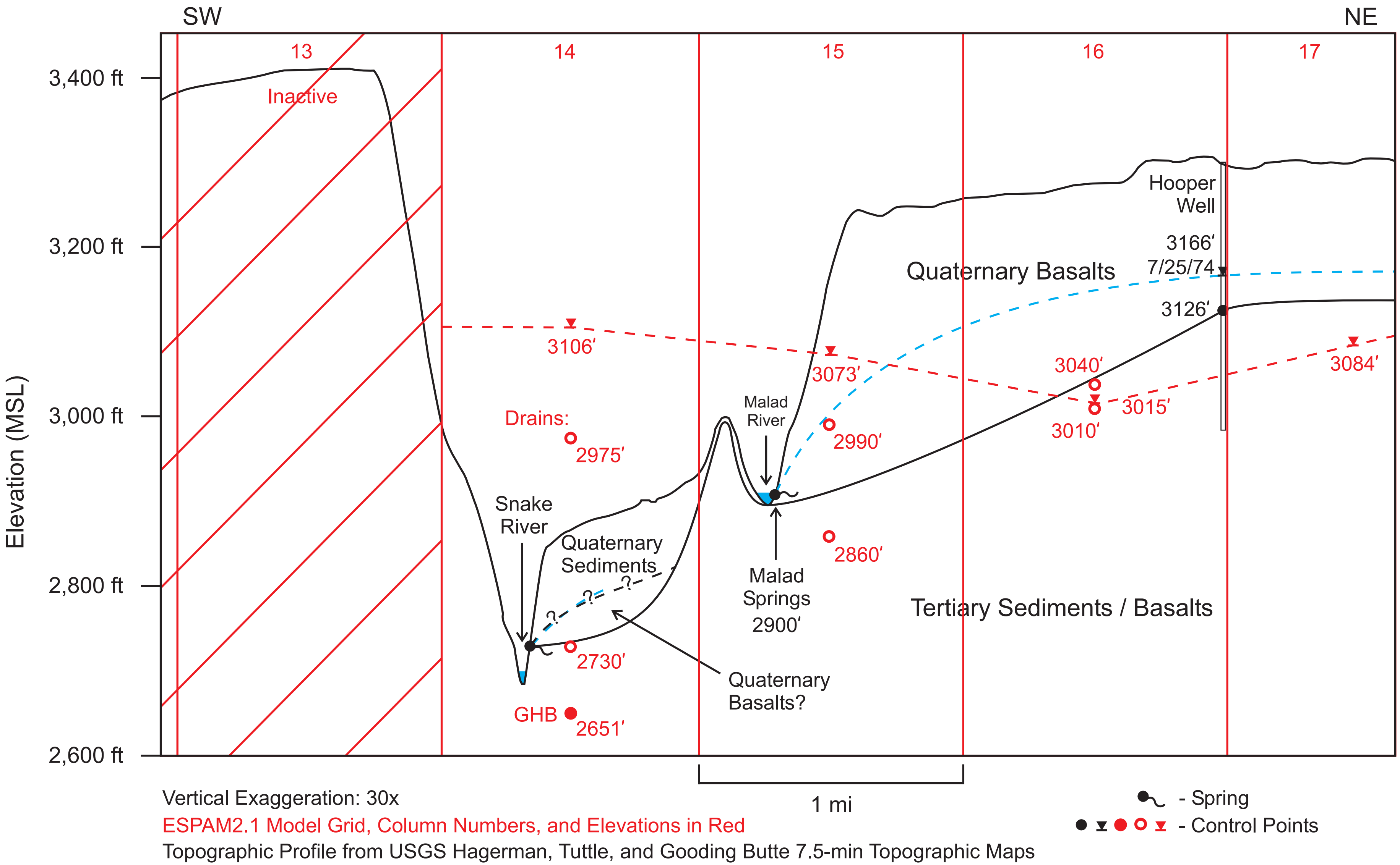


Figure 23 - ESPAM2.1 Row 36 Schematic Profile and Model Overlay

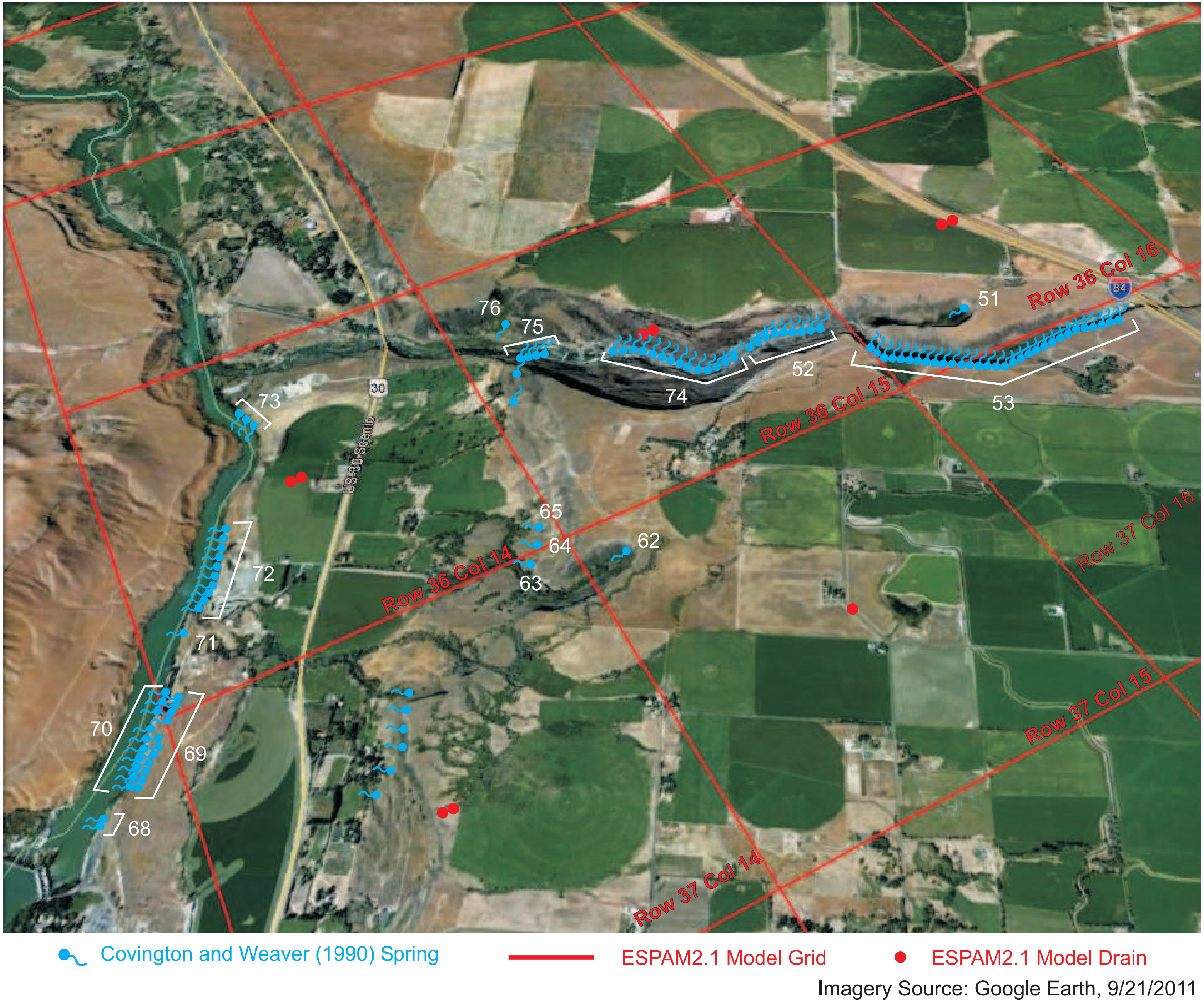


Figure 24 - Malad River ESPAM2.1 Model Area

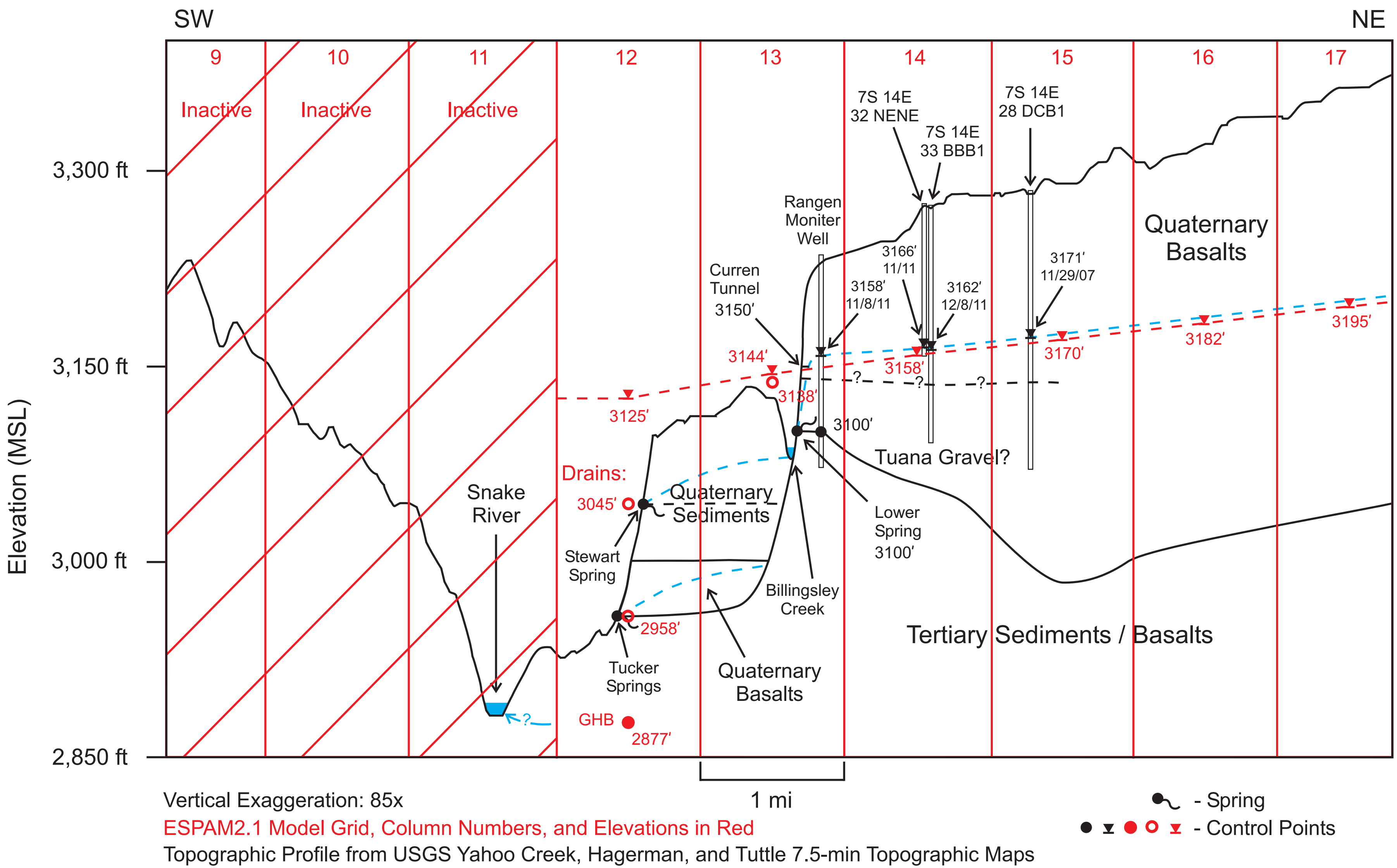


Figure 25 - ESPAM2.1 Row 42 Schematic Profile and Model Overlay

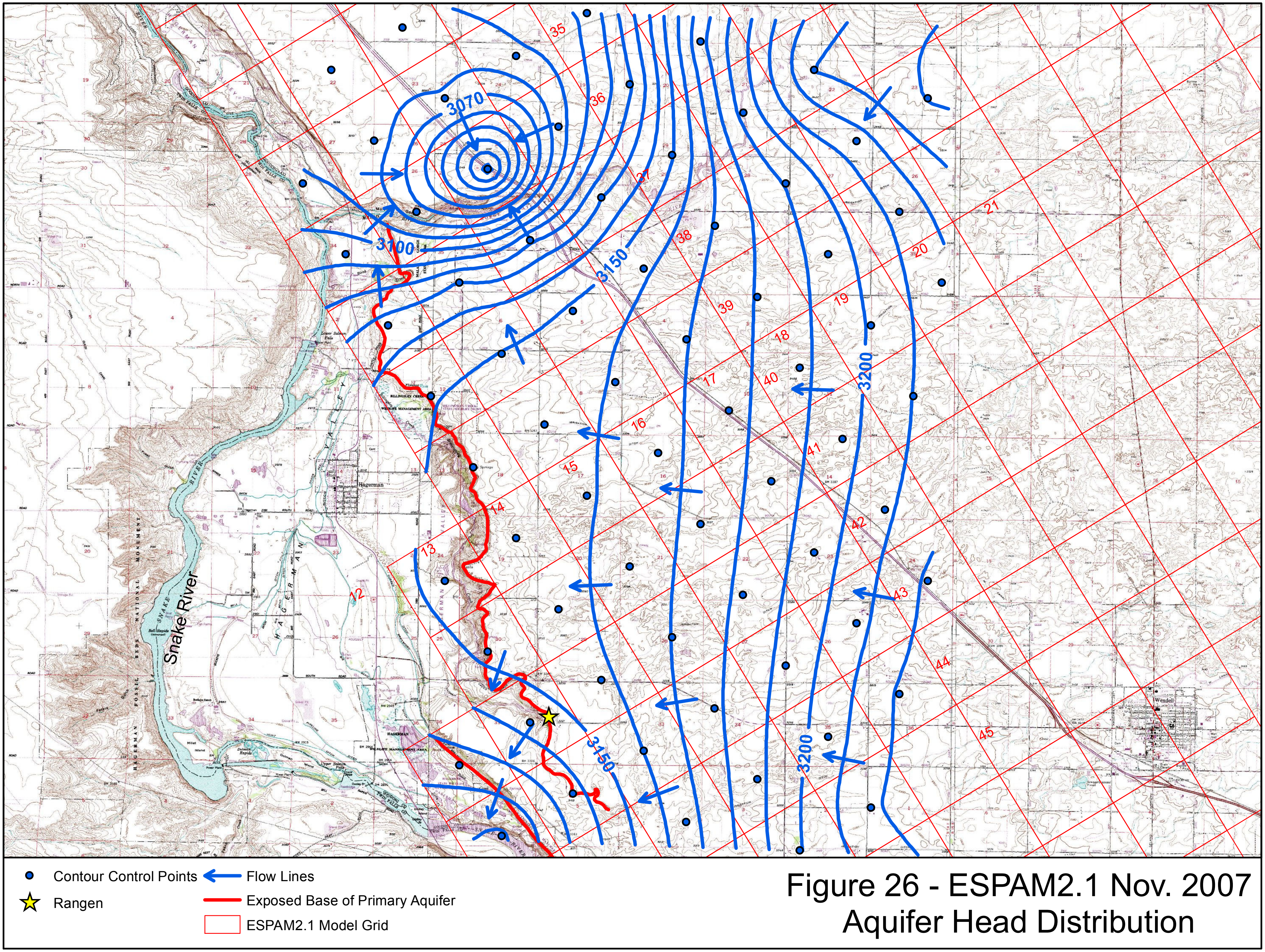


Figure 26 - ESPAM2.1 Nov. 2007
Aquifer Head Distribution

Figure 27 - ESPAM2.1 "Rangen" Cell (42-13) Modeled Water Level

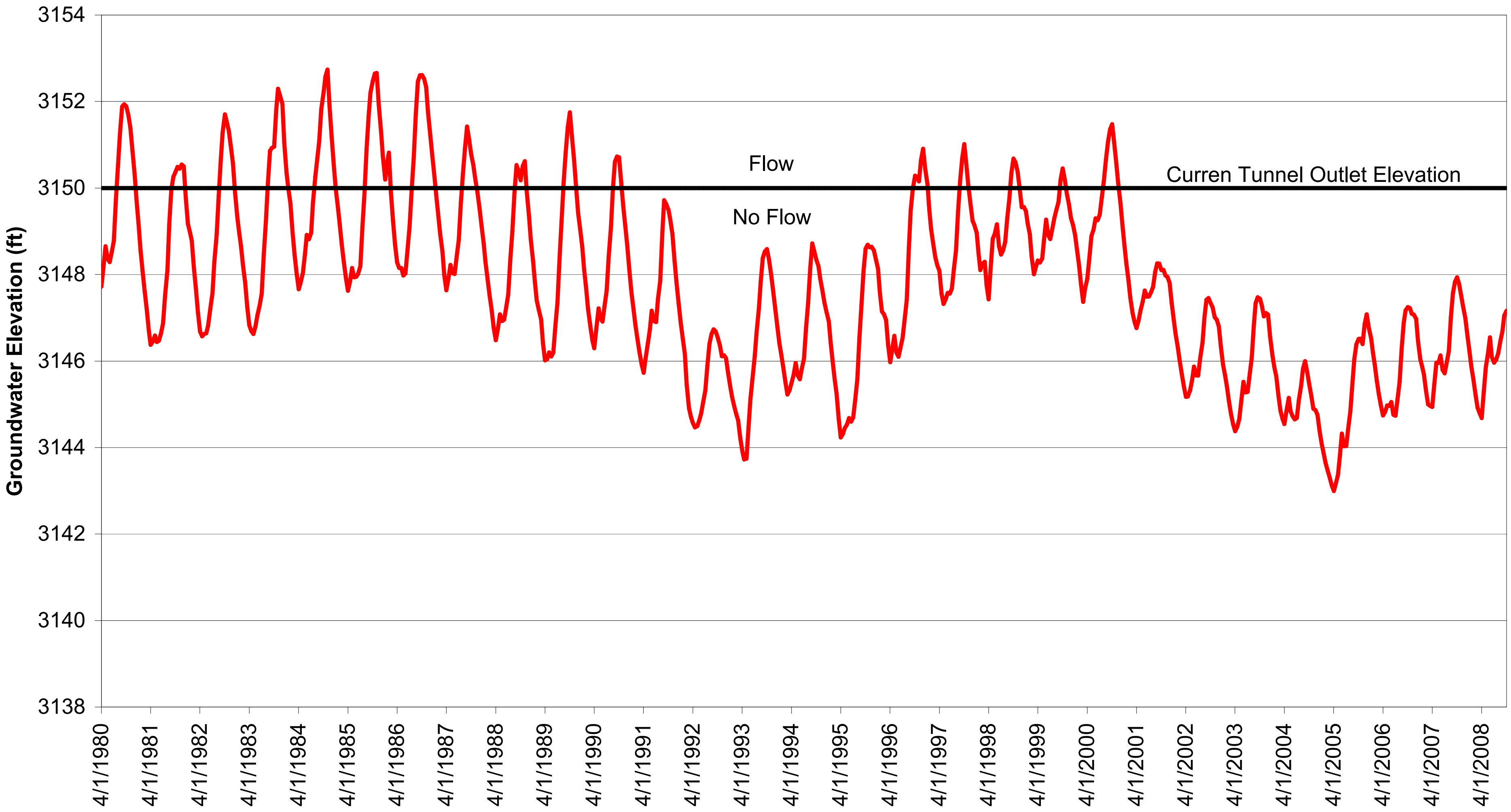


Figure 28 - Curren Tunnel Discharge Deviations from Linear Function
Rangen Monitor Well 7S 14E 32 SENW

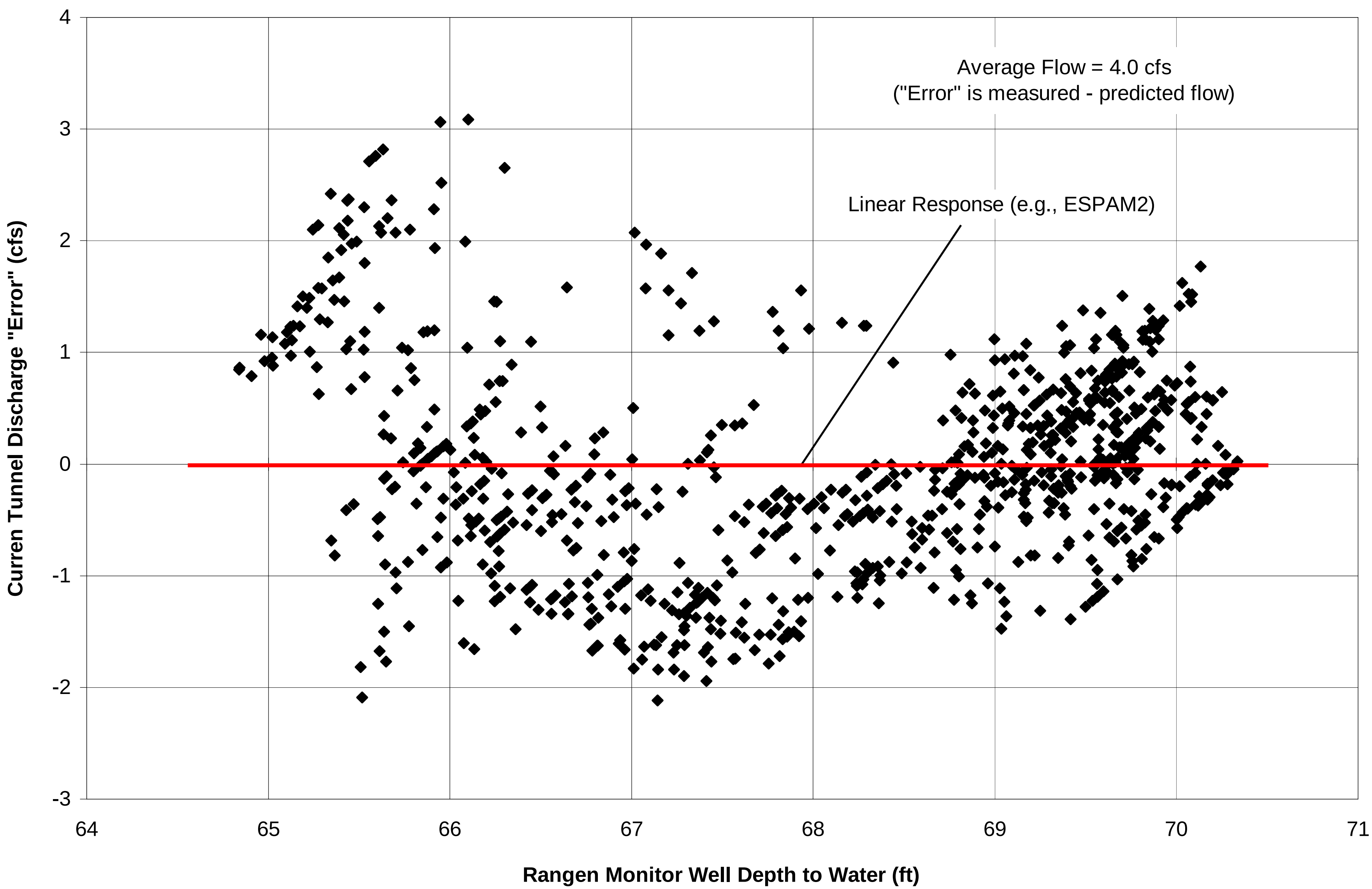
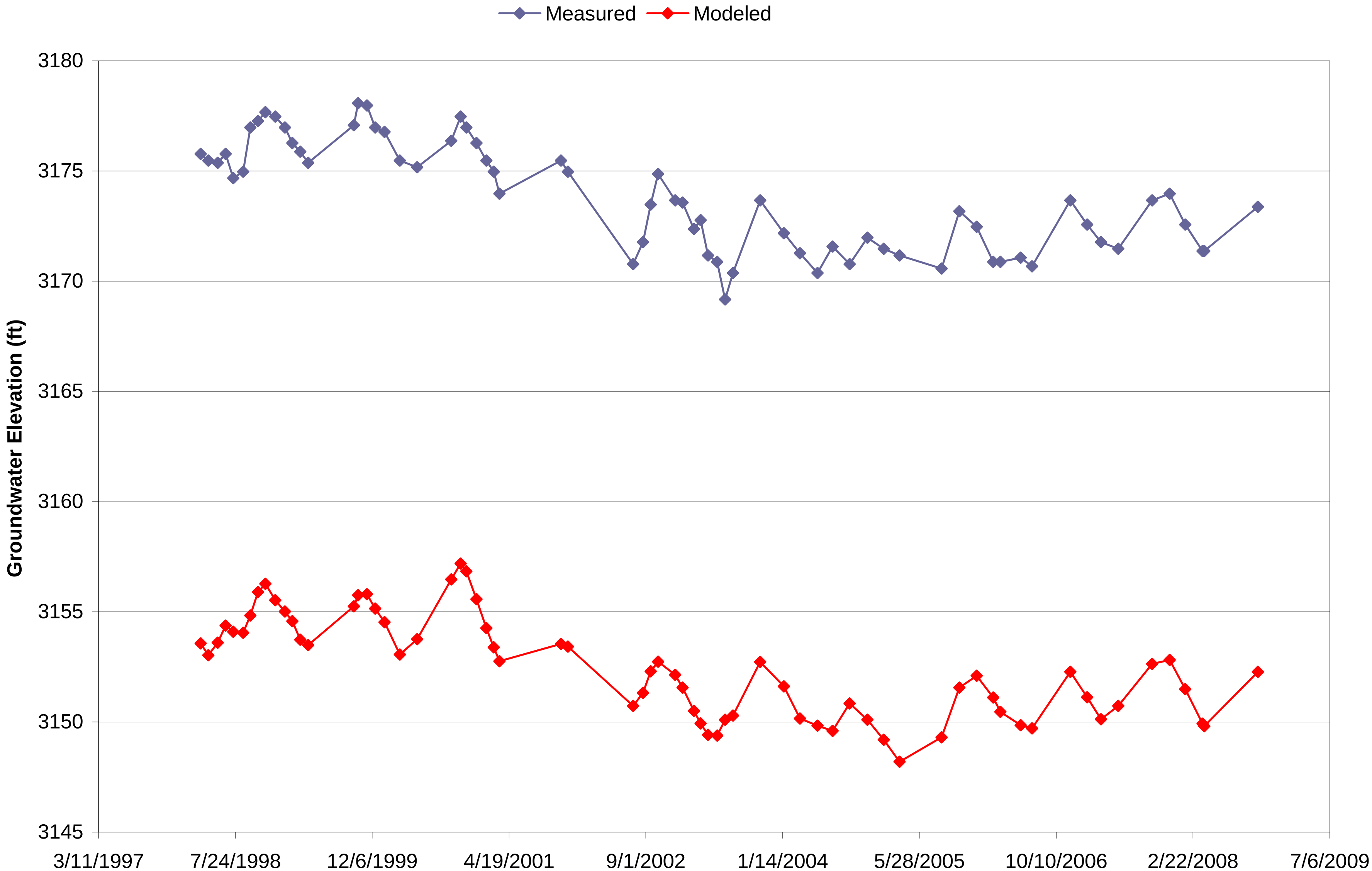


Figure 29 - ESPAM2.1 Calibration Well #989
(7S 14E 29 CDC1)



Source: IDWR Excel File "ESPAM2_ESPAM21.xlsm"

Figure 30 - Rangen Groundwater Flow Calibration

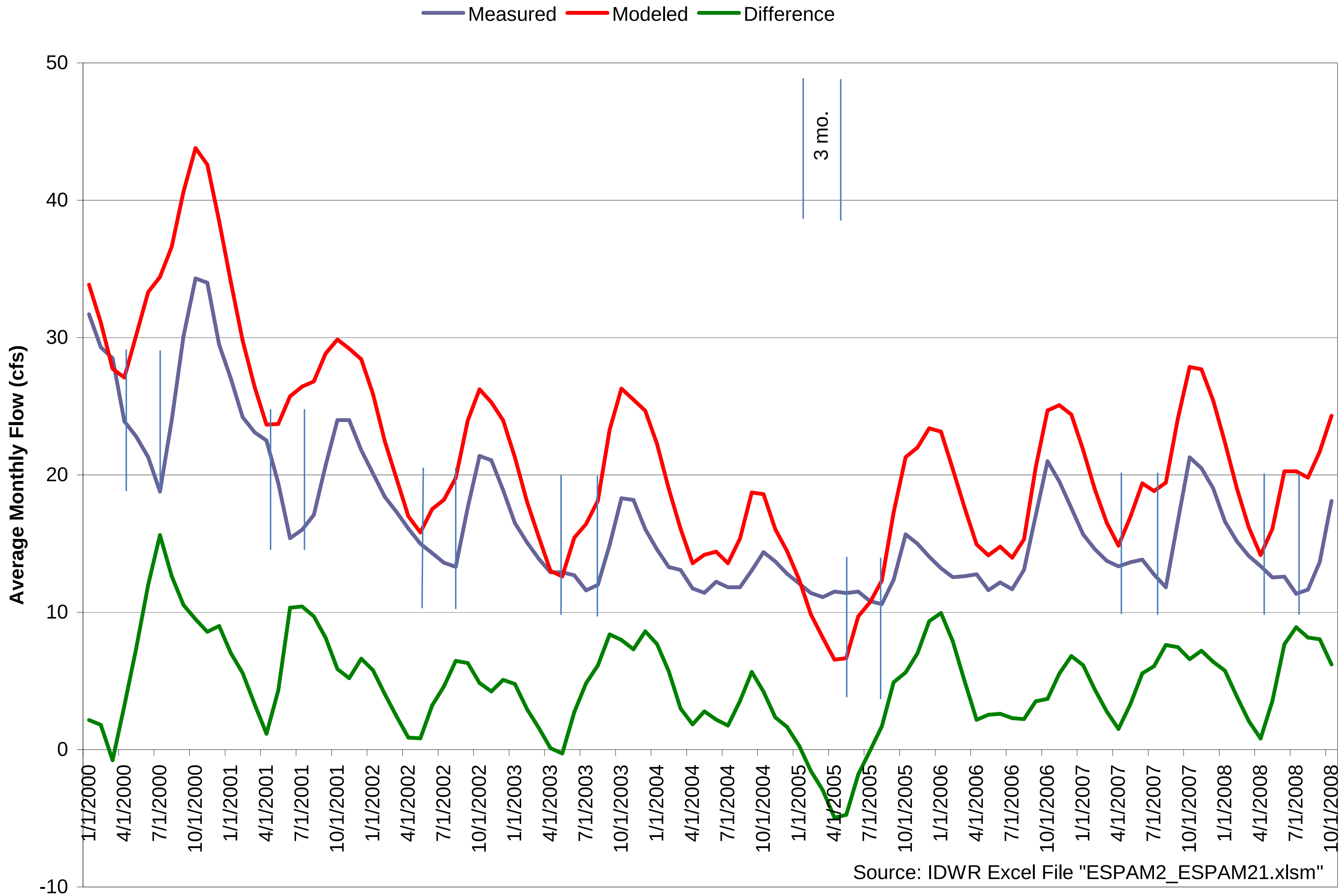


Figure 31 - Buhl-to-Lower Salmon Falls Reach Gains Calibration

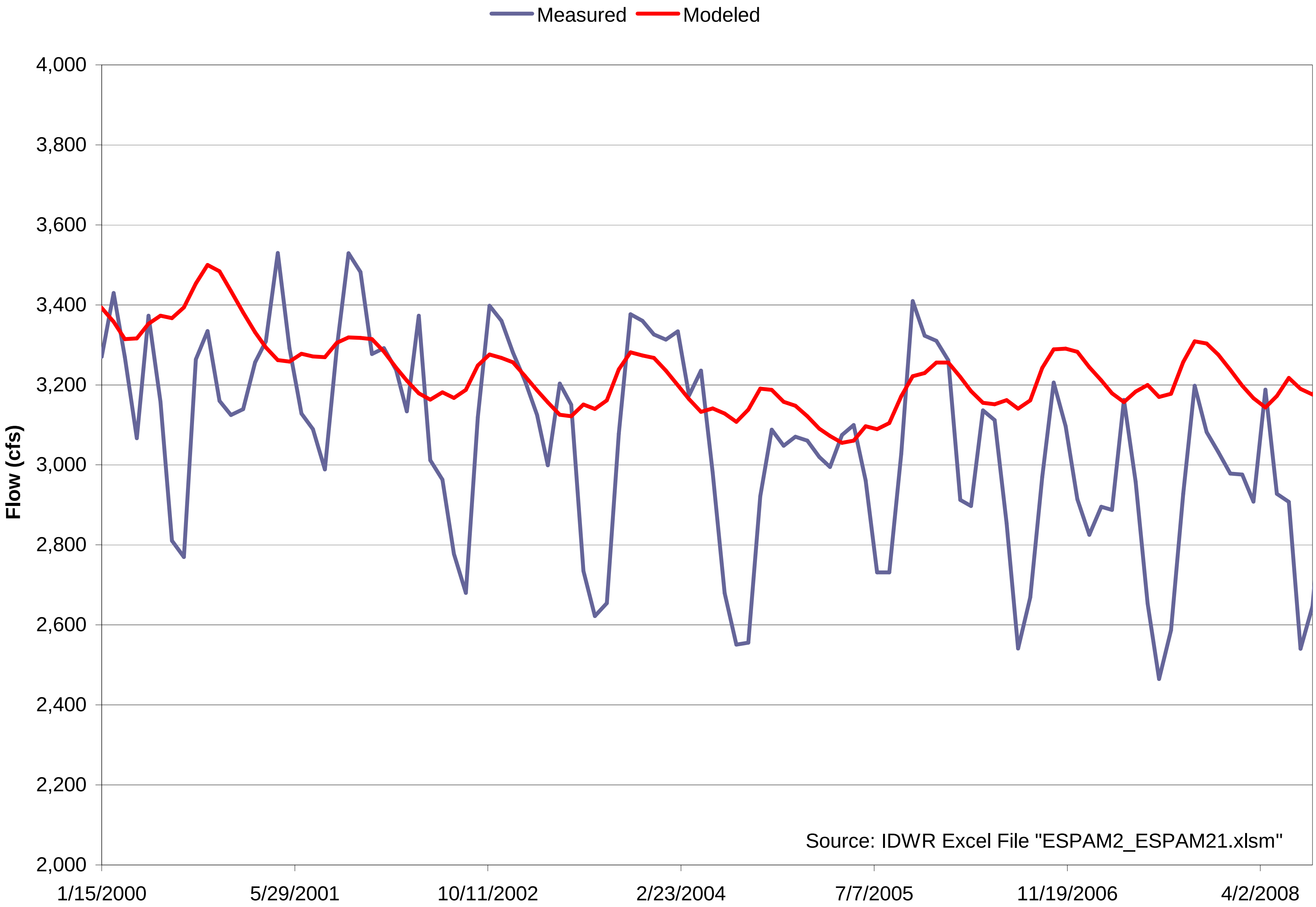


Figure 32 - Magic and Thousand Springs Measured and Modeled Discharge