Groundwater Technical Memorandum No. 2
2015 Laramie Master Plan, Level I – Appendix 420

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City of Laramie
WWC Engineering

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HYDROGEOLOGIC SETTING FOR THE LARAMIE GROUNDWATER SUPPLY

This technical memorandum is the second of a series of four regarding the groundwater supply of the City of Laramie. Companion memoranda present the history of City groundwater development and current groundwater production facilities, water quality and related City programs to protect and monitor the Casper Aquifer, and recommendations for aquifer management and future use.

Tables and figures are provided in sequential order at the end of this memorandum. In addition to the tables and figures, Plate I is a comprehensive geologic map of the Laramie area that identifies the location of wellfields, wells, and hydrogeologic features discussed in the memoranda. References cited in technical memoranda are listed in the "References" chapter of the main report.

This memorandum describes the hydrogeologic setting for the Casper Aquifer. Although the focus of attention is the Casper Formation, the full setting includes overlying strata with potentially developable production potential: the Satanka Shale, Forelle Limestone, and Chugwater formations. The hydrogeologic setting includes the water-bearing characteristics of the relevant formations and the patterns of groundwater recharge and discharge, both natural and man-made.

The memorandum begins with a generalized view of the Casper Aquifer as a large reservoir into which water flows as seasonal recharge and from which water discharges via springs, wells, leakage, and underflow. As with any natural system, there are many local variations on the general pattern, depending on the scale of the examination. Following presentation of the overall conceptual framework, significant details of the aquifer system are presented and then discussed on a wellfield-by-wellfield basis. The final sections present conclusions about the current status of the Casper Aquifer and suggest focused research opportunities at the existing wellfields.

To the extent the word "aquifer" applies only to the water-saturated portions of a formation, the "Casper Aquifer" is the saturated portion of the Casper Formation. For our purposes, the terms "Casper Aquifer" and "Casper Formation" and "Casper" will be used interchangeably.

I. Previous Studies and Information Updates

There is an enormous body of work dating back to 1932 regarding the hydrogeology of the Casper Aquifer (see References chapter in main report). Information from previous investigations will only be generally summarized here, with an emphasis on general aquifer concepts and new information developed since 2006. The interested reader is encouraged to consult Chapter 10 of the 2006 Master Plan (WWC Engineering, 2006) and appropriate references for a more comprehensive treatment of specific topics.

Information developed since the 2006 Water Management Plan is listed below.

- Acquisition of an additional 10 years of climate data helps refine our understanding of recharge cycles.

- Acquisition of an additional 10 years of water-level monitoring data helps refine our understanding of the Casper Aquifer's response to recharge fluctuations. For example, the period of record for detailed water-level monitoring in the Spur area has been doubled and, importantly, includes the substantial post-2009 recovery from the drought of the 2000s.

- Specific Casper groundwater-development investigations at LaPrele Park (Wester-Wetstein, 2013), Simpson Springs (Weston Engineering, 2013a), and the Laramie Fault (Weston Engineering, 2012) provide details for those areas.

- The first project under the Casper Aquifer Monitor Program was recently completed for areas up-gradient from the Turner Wellfield (Hinckley Consulting and Wyoming Groundwater, 2015). This study included pumping tests and geophysical investigations along the Sherman Hills Fault at the Imperial Heights Park.

- There is an on-going program to establish Casper water-level and groundwater-quality monitor wells in the Telephone Canyon area associated with potential contamination events on Interstate-80 (Trihydro, 2011).

- The City's Casper Aquifer Protection Plan was updated in 2008, and approximately 53 site-specific investigations (SSI) have since been completed under the guidance of that plan. Some SSIs contain additional information on aquifer stratigraphy, structure, and protection.

- The City conducted downhole camera surveys at Pope No. 2 in 2007 and at Turner No. 1 in 2011 (Wyoming Groundwater, 2011a).

Relevant results from these recent studies are incorporated into this memorandum.

II. Generalized Hydrogeology - the "Reservoir"

Plate I is a comprehensive geologic map of the Laramie area that also identifies the location of wellfields, wells, and features discussed in this memorandum. Figure TM 2-1 presents the basic layout of the Laramie groundwater resource, showing the general occurrence of the various formations at the ground surface. Surface deposits are not shown, but cover portions of the bedrock formations at many locations. Buried contacts are indicated by dashed lines.

Figure TM 2-2 is a schematic east-west cross section, illustrating the aquifer as a reservoir. At a generic porosity of 5%, this reservoir contains 7 billion gallons of water per square mile where the full 700 feet thickness of the Casper Formation is saturated, i.e. west of the contact with the overlying formations. Proceeding eastward, the volume of water in the aquifer is correspondingly less as the saturated thickness decreases. Thus, approximately between the Laramie River, the east edge of the Casper Formation outcrop at the crest of the Laramie Range, the Spur Wellfield to the north, and Simpson Springs to the south, the aquifer contains on the order of 1 million acre-feet (326 billion gallons) beneath the recharge area and another 1 million acre-feet beneath the 4-mile wide strip immediately to the west. Only a small fraction of this full volume is practically recoverable, of course, but the estimated volume defines the upper limit of the size of the "reservoir" one has to work with. There is in groundwater storage, 600 times the current average annual groundwater production by the City.

Basically, water enters the aquifer as recharge from precipitation (rainfall, intermittent streamflow, and snowmelt) on the outcrop area[1]. Mean annual precipitation as measured at the Laramie Airport is 10.59 inches (1949-2014 average). However, the aquifer recharge area extends to higher elevations along the west slope and crest of the Laramie Range and is subject to more precipitation in these areas. Comparison with the much shorter period of record available at the Crow Creek SNOTEL site located just east of the Happy Jack area at the top of the Laramie Range shows 2004-2014 annual averages of 10.7 inches at the Laramie Airport and 24.1 inches at the top of the range (Plate I).

[1] Isotopic research indicates that the Casper Aquifer may also be partially recharged from below by fractures in the Sherman Granite (Toner, 2000).

Based on the airport precipitation record, some 40 million gallons per day (mgd) of precipitation falls on the 50,000 acres of outcrop shown on Figure TM 2-1. The majority of this water is lost to evaporation and vegetation evapotranspiration, with some unmeasured portion running off the outcrop area during local flood events[2]. Groundwater recharge rates vary widely, but at a "rule-of-thumb" proportion of 10% of total precipitation[3], an average annual value on the order of 1.4 billion gallons (4 mgd average) is suggested. This would be a long-term annual average because considerable seasonal and long-term fluctuations occur. Splitting the difference between the airport and Crow Creek precipitation values and applying the same generic 10% value suggests an average annual recharge of 2.3 billion gallons (6.3 mgd average).

As the aquifer fills with water, a groundwater "reservoir" is created, contained within the Casper Formation by the generally much less permeable rocks below and above (Figure TM 2-2). Thus, the contact between the Casper Formation and Satanka Shale approximates the "rim" of the groundwater reservoir, and groundwater spills out of the reservoir at low spots along this rim, creating natural springs (e.g. City, Pope, Soldier, and Simpson springs). Water is extracted from the reservoir for municipal, domestic, and industrial use. Water leaks out of the reservoir through the overlying deposits, e.g. creating the numerous springs along Spring Creek and feeding artesian wells west of the Satanka/Casper contact. And water not discharged at the springs, termed "underflow", continues to flow in the Casper westward into the Laramie Basin.

Like surface water, groundwater flows "downhill". In this case, that means groundwater flows generally from east to west within the Casper Formation, but converges on local discharge points, both natural (springs) and man-made (wells).

<u>Recharge</u>

Figure TM 2-3 presents annual[4] precipitation data from the Laramie airport station. Figure TM 2-4 provides a more comprehensive treatment of the area's moisture balance, as the Palmer Drought Severity Index (PDSI) which includes multiple stations and the effects of temperature, antecedent soil moisture and other factors in the assessment of available water. Included on Figures TM 2-3 and TM 2-4 are the average of the annual

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[2] Significant runoff beyond the Casper Formation outcrop is relatively rare due to the high infiltration capacity of the exposed sandstone members.

[3] For example, Lundy (1978) estimated a recharge rate of 10% for the Casper Aquifer.

[4]In this case "annual" refers to water year, October - September, to capture the association between winter precipitation and the following spring and summer water levels.

maximum water levels (i.e. highest in elevation) measured in the Huntoon Nos. 1 and 2 monitor wells (see Plate I and Figure TM 2-1 for locations) which have the longest available record of water levels in the Casper Aquifer.

While the general correlation between climate (e.g. PDSI) and aquifer water levels is obvious, the details of that association are quite complex. Such factors as the seasonal timing of precipitation, the intensity and duration of individual precipitation events, the detailed geographic patterns of precipitation/snowmelt with respect to receptive recharge features (e.g. high permeability zones/strata, topographic concentrations of runoff), the attendant temperatures, and the vigor of vegetation competing for soil moisture all contribute to the precipitation/aquifer response relationship and frustrate detailed prediction of aquifer recharge on a year-to-year basis.

Lundy (1978), WWC (1996a), and Taboga (2006) have suggested that March and April precipitation and snowmelt dominate aquifer recharge, based on the obvious availability of water during snowmelt and spring rain events. Taboga examined the 2003-2006 period in detail and was able to link measurable rises in monitor well water levels with specific precipitation or snowmelt events.

For the present study, we examined statistical correlations between: 1) aquifer water levels measured at the Huntoon No. 1 and No. 2 monitor wells and at five Spur monitor wells, as calendar year (Jan-Dec) average, maximum, and minimum; and "recharge" year (May-April) average; and 2) a portfolio of climate variables including calendar year (Jan-Dec), water year (Oct-Sept) and "recharge" year (May-April) Laramie precipitation, Region 8 (lower North Platte) PDSI, Region 10 (upper North Platte) PDSI; and the Crow Creek SNOTEL snow survey data. No single climate variable produced a correlation coefficient ("r^2") greater than 50% (i.e. 50% of the variation in water level can be explained by the climate variable). The lack of consistent correlation between annual precipitation fluctuations and expected water level response can be seen clearly in Figure TM 2-3. The PDSI variables were somewhat better correlated with water levels than simple precipitation, but none of these climate variables provide a reliable, quantitative predictor on a year-by-year basis. The poorly-constrained quantitative correlations between climate variables and aquifer water levels demonstrate the high complexity of the recharge process.

Nonetheless, the physically-required general association with climate patterns, i.e. basic water availability and aquifer recharge, is readily apparent on a multi-year basis. For example, the combined hydrograph for the Huntoon No. 1 and No. 2 wells (Figures TM 2-4 and 2-5) shows water levels for this period of record start during a time of less-than-average water availability, clearly reflect the extraordinary precipitation/recharge event of 1983/84, decline through the early 1990s, rebound with the increased recharge supply of the mid-1990s, decline with the drought of the 2000s, and have been generally increasing over the last 6 years since 2009.

Examination of the full period of the climatic record (Figure TM 2-4) demonstrates that the 2000s were the driest period of the last century. It is not unreasonable to expect the aquifer water levels of this period to have been at century lows as well. Were the climatic conditions of the first-half of the twentieth century to be repeated, aquifer water levels (and spring flow) well in excess of historically measured levels would likely occur. Future climate conditions are difficult to predict, of course, but the indication from the historical record is that the Huntoon hydrograph captures the long-term lowest water levels and provides a period of record of generally lower-than-average aquifer recharge rates. Thus, reference to this hydrograph for low, average, and high groundwater levels provides a somewhat conservative view of what to expect in the future.

That the Huntoon No. 1 and No. 2 hydrographs are representative of the Casper Aquifer throughout the Laramie area is demonstrated both by their similarity to one another and by comparison with other points of measurement of aquifer conditions. Figure TM 2-6, for example, compares the Huntoon hydrographs with each other and with the shorter period of record from the Spur monitor wells, expressed as the annual minimum depths to water (i.e. following spring recharge) and normalized by each well's average depth to water.

The two Huntoon wells track each other very closely; they are approximately 1 mile apart. Although the Spur wells are 5-6 miles to the north, they are obviously responding to similar general patterns of recharge as the Huntoon wells. However, the two areas' wells do not match year-for-year declines/rises for 2001/02, 2008/09, or 2012/13. These differences suggest the scale of natural variations in climate/recharge differences across the recharge area.

Even among the Spur monitor wells which span an area of just over a mile, local differences can be seen in Figure TM 2-6 and include:

- Spur MW-12, the farthest east of the set, shows similar amplitude to the Huntoon wells, but hit its low level a year later (2009 vs. 2008), and rose rather than fell from 2012 to 2013.

- Spur MW-12 is the only one of the five that has risen to a point above its 2000 value. Perhaps the other monitor wells will "catch up" as a recent recharge pulse moves westward through the aquifer.

- Spur MW-10, the farthest south of the set, remained relatively flat from 2001 to 2003 as its companions fell, and hit its low level a year later (2010 vs. 2009).

The Taboga (2006) water level measurements from September 2003 to July 2006 (i.e. a drought period) cover a much shorter period, but provide greater geographic detail. At the Huntoon and Spur wells, recovered[5] aquifer water levels dropped approximately 3 feet over this three-year period. In fifteen other wells across the aquifer, seven showed little difference, two dropped 6-9 feet, and eight declined approximately 2 feet, without apparent geographic or structural pattern. A general water-level decline across the aquifer, with significant local variations is demonstrated over this period.

Tritium data collected and analyzed by Dr. Carol Frost and Rachel Toner in 1996 (Toner, 2000) provide information regarding the age of groundwater at the Spur. Tritium values at Spur MW-7 and MW-2 indicate a mixture of pre- and post-1953 water (year of recharge) such that the average residence time of these waters in the aquifer is less than 43 years. These ages indicate an active groundwater flow system at the Spur.

Logically, the higher the water levels in the aquifer, the greater the "overflow" as water discharges at springs and passive discharge facilities (e.g. flowing wells). The Soldier No. 1 well is generally operated as a passive discharge facility, and the annual production record at Soldier No. 1 has a discharge pattern very similar to that of water levels at the Huntoon monitor wells, i.e. a decline from 1983 through 1994, an increase through twin peaks in 2000 and 2002, a decline through 2008, and an increase since 2008 (Figure TM 2- 7).

Similarly, water levels measured in the Pope No. 1 well (WWC, 1995; p. 6-15) showed a steady decline of approximately 9 feet from 1984 to 1990, then no trend through 1991 and 1992. This water level pattern is a good match with that observed in the Huntoon monitor wells.

In addition to the continuous records of water levels discussed above, there is abundant anecdotal and indirect evidence on the multi-year cycles of aquifer recharge. Most conspicuous was the abundant recharge of 1983/84. In addition to showing up dramatically in the Huntoon wells, "the 1983 recharge event caused noticeable head increases throughout the Casper Aquifer along the west slope of the Laramie Range as evidenced by above-average discharge at City Springs, Soldier Spring, upland springs, and high water levels in the Pope wells from 1983 to 1990" (WWC, 1996a).

Figure TM 2-8 presents the seasonal high water levels and the daily fluctuations in water level throughout each year for a typical Spur-area monitor well (Spur MW-7)[6]. Each

[5] " Recovered" means a water level measured at a sufficiently long time after well pumping has stopped that the measurement reflects general conditions in the aquifer.

[6] The water level records for all five of these wells are quite similar; see Attachment 1 for hydrographs of the individual monitor wells.

downward spike reflects the increased pumpage from the aquifer to meet summer demands of nearby domestic and municipal-supply wells. Each upward spike reflects the winter/spring equilibration of the aquifer as water moves from areas of higher water levels to "fill in" areas of lower water levels, and as each season's recharge is realized.

The Spur-area monitoring data provide an opportunity to separate seasonal from long-term effects due to the large variations in municipal well production. Figure TM 2-8 overlays annual Spur Wellfield production[7] with the measured water levels. Clearly, the high production volumes of 2001 and 2002, and, to a lesser extent, 2005, produced short-term drawdown in the vicinity of the wellfield[8]. Equally clear, however, is that the multi-year decline in water levels through the 2000s and the subsequent rise in water levels during the 2010s are largely unrelated to annual wellfield production volumes. Rather each year's "recovered" water levels (the high spots on Figure TM 2-8) reflect regional aquifer recharge in response to climate parameters.

2002 may have been an exception in that both the Spur and the Huntoon monitor wells experienced the largest one-year decline of the period, coinciding with peak-year production from the Spur and Turner wellfields. However, that production was driven by an extraordinarily dry year, in which aquifer recharge would have been minimal as well.

This conclusion is consistent with the similarity of long-term aquifer levels throughout the aquifer discussed above, as the aquifer in the vicinity of the Turner and the Soldier-Pope wellfields have been subject to continuing production rather than the sporadic production seen at the Spur Wellfield. It is also consistent with the conceptual model of the wellfields basically capturing only a portion of the natural aquifer output (see Technical Memorandum No. 1) which is governed by climate patterns, rather than drawing significantly on aquifer storage. Multi-year aquifer water levels under the current management approach are basically independent of annual municipal groundwater production.

Limited recharge also occurs to the outcrops of the strata overlying the Casper Aquifer. These additions to the groundwater system are considered minor compared with that of

[7] Only municipal production is shown here. Aquifer water levels will also respond to production from local domestic wells, but this volume is small and presumably changes only moderately from year-to-year. At the net aquifer depletion rate of 0.4 ac-ft/yr per rural residence developed for the North Cheyenne Master Plan (States West Water Resources, 1993), the 35 domestic wells in the Casper Aquifer in this area (WWC, 1997c) would consume approximately 4.5 mg annually.

[8] Spur MW-7 is 1,800 feet from the Spur No. 1 production well. A very similar pattern of drawdown, at about ½ this amplitude was recorded at the Spur MW-8 well, 3,700 feet away.

the Casper Aquifer due to the lower elevation (i.e. less precipitation), lower-permeability of soils and outcrops (i.e. greater runoff), greater prevalence of paved surfaces, and denser vegetation on the outcrops of these formations. Also, due to the presence of upward groundwater gradients from the Casper (discussed below), recharge to these overlying formations cannot generally contribute to the groundwater supply in the Casper.

Discharge

Groundwater within the Casper Aquifer moves generally westward from the recharge area to discharge from the aquifer in one of four ways: 1) as springs, essentially "overflow" points for the groundwater reservoir; 2) via wells, as the aquifer is pumped for private, commercial, and municipal use; 3) as leakage upward from the Casper into overlying formations; and 4) to continue flowing westward within the aquifer as "underflow" beneath the Laramie Basin west of the City (e.g. see Figure TM 2-2).

Lundy (1978) developed the first water balance for the Casper Aquifer. He estimated a total of 5.37 mgd either discharges directly from the aquifer via springs and wells, discharges via springs from the immediately overlying strata, or continues westward beneath the Laramie Basin ("underflow"). Table TM 2-1 presents an approximate water balance, as compiled for the present study. The total groundwater discharge indicated here is 6.7 mgd (long-term average). Many of the individual values in the table are not well constrained, but reflect approximations based on current knowledge and available data.

The great majority of the water balance is consistent with other measurements and estimates over the last 75 years. The largest single modification of past estimates is the addition based on the detailed evaluation of groundwater underflow along the Spur structure. Lundy (1978) estimated underflow in this area only as part of the entire Spur to Simpson study area, using a generic gradient of 25 feet/mile and an aquifer transmissivity[9] of approximately 130 ft^2/day. Detailed drilling and testing at the Spur identified a transmissivity of approximately 200,000 ft^2/day, and a quite-low gradient of only 1 feet/mile (WWC, 1997c). Applied to a 1-mile wide structure, these values produce a groundwater flux estimate of 1.5 mgd. A local recharge estimate for the Spur Wellfield area of 1.3 mgd was developed by WWC (1997c). For Table TM 2-1, the underflow values are discounted to approximately 1.0 mgd.

On a long-term average, the discharge from an aquifer should be approximately equal to the recharge. Earlier in this memorandum, an annual recharge of 6.3 mgd was calculated using reasonable estimates of total precipitation and percent infiltration over the study area. The more complicated inventory of estimated discharges from the aquifer provided

[9] "Transmissivity" is the permeability times the aquifer thickness; it is an overall measure of the realized productivity of a well.

Table TM 2-1: Casper Aquifer Water Balance			
A. Spring Discharge		Discharge (average mgd)	Notes
	City Springs	1.6	1.65 mgd (Morgan, 1947); 1.64 (1967-1981; WWC, 1996); 1.47 – 1.63 (2007, 08, 09, 12, 13 avg)
	Pope/Soldier	0.3	Pope springflow = 0 mgd; Soldier Spring flow approx. 0.3 (visual est.)
	Simpson	0.28	(WWC Engineering, 2006)
B. City Production			
	Spur	0.07	
	Turner	no net increase	Pumping displaces springflow; no net increase in spring/well total.
	Soldier-Pope	1.82	Soldier No. 1 flow = 1.8 (1999-2014); Pope pumping = 0.13 mgd (1999-2014); Soldier No. 1 pumping rare. 1941-43 average total = 1.94 (Morgan, 1947).
C. Subdivision "net" Pumping (outcrop)		0.2	550 homes * 0.4 af/yr (States West, 1993)
D. Pumping (west of outcrop)			
	University of Wyoming	0	Casper wells inactive
	Mtn. Cement	0.45	permit total (WWC Engineering, 2006) assumed used 50%
	Other	0.35	Cathedral Home, WyoTech, and WRI permit total assumed used 50%
E. Leakage (local)		0.16	Spring Creek springs (WWC, 1997b); 0.29 (Lundy, 1978)
F. Underflow to deep basin		1.5	0.53 Lundy (1978) + 1.0 per flux calculation at Spur
TOTAL		6.7	

a total of 6.7 mgd. These two values are within 6% of each other and suggest that despite the uncertainty and assumptions made regarding some of the input values, the actual recharge/discharge value may be quite close to these estimates. For planning purposes, the calculated discharge value of 6.7 mgd will be used.

III. Detailed Hydrogeology - Local Variations

In detail, the Casper Aquifer is not the simple "reservoir" schematic shown in Figure TM 2-2, but consists of many individual strata with varying water-bearing characteristics. Figure TM 2-9 and Plate I provides a more detailed look at the stratigraphy of the Casper, including delineation of five sub-aquifers termed alpha, beta, gamma, delta, and epsilon. Each of these may have different water-bearing characteristics. Also important at the local level, the Casper is deformed by folds and faults that create huge variations in local permeability, with attendant impacts on groundwater flow rates and directions, recharge response, and well productivity. The most prominent of these mapped features are indicated on Plate I and Figure TM 2-1[10]. Finally, the overlying "cap" for the Casper Aquifer is not a uniform, impermeable layer, but a series of formations with their own variations in water-bearing and water-transmission characteristics. The following paragraphs, excerpted in large part from the 2006 Water Management Plan, explore these issues.

The Casper Aquifer is comprised of water saturated portions of the Casper Formation that consists of approximately 700 feet of interbedded sandstone, limestone, and minor siltstone and shale. In the vicinity of Laramie, sandstones comprise approximately 85% of the total thickness of the Casper Formation with limestones comprising most of the remainder. Relative to Laramie, sandstone percentages increase to the south and decrease to the north and west. Sandstone layers bounded above by a regionally continuous limestone were informally subdivided by Lundy (1978) into five members; designated from top to bottom of the Casper Formation as the epsilon, delta, gamma, beta, and alpha. Water is stored and transmitted primarily in the sandstones whereas the relatively impermeable limestones can function as aquitards between the sandstones.

Previous investigators have widely acknowledged the likely locally confining nature of the limestone strata within the Casper Aquifer. Of course, "confined" is a relative term, describing conditions ranging from a local inhibition of vertical flow to regional flow barriers. The former is more descriptive of the members of the Casper Aquifer. For example, this condition was documented at the intersection of Vista Drive and Grand Avenue, where a head difference of 5 feet and a nitrate concentration difference of greater than 1.3 mg/l were measured across the limestone at the top of the delta member of the Casper Formation (Hinckley Consulting and Wyoming Groundwater, 2015). In many places, most notably at the Spur and the Turner wellfields, vertical

[10] Vertical and near-vertical features are mapped where they intersect the ground surface. Important horizontal features like bedding-plane fractures cannot be seen and, therefore, are not mapped.

fractures associated with faults and folds have disrupted the limestones and have hydraulically integrated the sandstones of all members (WWC, 1997c; WWC, 1996a).

The Casper Aquifer has complex water storage and transmission characteristics because of the presence of both intergranular and fractured permeability/porosity (i.e. a dual porosity media). The intrinsic permeability of the limestone matrix is very low while the intrinsic intergranular permeability of sandstone matrix is variable. Due to observations of relative grain size and cementation, it is generally believed that the epsilon sandstone has the largest intrinsic permeability and the alpha sandstone has the smallest. However, the intrinsic porosity/permeability of the individual sandstone members has not been rigorously determined by field or laboratory testing. Production from water wells that rely only on the intrinsic permeability of sandstone and limestone is on the order of 5 to 50 gallons per minute (gpm) with substantial drawdown during pumping. The average porosity of the epsilon sandstone is approximately 24% (Davis, 1976). Sandstones in the lower-most alpha member probably have lower porosity values. The intergranular porosity of the sandstones serve to store enormous quantities of water.

Superimposed on the intrinsic permeability of sandstone and limestone is fracture permeability associated with: 1) faults and folds created by compressional and extensional forces that occurred during the Laramide Orogeny that uplifted the Laramie Range; and 2) sub-horizontal bedding-plane "fractures[11]" related to dissolution/piping of aquifer material, tectonic forces, and/or variations in sedimentary lithology. Vertical fractures play an important role in the hydraulic integration of the members and create local zones of high permeability, but may not be the primary determinate for the high yields observed at municipal wells. Observations during drilling and/or downhole camera surveys at the Spur No. 1 and No. 2 wells, the Turner No. 1 and No. 2 wells, Soldier No. 1, and recently installed Casper Aquifer monitor wells (Hinckley Consulting and Wyoming Groundwater, 2015) indicate the presence of horizontal bedding plane fractures/openings within the sandstone and immediately above/below the sandstone/limestone contacts in the epsilon, delta, and gamma members. These horizontal fractures/openings in sandstone obviously play a major role in the high yields at municipal wells.

Fractures can transmit tremendous quantities of water, as demonstrated by municipal well production in fracture zones on the order of 1,000 to 2,000 gpm with 4 to 40 feet of drawdown.

As shown on Plate I and Figure TM 2-1, the surface exposure of the Casper Formation is populated by numerous faults, folds, and monoclines. Additional detail on mapped faults and folds is available on the geologic maps of the Red Buttes, Howell, Pilot Hill, and Laramie Quadrangles (Ver Ploeg, 2007, 1996, 2009, and Ver Ploeg and McLaughlin,

[11] "Fracture" is used loosely in this context as the observed high-permeabilitiy, sub-horizontal openings may be the result of various post-depositional mechanisms other than simple mechanical breaks.

2009, respectively). Many of these structural features originate from high angle faults in the Precambrian basement (e.g. Sherman Granite). The basement faults propagate upward into and through the Casper Formation, and sometimes through the formations that overlie the Casper. Reverse faults are usually offset and terminated by major normal faults that extend laterally from Precambrian outcrops into the Casper Formation where the faults are exposed on the surface. The Jackrabbit, Red Buttes, and Telephone Canyon faults originate as normal faults in the Sherman Granite. Ver Ploeg (2007, 2009) has documented right-lateral strike-slip motion on the north-south trending Red Hills Fault and suspects that strike-slip motion on some of Laramie's prominent faults may be more common than originally thought.

Municipal production wells have targeted the enhanced permeability associated with specific fault, fold, or fault/fold systems. Municipal well exploration and development history provides many examples of "hitting" or "missing" these critical zones, commonly over relatively small distances within a fault/fold system.

Large contrasts in productivity over short distances are to be expected in fracture-dominated aquifers like the Casper. This has been demonstrated in the Laramie wellfields themselves. For example, the Turner No. 1 well has 18 times the specific capacity of the Turner No. 3 (i.e. a "failed" first well drilled during the installation of the Turner No. 1 and Turner No. 2 wells in 1982) despite the latter having nearly twice the open interval and being only 500 feet away (WWC, 1995). Similarly, at the Spur Wellfield, the initial exploration program found zones subsequently developed with 2,000 gpm wells (500 gpm/ft specific capacities) within 200 feet of boreholes without nearly the same production potential as indicated during air-lift drilling.

The heterogeneous distribution of permeability in the Casper Aquifer is also evident in the drawdown behavior of individual production wells. When drawdown data are examined in detail (e.g. during careful pump tests), the rates of drawdown early in the pumping period are commonly indicative of high permeability, with drawdown rates at later time that indicate the cone of depression "reaching out" into less permeable zones of the surrounding aquifer. One or two such "boundaries" are commonly displayed in detailed test data (WWC, 1993b; WWC, 1993d; WWC, 1996a). These are interpreted as the drawdown (either actual de-watering of unconfined portions of the aquifer or de-pressurization of confined portions of the aquifer) initially spreading quickly along high-permeability pathways, providing ready access to large quantities of groundwater. Subsequent drawdown is a function of these pathways draining portions of the surrounding aquifer and requiring additional drawdown to coax water from lower permeability material.

Faults and Groundwater Flow

Faults in fractured aquifers can function as hydraulic conduits (Huntoon and Lundy, 1979a), barriers, or both (Caine et al., 1996). Pump tests conducted at the Spur, Turner, Pope, and Soldier municipal wells, and a salt tracer test at Turner No. 1 (WWC, 1997c; WWC, 1996a; WWC, 1995; WWC, 1997a; and WWC, 1993b, respectively) confirm the highly permeable and conduit-like character of the Casper Aquifer at locations near mapped faults and folds.

Where a fault orientation is oblique to the overall groundwater gradient, groundwater flow may preferentially follow the higher permeability provided by the fault zone. For example, the City Springs Fault is understood to guide groundwater to discharge at the historical City Springs (Huntoon and Lundy, 1979a). Faults can also provide pathways for vertical circulation within and between formations that possess significant matrix permeabilities (Huntoon and Lundy, 1979a; Younus, 1992).

Sandstones/Faults/Fractures and Recharge

The rapid infiltration of surface water from rainfall and snow melt into Casper Formation sandstones has been observed by Beckwith (1937) and Lundy (1978). For example, following a spring snow storm, Beckwith observed 3 to 4 cubic feet per second of stream flow infiltrate into sandstones over the course of a few hundred feet. Lundy also observed the rapid infiltration of overland flow into sandstone exposures during a rain storm. During field work, Taboga (2006) observed the rapid infiltration of overland flow from snow melt into sandstones exposed in upland drainages. The ability of exposed sandstones to absorb surface water is illustrated by the fact that surface water rarely flows out of the drainages that dissect the west slope of the range. The exposed limestones shed and/or pond water unless highly fractured.

Testing of a high production Casper well (Brow #2) southeast of Simpson Springs in 2005 (CBMA, 2006; see Plate I) illustrated the high rates of infiltration and aquifer recharge quantitatively. The Brow #2 well is spudded on the delta member and has a depth to water of 68 feet. During a pump test, water from Brow #2 was discharged to the ground surface approximately 600 feet west of the well which corresponds to the west edge of the delta member exposure. Approximately 1,200 minutes into the pump test, the rate of drawdown in Brow #2 declined and was followed by a brief rise in water level. Apparently, in less than a day, pump test water discharged to the ground surface had infiltrated through approximately 50 feet of unsaturated material (i.e. epsilon member) and was recycling through the aquifer to the Brow #2 well (WWC Engineering, 2006; CBMA, 2006).

The influence of structures on aquifer recharge was the subject of field-intensive research by Karl Taboga from 2003 to 2006 (see Appendix 10-B in WWC Engineering, 2006).

His data indicate that well hydrograph behavior is strongly dependent on the spatial position of a well relative to mapped geologic structures. At fault associated wells, head increases caused by recharge events tend to be of lower magnitude (e.g. less than 1.5 feet) relative to upland wells. Fault associated wells tend to exhibit low slope declines during dry periods and corresponding gradual head increases during recharge periods. For example, Peanut, a fault-associated well located on the Red Hills Fault, shows a steady linear head decline during 2004 when snow pack was low, then increases moderately in response to snowmelt in the spring of 2005 and to a late spring snowstorm in June 2005. In addition, head elevations are depressed in fault-associated wells.

Preliminary analyses of the Taboga data strongly suggested that faults intercept and redirect groundwater flow. The potentiometric surface along strike of the City Springs Fault shows a markedly lower rate of decrease in head elevation relative to the change in the topographical surface. This relationship suggests that City Springs Fault is highly transmissive throughout its length and not just at its southwest end in the vicinity of the Turner Wellfield.

Although fault systems in the Casper Aquifer have been widely accepted as groundwater conduits and zones of locally enhanced permeability, the permeability and role in groundwater flow of the Sherman Hills Fault has been the subject of some debate. Residents of the Sherman Hills Subdivision, on the south side of the fault, have suggested that this fault prevents movement of groundwater potentially contaminated by subdivision septic systems and land use from moving northwestward into the portion of the aquifer supplying the Turner Wellfield.

This concept was explicitly addressed in the 2015 Laramie Monitor Well Project which documented the movement of groundwater and attendant chemical constituents across the Sherman Hills Fault at Imperial Heights Park (Hinckley Consulting and Wyoming Groundwater, 2015). The investigation involved the collection of detailed stratigraphic, potentiometric, water quality, and aquifer testing data. In association with that investigation, the University of Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG) performed multiple surface and borehole geophysical surveys at project sites and monitor wells. Conclusions from this detailed investigation include:

- The fault does not provide a barrier to groundwater flow and does not prevent contaminants from migrating across the fault. The fault is not a single, linear feature, but consists of multiple offsets to create an overall stratigraphic displacement of 39 feet (down on the south side) measured between the north and south sides of Imperial Heights Park. Surface geophysics suggested a fault-zone displacement of approximately 60 feet.

- The main fault offset occurs beneath the northern portion of the park, with a steep northward dip of approximately 77 degrees. North of the fault, a coherent bedrock block is indicated by the geophysics which is consistent with the observable outcrop pattern. South of the fault, the geophysical characteristics suggest a zone on the order of 200 feet wide of disrupted strata, e.g. subsidiary faults and associated fracturing.

- Near-horizontal fractures/openings within the sandstone units of the Casper Aquifer provide high-permeability pathways and create high specific capacities in areas removed from mapped faults and folds. Figure TM 2-10 and Plate I presents a sampling of images of these important features including a well in known vertical fault zones (“Middle”) and in a well with no mapped fault/fold associations (e.g. “Triangle”).

In association with the LaPrele Park investigation (WWC, 1997b), a potentiometric surface map was created that suggests groundwater flow obliquely across the Sherman Hills Fault from the southeast, feeding water into the Turner Wellfield area. This was also the preliminary conclusion of the 2015 Laramie Monitor Well Project report (Hinckley Consulting and Wyoming Groundwater, 2015) based on examination of water levels over a somewhat wider area. The permeability of the fault zone along its entire length may be variable, however, as the LaPrele Park investigation found the Casper Aquifer to be relatively tight along the expected westward projection of the fault. (WWC, 1997b).

<u>Redbeds</u>

The Casper Formation dips 3 to 5 degrees to the west, placing it beneath younger strata across most of the Laramie Basin (Figure TM 2-2 and Plate I). Formations immediately overlying the Casper Formation are, in ascending order, the Satanka Shale, the Forelle Limestone, and the Chugwater Formation. Based on the predominance of red-colored strata in this group, they are commonly collectively termed the “redbeds”.

Because the recharge area of the Casper Aquifer is at a higher elevation than the outcrops of the redbeds (and because the Casper is far better suited to receiving recharge), the Casper is pressurized relative to the overlying strata and water will flow upward into the redbeds given the opportunity. Vertical flow from the Casper Aquifer into overlying redbed formations occurs to some extend in all locations simply because the redbeds have some small vertical permeability. However, vertical flow from the Casper is enhanced or concentrated where the confining ability of the Satanka Shale, Forelle Limestone, and Chugwater Formation is compromised by vertical faults and fractures (e.g. Sherman Hills Fault and Laramie Fault).

City Springs and Soldier Spring which are universally understood to be sourced from the Casper actually appear at the surface in the lowermost Satanka Shale, a function of relatively permeable sandstone strata and the penetration of Casper Formation-based fracture systems. As noted in the 2008 Casper Aquifer Protection Plan (CAPP; p. 48):

> "the following observations of spring and well data indicate that the lower 50 feet of the Satanka Shale can be permeable and in hydraulic connection with the Casper Aquifer.
>
> - The base of the Satanka Shale is composed of interbedded fractured shale and sandstone.
> - The water at City Springs, Soldier Spring, and Simpson Springs flows from the Casper Aquifer through approximately 50 feet of basal Satanka Shale, presumably via vertical fractures."

The CAPP suggested a west boundary for the Aquifer Protection Overlay based on having "75 feet of undisturbed Satanka Shale cover" over the Casper Aquifer.

Due to the elevation of the recharge area relative to topographically lower areas to the west (Plate I and Figure TM 2-2), the Casper Formation continues to provide a source for upward migration of groundwater across the area west of the primary "Casper" springs. This situation produces free-flowing Casper wells across a wide area to the west.

An initial evaluation the hydrogeology and groundwater development potential of the redbeds were described in a groundwater evaluation at LaPrele Park in 1997 (WWC, 1997b) that involved the completion of three exploration wells in the Casper and Forelle (Plate I and Figure TM 2-11). The investigation provided a cursory evaluation of the Satanka Shale, Forelle, and Chugwater formations which occur at the surface and near sub-surface at LaPrele Park. Significant observations during the air-rotary drilling and air-lift testing of these wells include:

- The Chugwater Formation produced 20 to 30 gpm during airlift in two wells, and 100 gpm in the third, despite having the least available drawdown of the four formations involved.
- Penetration of the Forelle Limestone increased airlift production to over 100 gpm in two wells and to over 200 gpm in the third.
- Penetration of the Satanka Shale increased airlift production to 150-200 gpm.
- Surprisingly, the Casper had a free flow of only 12 gpm from one well and about 30 gpm from a second, despite a shut-in head of +44 feet. The specific capacity of the Casper was only 0.5 gpm/ft. The Casper was not fractured at this location and was clearly less permeable than the overlying

redbeds.

- A consistent upward groundwater gradient from the Casper and in the overlying redbeds was documented using the data listed below.

  - A static water level of 4 feet below grade in the Chugwater
  - Flow at the surface with a head of +2 feet from the Forelle
  - Increasing artesian flow as the Satanka was penetrated
  - A head of +44 feet in the Casper Formation (once it was hydraulically isolated from the overlying strata)
  - Hydraulic connection of the redbeds with nearby Huck Finn Pond as evidenced by decreased flow from the pond as redbed production was increased during drilling

Based on the results of the 1997 LaPrele Park study, WWC Engineering (2010) provided a conceptual design to the City for the potential use of the redbeds as a raw non-potable water supply for the irrigation of LaPrele and Washington Parks. The irrigation of these parks using raw water has been developed further by Wester-Wetstein (2013) with the fracking and pump testing of an existing Casper well, LaPrele No. 1, located at the east end of LaPrele Park, and a detailed irrigation system design. The proposed project design is to obtain Casper water from LaPrele No. 1 and a second well to be completed in the Satanka Shale at either LaPrele or Washington parks. As of this writing, construction planning is underway and production from the two proposed wells is anticipated to be adequate for the irrigation of both parks.

Groundwater remediation activities at the UPRR Tie Treatment Plant provide a unique opportunity to assess vertical gradients and groundwater flux in the strata overlying the Casper Aquifer. Due to the presence of contaminants associated with over a century of railroad tie treating, in 1995 a 200-acre plot on the south side of Laramie just east of the Laramie River was surrounded by a 60-feet deep bentonite slurry wall and equipped with an extensive groundwater monitoring network. Groundwater elevations inside the slurry wall are maintained slightly lower than elevations outside the wall to ensure against leakage out of the enclosure. Thus, the pumping records from the site provide an approximate measure of the upward groundwater flux within the enclosed area (plus the small addition of on-site precipitation infiltration).

The average pumping rate for this site from 2000 to 2005 was 107 gpm. In addition, an average of 8.4 gpm was pumped from the Morrison Formation outside the slurry wall to maintain toward-recovery-well gradients along the Laramie River just outside the wall.

Aquifer head data from the middle of the site (e.g. for May 2013) show the Chugwater Formation head to be 18 feet higher than in the overlying Sundance Formation, and the Sundance head to be 2 feet higher than in the overlying alluvium. The data are derived from semi-annual Corrective Action Monitoring Reports – 2000 to 2005 on file with Wyoming Department of Environmental Quality.

At the Spur, a head difference of 31 feet was measured between the Casper and a point in the Satanka Shale 44 feet above the Casper/Satanka contact (WWC, 1997c). In that area, the Satanka appears to provide a generally effective confining layer even across the crest of the anticline, as there are no springs and seeps resulting from concentrated upward groundwater flow from the Casper.

Not all of the groundwater present in the redbeds need be sourced from the Casper Formation, of course, but given the contrast in recharge area, elevation, and recharge characteristics, and the consistent observations of strong upward gradients, it is reasonable to assume most of the groundwater in the redbeds originates from the Casper.

Wellfield Hydrogeology

As explained above, due to the local variations, the Casper Aquifer can be very productive at some sites and have quite modest production characteristics at others. By targeting areas of natural discharge (e.g. City Springs, Pope Springs, Soldier Spring) and favorable geology (e.g. Spur), the City has developed four specific sites as wellfields, the details of which are presented below from north to south.

Spur Hydrogeology

The topographic feature called the "Spur" is a northwest-southeast trending ridge approximately 6 miles north and northeast of Laramie. This feature is created by a major fold in the strata, the Spur Anticline. The anticline is an asymmetric upward fold with steep 30 to 50 degree dips on the northeast side of the ridge and gentle 4 to 10 degree dips on the southwest side. The fold is probably cored by a high angle reverse fault (Lundy, 1978) that has uplifted the Sherman Granite and the Casper Formation to produce the prominent topographic ridge. The Spur ridge terminates abruptly at the west edge of the mountain range. The Spur Anticline continues due westward beneath overlying redbed strata as shown on Figure TM 2-12.

Three features of the Spur area are particularly attractive for groundwater development.

1. The Spur Anticline is the most sharply deformed structure in the Laramie area. Apparently, it has created locally very high permeability that supports very high groundwater production rates with relatively little drawdown.

2. The Spur Anticline likely serves to guide groundwater flow into the wellfield area from extensive areas of recharge to the north and east (Plate I).

3. The Spur area has no associated surface spring system. While drawdown impacts will spread through the aquifer under sustained production, potential impacts to springs/streams/wetlands is not an issue nor are there water quality concerns associated with groundwater/surface water interaction.

Figure TM 2-12 shows the location of the two Spur production wells, Spur No. 1 and Spur No. 2, and the twelve Casper Aquifer monitor wells installed in the Spur area as part of the Spur Wellfield project. Five of these monitor wells (MW-7, MW-8, MW-10, MW-11, and MW-12) have been in continuous use since 2001 to monitor aquifer water levels to ensure compliance with the Spur Wellfield Use Agreement (see Technical Memorandum No. 1).

An exploratory drilling program was conducted at the Spur in 1995, followed by a development program in 1997. Those projects provide the following results (WWC, 1995; WWC, 1997c):

- Spur No.1 and Spur No. 2 were each pumped for 5 to 6 days at 2,000 gpm with only 3 to 4 feet of drawdown; then they were pumped together at 2,800 gpm (1,400 gpm each) for 30 days. The observed specific capacities of 580 and 440 gpm/ft for the Spur No. 1 and Spur No. 2, respectively, are by far the highest of any Casper wells in the greater-Laramie area[12].

- The anticlinal crest of the Spur structure was identified in the subsurface by structure contour mapping of the top of the first limestone in the Casper Formation. The aquifer is strongly anisotropic, ranging from 4:1 to 14:1, with the direction of maximum permeability oriented parallel to the crest of the anticline.

- Numerous fracture zones were encountered in the Casper sandstones (e.g. TW-1 and MW-2). Fracture zones were identified by dramatic increases in water production, bit drop, rig chatter, rapid drilling rate, and large sandstone rock fragments in the cuttings.

- In Spur No. 1, Spur No. 2, and TW-1 the last 7 to 10 feet of epsilon sandstone immediately above the delta limestone was intensely fractured with potential cavities as indicated by the downhole camera survey conducted in TW-1.

- Head values in individual sandstone members of the epsilon, delta, and

[12] For comparison, the Turner wells have specific capacities of 36 and 66 gpm/ft; the Soldier No. 1 well has 191 gpm/ft; and the LaPrele No. 1 well, considered representative of run-of-the mill unfractured Casper has 0.5 gpm/ft.

gamma members were very similar as was the drawdown response to pumping. Hydraulic integration was demonstrated by drawdown observed in monitor wells completed in the delta and gamma members when pumping the Spur No. 2 well which is completed exclusively in the epsilon sandstone.

- The hydraulic gradient in the area of Spur No. 1 and Spur No. 2 is exceptionally low (0.0002 ft/ft). The low gradient may reflect the ability to transmit groundwater from the recharge area to discharge points to the west with the high permeability fracture network along the trend of the anticline.

- Water level recovery one month following 30 days of 2,800 gpm production was only 72% (i.e. 2 feet of residual drawdown). This is less than expected in an ideal aquifer, perhaps reflecting the stratigraphic and structural complexity in this area.

- Significant differences in water production and fracturing occur over very short distances as demonstrated by pilot hole pairs PH-4/PH-1, PH-5/PH-6, and PH-2/PH-7 (WWC, 1995).

Comparison of Figure TM 2-8 and Figure TM 2-6 shows both the generally high permeability of the area in that the production drawdown (e.g. in 2002) creates dramatic downward spikes at all locations, and the anisotropy of that permeability. For example, the drawdown observed at MW-11 is virtually identical to that at MW-7, and is approximately twice that observed at MW-8, the same distance from MW-7.

<u>Seasonal Drawdown.</u> In contrast with the long-term trends in aquifer water levels, Figure TM 2-8 also documents the seasonal impact of each year’s pumping. 2002 is the most dramatic example. The downward spike that summer, followed by recovery in the fall, is clearly a function of the large and summer-concentrated pumping of the wellfield. Figure TM 2- 13 shows the seasonal distribution of Spur Wellfield pumping.

Similar spikes in other years are roughly proportionate to seasonal pumping, although the depth and breadth of individual spikes are a function of seasonal details. Very high production for a short time will create a deeper spike; moderately high production for a longer period will create a broader spike.

Although wellfield production clearly has a short-term impact on aquifer water levels throughout the monitored area, the magnitude of impact attenuates with distance, as one would expect. For example, the 2002 seasonal spike in water level is approximately 10 feet “deep” at MW-7 and MW-11, 6 feet deep at MW 8, 4 feet deep at MW-10, and 3 feet deep at MW-12 (see Figure TM 2-12 for well locations).

Turner Hydrogeology

The Turner Wellfield is basically the well equivalent of City Springs. These large natural springs, arguably the reason for the founding of the City of Laramie at its present location, occur as a result of enhanced aquifer permeability due to vertical and horizontal fractures associated, to some degree, with deformation of the Casper Formation along the City Springs Fault, Spur Fault, Quarry Fault, and Quarry Anticline all of which converge upon the City Springs area. It is also the lowest elevation (7,270 feet) of the surface exposure of the top of the Casper Formation in the region, making it a primary “overflow” point for the Casper Aquifer groundwater reservoir.

The Turner wells were installed a short distance west and southwest of City Springs, where the Casper Formation is fully saturated and overlain by the Satanka Shale. Springs issuing from the Satanka along Spring Creek (e.g. Satanka Springs on Plate I) and tributaries in the vicinity demonstrate the compromised nature of the Satanka as a confining unit.

Downhole videos of the Turner No. 1 and Turner No. 2 wells reveal large horizontal openings and fractures in the epsilon, delta, and gamma member sandstones of the Casper Formation (Wyoming Groundwater, 2004 and 2011a). Some fracture zones occur in sandstone immediately above and below limestone strata while other fracture zones occur within the sandstone units.

Natural discharge from City Springs is captured by a clay pipe and springbox system buried approximately 4 to 5 feet into the Satanka Shale throughout the City Springs area (i.e. the enclosure). When the hydraulics of the springbox system is restricted and/or the head in the Casper is high due to recharge or non-pumping of the Turner wells, groundwater will discharge to the ground surface at the original location of City Spring.

When operating, the Turner wells are capable of capturing all of the natural discharge at City Spring such that the head in the Casper Aquifer is lowered below the level of the buried pipe in the springbox system. Turner No. 2 is located west of the spring and is capable of eliminating flow from the springbox outlet pipe after 3 to 4 days of pumping at a rate of 1,400 gpm. When both the Turner No. 1 and No. 2 wells are operating at a total withdrawal rate of 3,300 to 4,100 gpm, flow from the springbox outlet pipe will cease in 1 to 2 days following the commencement of simultaneous pumping. When the Turner wells are shut-off, the head in the Casper Aquifer will begin to recover, and flow from the springbox outlet pipe will eventually resume and gradually increase with time. When the Turner wells are off for an extended period, the combined discharge rate from the springbox outlet pipe and artesian flow from Turner No. 2 will equal the natural discharge rate of the spring.

In this manner, the head in the Casper Aquifer at City Springs fluctuates up and down, above and below the level of the pipe-springbox system, and water periodically discharges from the springbox outlet pipe and into Spring Creek. Turner No. 2, due to its proximity to the spring and a pump rate (1,400 gpm) greater than the average natural discharge of the spring (1,140 gpm), is capable of eliminating discharge from the springbox system. However, after approximately 7 days of pumping, the water level in Turner No. 2 approaches the pump bowls and the well must be shut-off; consequently, the aquifer head recovers and discharge from the springbox outlet pipe resumes.

Pump testing of the Turner wells at 3,650 gpm (combined pumpage) for 7 days in 2005 produced 4.9 feet of drawdown at the 41T3 well located 5,500 feet northeast of City Springs; 8 feet in monitor well SHFCA-1 located 2,500 feet southwest (Plate I); and 3 feet in monitor well SHFCA-2 located 3,200 feet south (note: SHFCA-2 has since been plugged and abandoned). As with the Spur area, the asymmetrical drawdown likely reflects the influence of high-permeability pathways in the aquifer. In this case, the test was interpreted as identifying preferential drawdown in a north-south direction (WWC Engineering, 2006).

Using a downhole packer, pump testing of the alpha member (i.e. the lower most member of the Casper Formation) at the 41T2 well (Plate I) demonstrated hydraulic connection with the overlying sandstone members of the formation such that the intervening limestone strata do not serve as confining layers in the City Springs area (WWC, 1996a).

Soldier-Pope Hydrogeology

Unlike the Spur and Turner wellfields, the Pope Springs area is not associated with prominent mapped geologic structures in the Casper Formation. Rather, these springs issued from the lower part of the overlying Satanka Shale at a locally low topographic elevation. However, there is abundant small-scale faulting/fracturing of the Casper in this area, as mapped on exposures immediately east of Pope Springs. These features include two small-displacement faults, the westward projection of which intersects the Pope Springs area. Also, a small anticline parallels this alignment, just to the north. Formation dips show slight deformation, but remain in the range of 2 to 5 degrees. (Ver Ploeg, 2009). However, surface mapping is largely blind to near-horizontal (e.g. bedding plane) fractures which may provide important conduits for groundwater flow.

The natural Pope Springs ceased flowing in 1934. Figure TM 2-4 suggests this was, in part, the result of the large reduction in recharge available that year, the lowest in 32 years, and dramatically lower than the wet period from 1904 to 1931. The flow of Pope Springs was also reduced by the lowering of the discharge works at Soldier Spring in 1929 and 1932 (Beckwith, 1937). Specific capacities for the Pope wells range from 40 to 125 gpm/ft, also suggesting the occurrence of fracture-enhanced permeability.

The setting of Soldier Spring and the Solder No. 1 well is quite similar to Pope, with springs issuing from the lower Satanka Shale just west and north of an area of mapped faulting and folding in the Casper Formation. In this case, the deformation is much more pronounced than at Pope Springs, with dips up to 51 degrees along the Soldier Fault and the Soldier Monocline (Ver Ploeg, 2007). The model of the Casper Aquifer groundwater reservoir overflowing at topographically low spots and potentially aided by the presence of permeability-enhancing structures is suggested.

The Soldier No. 1 well penetrates 41 feet of Satanka Shale and is completed in the Casper Formation to a depth of 289 feet. Fractures and thin red shale layers in the epsilon sandstone of the Casper Formation were exceptionally productive. Additional fractures and red sandy shale layers also occur in the first sandstone of the delta member. Pump testing of Soldier No.1 at a rate of 1,800 gpm for 6 days produced a specific capacity value of 191 gpm/ft. Soldier No. 1 is a flowing artesian well because the head in the Casper is approximately 6 feet above ground surface.

An important aspect of the Soldier-Pope Wellfield is the obvious hydraulic connection between Pope and Soldier Springs. Morgan (1947) used water production trends to show that discharge at Soldier Spring is affected by withdrawals at the Pope Wellfield. To verify this early observation, a monitor well (Soldier MW No.1) was installed in 1993 near Soldier Spring and a 5-day pump test was conducted at the Pope Wellfield (WWC, 1993d). The results of the pump test confirmed that, indeed, excellent hydraulic connection exists between the Pope wells and Soldier Spring. Currently, the water system operator sees immediate and significant declines in the artesian flow from Soldier No. 1 when the Pope wells are operating.

The nature of the hydraulic connection in the aquifer between Pope and Soldier is unclear. An unmapped north-south fault between Pope and Soldier and at Simpson Springs has been postulated (WWC, 1995; Wyoming Groundwater in Lord Consulting, 2011) which would be consistent with the orientation of mapped north-south trending faults to the east and west of Soldier-Pope (i.e. the Red Hills Fault and the Laramie Fault, respectively). A high-permeability feature in the Satanka Shale, as identified at Simpson Springs (Weston Engineering, 2013a), or an extensive horizontal fracture system in the Casper are also possibilities. Although not documented in the pump test analysis by Weston Engineering (2013a), water system operators observed the drying up and re-emergence of a spring at Soldier Spring during and after, respectively, the pump test at Simpson Springs in December 2012. This observation may indicate that excellent north-south hydraulic connection continues farther south from Soldier Spring.

Historical artesian flow production data indicate that Soldier Spring currently flows at the same rate, if not slightly higher, than rates documented during early development of the spring in the 1940s. From 1999 to 2014, total monthly and annual production records indicate that average daily production from Soldier No. 1 varied from 1.5 to 2.1 mgd with an average of 1.8 mgd. These values are a reasonable approximation of natural artesian flow given the rare use of the pump in Soldier No. 1. During the same time period, average daily production from the Pope Wellfield was 0.13 mgd such that the combined average daily production from Soldier and Pope was approximately 1.9 mgd. This value is identical to the combined average daily production from Soldier and Pope of 1.94 mgd during 1941 to 1943 (Morgan, 1947).

Simpson Springs Hydrogeology

There is no current municipal groundwater production from the Simpson Springs area (Plate I and Figure TM 2-14). Discussion of the area is included here due to relevance to general Casper Aquifer features and long-term interest in developing production from this location.

The furthest south of the Casper Aquifer natural spring systems of interest is at Simpson Springs. Like those spring systems which have been successfully developed at Soldier Spring, Pope Springs, and City Springs (Turner Wellfield), the springs at Simpson Springs appear to mark the conjunction of favorable geologic structures along the contact between the Casper Aquifer and the overlying Satanka Shale. The area has long been on groundwater prospect lists generated by general considerations of hydrogeologic conditions along the western flank of the Laramie Range, and has the additional attraction of being partially located within the City-owned Monolith Ranch property.

A water-level monitoring well (Simpson MW-1) was installed into the top of the Casper Formation at Simpson Springs in 1997 in association with development activity at Soldier Spring. "Possible fractures" were noted in the epsilon member of the Casper Formation and the well produced approximately 120 to140 gpm during air-rotary drilling.

The 2006 Water Management Plan cites a flow of 200 gpm for the natural spring system. Pump testing at 900 gpm of the nearby Brow #2 irrigation well (Figure TM 2-14) completed in the Casper (CBMA, 2006) indicates a specific capacity of approximately 47 gpm/ft. Consequently, Simpson Springs was been described as "the best prospect for the expansion of new groundwater supplies" for the City. Based on 350 gpm flow from various springs issuing from the lower part of the Satanka Shale south of Simpson Springs, the 2006 Water Management Plan suggested that the capture of Casper water that leaks upward into the Satanka is an attractive aspect of groundwater-development target at Simpson Springs.

Since completion of the 2006 Water Management Plan, a detailed evaluation plan for the Simpson Springs area (and the adjacent Laramie Fault, also on the City-owned Monolith Ranch) was developed by Wyoming Groundwater in 2011. The 2011 report (Wyoming Groundwater, 2011b) provided an overview of the area, suggesting yields for favorably located and completed wells on the order of 1,000 gpm.

In 2012, three test wells and two additional monitoring wells were completed in the lower Satanka Shale or Casper Formation in the Simpson Springs area (Weston Engineering, 2013a). Test wells completed in the Casper (Test Well No. 1 and Test Well No. 2) were only modestly productive (125 and 30 gpm, respectively), but a gravel-rich deposit interpreted as a “channel” in the lower Satanka was found to be productive at Test Well No. 3 (350 gpm). Test results suggested local transmissivities on the order of 14,000 and 500,000 gpd/ft for the Casper and the channel deposit, respectively.

Drilling density at Simpson Springs was insufficient to delineate the extent of the high-permeability deposits observed at Test Well No.1 and Test Well No. 2, but the potential value of this “channel” in collecting lower-Satanka and Casper groundwater for high-capacity well extraction is obvious.

The Weston Engineering (2013a) report concluded that the hypothesized structural enhancement of Casper permeability by folding or faulting at Simpson Springs was largely absent. However, a subsequent review of the Weston Engineering (2013a) report and related available data by Wester-Wetstein (2015) concluded that a “north-south or northeast-southwest trending fault” of undetermined location was indeed present through the area, delineated a “possible fracture zone in the Casper Aquifer”, and concluded the “projected production from the gravel source could be significantly overestimated”. A fault/fracture zone in the Casper Aquifer in the Simpson Springs area (i.e. see Plate I for location of possible fault) may be related to the substantial productivity of the Casper indicated at the Simpson MW-1 monitor well located northeast of the main spring and the high productivity of the Casper at the Brow #2 well (900 gpm with 19 feet of drawdown) located 0.7 miles to the south-southeast, and would provide a source of recharge to the gravel deposit in the Satanka Shale encountered at Test Well No. 3.

Given current water-supply and demand conditions for the City, there is no urgency to develop additional municipal groundwater supplies in areas like Simpson Springs, remote from existing infrastructure. Similarly, the thickness of the aquifer at this location and the absence of potentially competing development pressure suggest little need for immediate exploration/development to establish a priority position with respect to water rights. However, experience and exploration continue to indicate the potential for a substantial contribution to the municipal groundwater supply. At such time as it becomes appropriate in the context of the overall municipal water supply/demand and consideration of other options for groundwater development, the Simpson Springs area may merit further investigation of the geometry, recharge characteristics, potential surface connections, and sustainable production of the suggested channel deposit and possible fracture zone(s) in the Casper Aquifer.

Laramie Fault Hydrogeology

The Laramie Fault was mapped by Lundy (1978) as a north-south trending fault with the north end located 2 miles west of Pope Springs and continuing at least 5 miles to the south. Fault motion was designated up on the east, down on the west, with 250 feet of vertical displacement. The fault trace is mapped on the Chugwater Formation which suggests displacement throughout the Casper-Redbed sequence.

Subsequent geologic mapping of the Howell, Laramie, and Red Buttes Quadrangles by Ver Ploeg (1996, 2009, and 2007, respectively) significantly expanded the extent of the fault (i.e. 30+ miles) both north and south. Based on drilling logs from two domestic wells on opposite sides of the fault, Ver Ploeg (1998) identified an opposite sense of vertical motion reported by Lundy (i.e. up on the west, down on the east) and possible right-lateral strike-slip motion. The domestic water wells (Spiegelberg #1 - P81933 and O'Malley #1 – P44386) are located in Section 16, T15N, R73W and the elevation of the top of the Casper Formation at these two wells indicate approximately 100 feet of vertical displacement along the fault at this location (Wyoming Groundwater files).

The Laramie Fault trace is poorly expressed because of extensive alluvial/colluvial cover and the homogeneous and ductile nature of the Chugwater shales. Consequently, the fault trace is covered, queried, or approximately located along most of its mapped length. Gypsite deposits occur frequently along the fault trace and as stated by Ver Ploeg (1998), "The source of the gypsite deposit was the gypsum beds in the lower Chugwater Formation that were brought to a near-surface position by the Laramie fault and then subjected to Quaternary erosion." It is probable that the mobilization of redbed gypsum to the ground surface occurs as a result of the upward flow of groundwater from Casper Aquifer which has sufficient head to flow to the surface (i.e. the Spiegelberg and O'Malley wells are completed in the Casper and are flowing artesian).

The Laramie Fault has been identified in previous Master Plans and water resource studies (Snowy Range Water Consultants, 1991; WWC, 1995; WWC Engineering, 2006; Aspen-Banner Engineering, 2007; Lord Consulting, 2011) as a potential high permeable/high yield feature in the Casper Aquifer, but the hydrogeology of the fault has not been evaluated in detail. The Hunziker irrigation well on the City-owned Monolith Ranch is located on the fault trace and produces 600 to 1,000 gpm. The well is 325 feet deep and produces water from the Chugwater, Forelle, and the middle portion of the Satanka Shale (WWC, 1993c). The excellent production from the redbeds at the Hunziker well suggests that fracture permeability may occur along the Laramie Fault.

In 2012, the South Laramie Water and Sewer District drilled an 897 feet deep well (SOL No. 1 Well – P170795) with 247 feet of open hole in the Casper Formation (Weston Engineering, 2012). The well is located directly on the Laramie Fault just north of Howe

Road. The static head is 2 feet below ground surface. The well was pumped at 30 gpm for 24 hours with 370 feet of drawdown. Calculated transmissivity and specific capacity values were 600 gpd/ft and 0.08 gpm/ft, respectively. These parameter values are representative of unfractured Casper. Subsequent well stimulation efforts (i.e. pressure frack) did not adequately enhance well production. Because the well is not adequate as a redundant public water supply well, the District is currently considering drilling another Casper well at a different location.

Although the South Laramie District well indicated extremely low permeability on or near the fault at that location, the potential of the Laramie Fault as a feature for municipal development has not been fully characterized. In general, the fault's north-south orientation, extensive length (30 miles), and location west of the Satanka/Casper contact provides the opportunity to capture groundwater underflow that is presently not being captured by the Turner and Soldier-Pope wellfields and provides far greater available drawdown than at any of the existing wellfields.

IV. Current Conditions and Research Opportunities

The discussion of recharge, and Figure TM 2-6 specifically, demonstrate that aquifer water levels are currently at relatively high levels - as high as they have been for the last 40 years. In the Spur area, where monitoring data can be most closely compared with municipal well production[13] , measured water levels are currently near or above those measured immediately prior to wellfield development. At the Huntoon monitor wells (Figure TM 2-5), the record demonstrates that groundwater levels have been another 17 feet higher, but at some point increases in aquifer discharge at City Springs and Soldier Spring are likely to limit additional groundwater level rise in those areas. The "reservoir" cannot get much fuller as it just increases the overflow.

Comparison of the total average municipal Casper Aquifer groundwater production presented in Technical Memorandum No. 1, i.e. a 2003 to 2014 average of 961 mg (2.6 mgd), with the total available groundwater compiled in Table TM 2-1 indicates that the average annual municipal production is substantially less than the steady-state discharge of approximately 5.0 mgd from the Spur/Turner/Soldier-Pope area. Thus, while aquifer water levels will continue to rise and fall in response to recharge cycles, the aquifer is currently under no long-term stress from municipal production.

Safe yield is often equated to the amount of recharge to the groundwater aquifer system. Bredehoeft (2002) emphasizes that using recharge to estimate safe yield is incorrect, and states, "The size of a sustainable groundwater development usually depends on how much of the discharge from the system can be captured by the development. Capture is

[13] Unlike the relationship between the Turner Wellfield and the Huntoon monitor wells, at Spur there are no intervening faults to potentially attenuate the drawdown impact of municipal pumping, nor is there surface overflow of the aquifer to constrain aquifer water levels.

independent of recharge; it depends on the dynamic response of the aquifer system to the development."

When a well is pumped, the cone of depression expands and captures groundwater that would otherwise discharge to a spring or stream, leak into adjacent formations, flow into an intermountain basin, or be lost to evapotranspiration. The cone of depression may capture water directly from a stream/lake or other hydraulic boundary. In the case of the Casper Aquifer, estimating the sustainable yield of a prospect solely on the assumed ability of a well to capture the discharge from a local spring may significantly underestimate the potential yield. Other discharges besides springs, such as leakage into overlying formations and underflow into the Laramie Basin need to be considered in the estimation of the water balance associated with a wellfield or groundwater development prospect.

Also, the availability of aquifer storage is critical to the aquifer's ability to provide long-term averaging of production and the natural discharge being captured. Given small aquifer storage, only virtually contemporaneous discharge can be captured. Given large aquifer storage, groundwater production can exceed historical low-discharge rates.

It is often impossible to accurately quantify all the discharges that a well may be able to capture. This is the case with groundwater development of the Casper Aquifer. The sustainable yield cannot be determined precisely because the discharges from the Casper Aquifer, especially leakage into overlying formations, and the dynamic response of the aquifer to pumping are not known precisely.

Spur Wellfield

The Spur Wellfield has been little used in recent years, apparently as a result of the unfortunate coincidence of the peak production (360 mg) and the largest single-year drop in recovered water level in 2002. As discussed above, subsequent measurements provide strong evidence that the latter was largely unrelated to the former, but the alarm was understandable. The current relatively high water levels in the aquifer provide an ideal opportunity to aggressively evaluate the production potential of the aquifer at the Spur without significant risk of compromising its status as an emergency "back-up" supply for the surface water treatment plant. For example, even if the entire 3.5-feet difference between the recovered water levels in January 2002 and January 2003 at the Spur were attributed to the 360 million gallons of wellfield production (rather than to climate-based decline), that decline could continue for 3 to 4 years before reaching the natural aquifer levels experienced in 2009. An additional year's decline at this rate could be sustained before the first increment of reduction would be triggered under the Spur Wellfield Use Agreement.

Absent a well-calibrated groundwater model of this obviously complex aquifer, the most powerful research tool is a straightforward empirical approach, using actual wellfield operation as a direct test of aquifer response. Thus, concentration of summer 2016 pumping at the Spur Wellfield is recommended. Assuming the near-term drawdown relationships measured in 2002 hold constant,[14] 2 years' production at the full 391 mg allowed under the agreement could be accommodated, and at the maximum allowed rate of 4 mgd. Additional years' production of the maximum volume could require a less peaked annual rate in order to keep the short-term drawdown (the downward spike on Figure TM 2-6) from hitting the trigger level for MW-7 (the closest control point for the agreement). A decision on 2017 pumping would of course be based on careful review of the aquifer response and recovery measured in 2016, but there appears to be opportunity for several years of experimentation.

To evaluate both the long and short-term water-level impacts of significant wellfield production, and as can best be coordinated with overall municipal demands, we recommend:

- A period of peak production rate (e.g. 4 mgd) accompanied by careful monitoring of short-term response in monitor wells. Ideally, this would occur outside the period of peak domestic well use in order to better isolate the impact of wellfield production.

- A season of maximum production volume (e.g. 390 mg) accompanied by careful monitoring of the long-term response in aquifer levels.

A better understanding of the relationship between long-term water levels and wellfield production at the Spur Wellfield would provide the basis for reassessment of how this valuable asset should best be integrated into future aquifer management planning and modification of the use agreement in 2020.

Given the present relatively high aquifer water levels, conditions are well suited to additional exercising of the Spur Wellfield.

Turner Wellfield

For the Turner Wellfield, the primary concern appears to be inadequate wellfield recovery during repeated pumping cycles in the summer. Mike Lytle (pers comm., 5/2015) describes pumping the Turner No. 1 well down to within 10 feet of the pump setting, letting the water level recover to the point of surface flow, then taking much less time to pump back down to the shut-off point. Possible explanations include that recovery is less than complete with respect to relatively shallow, high-productivity strata, or that recovery appears relatively complete locally, but does not reflect conditions across

[14] Short term drawdown at the Spur MW-7 monitor well was approximately 10 feet in 2002. This was the result of an average July pumping rate of 4.1 mgd.

the wider aquifer.

It is recommended that the successive pumping cycles of the Turner wells be conducted with careful monitoring of aquifer water levels in the Turner wells and at nearby monitor wells (e.g. Plate I: 41T2, SHFCA-1, LCCC MW-1, and Triangle). These tests would provide valuable information upon which to base this component of aquifer management.

Soldier-Pope Wellfield

For the most part, Soldier Spring is fully utilized by the design and operation of Soldier No. 1. Substantial quantities of groundwater can be obtained by artesian flow and use of the variable frequency drive motor control to modify pumping rates. However, the persistence of leakage into Soldier Creek even when pumping Soldier No. 1 at 2,300 gpm suggests that there may be an opportunity to capture additional groundwater, if need be, by more aggressive pumping. During this current condition of high water levels, we recommend an extended period of pumping Soldier No. 1 and careful documentation and quantification of the capture/decline of leakage into Soldier Creek.

Additional Research Opportunities

Existing wells outside the current wellfields also provide opportunities for improved understanding of the Casper Aquifer system. Downhole geophysics, televiewer logs and periodic water-level monitoring at City-owned wells (e.g. Plate I: Spur TW-1, 41T3, 41T2) and coordination with measurements by others (e.g. Laramie County Community College) should be instituted. Continued geophysical investigations of Casper Aquifer wells by WyCEHG, both adjacent to the municipal wellfields and in hydrogeologically similar areas to the south (e.g. Red Buttes) should be encouraged/supported by the City and integrated into the "working" knowledge of the Casper Aquifer.

Evaluation of groundwater development potential in areas that are not presently part of the Laramie municipal supply are discussed along with the potential to increase supply from the existing wellfields in Technical Memorandum No. 4 (e.g. Turner Wellfield improvements, Simpson Springs, Laramie Fault, and redbed aquifers).

V. Conclusions and Recommendations

The Casper Aquifer provides a large reservoir of groundwater which has historically been exploited by simply capturing a portion of the overflow. While ensuring that the reservoir stays as nearly full as possible by this approach, significant potential contributions to municipal water supplies are precluded. These include:

- Substantial, continuing quantities of groundwater are available beyond the "overflow" represented by existing springs and flowing wells. As indicated by Table TM 2-1, total, long-term average output from the aquifer may be as high as 6 mgd. The single most dramatic example of untapped aquifer underflow is likely the Spur area, where the aquifer has demonstrated huge production potential with no natural surface discharge[15] .

- The ability of the aquifer to provide larger quantities of water for both seasonal peaking and even for multi-year leveling of production during drought periods.

To a large extent, this memorandum is a reiteration and update of an incisive article by local hydrogeologists published in 1979 (Huntoon and Lundy, 1979b). Describing the City's water-supply management of the 1970s, they concluded that:

> "by ignoring the total system in the vicinity, the City of Laramie has been operating under a restrictively conservative safe yield policy.";
>
> "Currently 1.4 Mgal/day is lost from the system in that it is not put to a recognized beneficial use."; and
>
> "Development of wells designed to capture underflow and water lost from undeveloped springs could provide another 1 Mgal/d to the total supply available in the area and not significantly affect the total sustained yield of the existing municipal sources."

[15] To maintain recharge-to-discharge circulation, groundwater at the Spur must be ultimately discharging to the surface. This is assumed to occur in a diffuse manner, including upward flow into overlying strata over a large area and likely including, ultimately groundwater inflow to the Laramie River.

List of Tables (embedded in text)

List of Figures

List of Attachments

TECHNICAL MEMORANDUM NO. 2

FIGURES

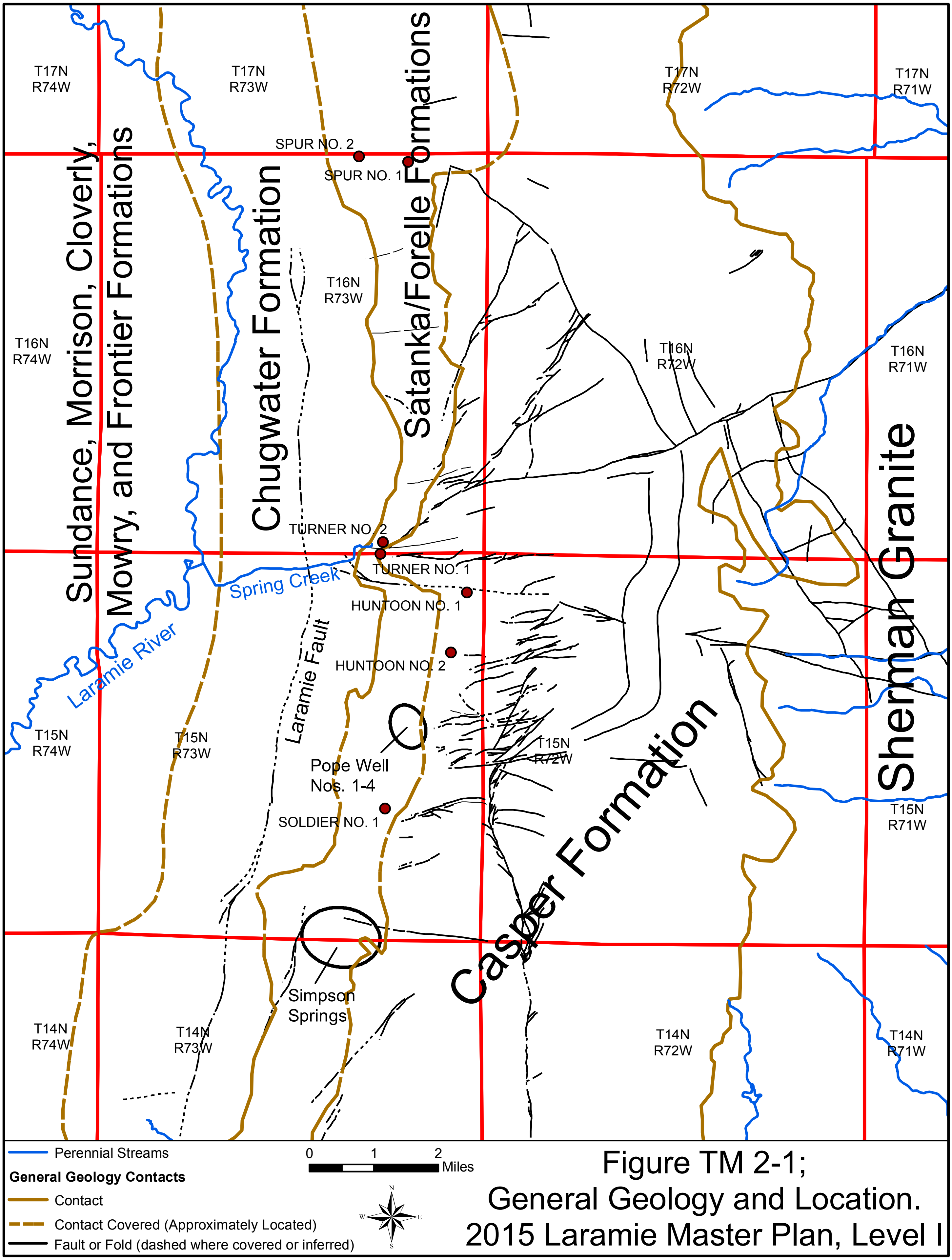


Figure TM 2-1;
General Geology and Location.
2015 Laramie Master Plan, Level I

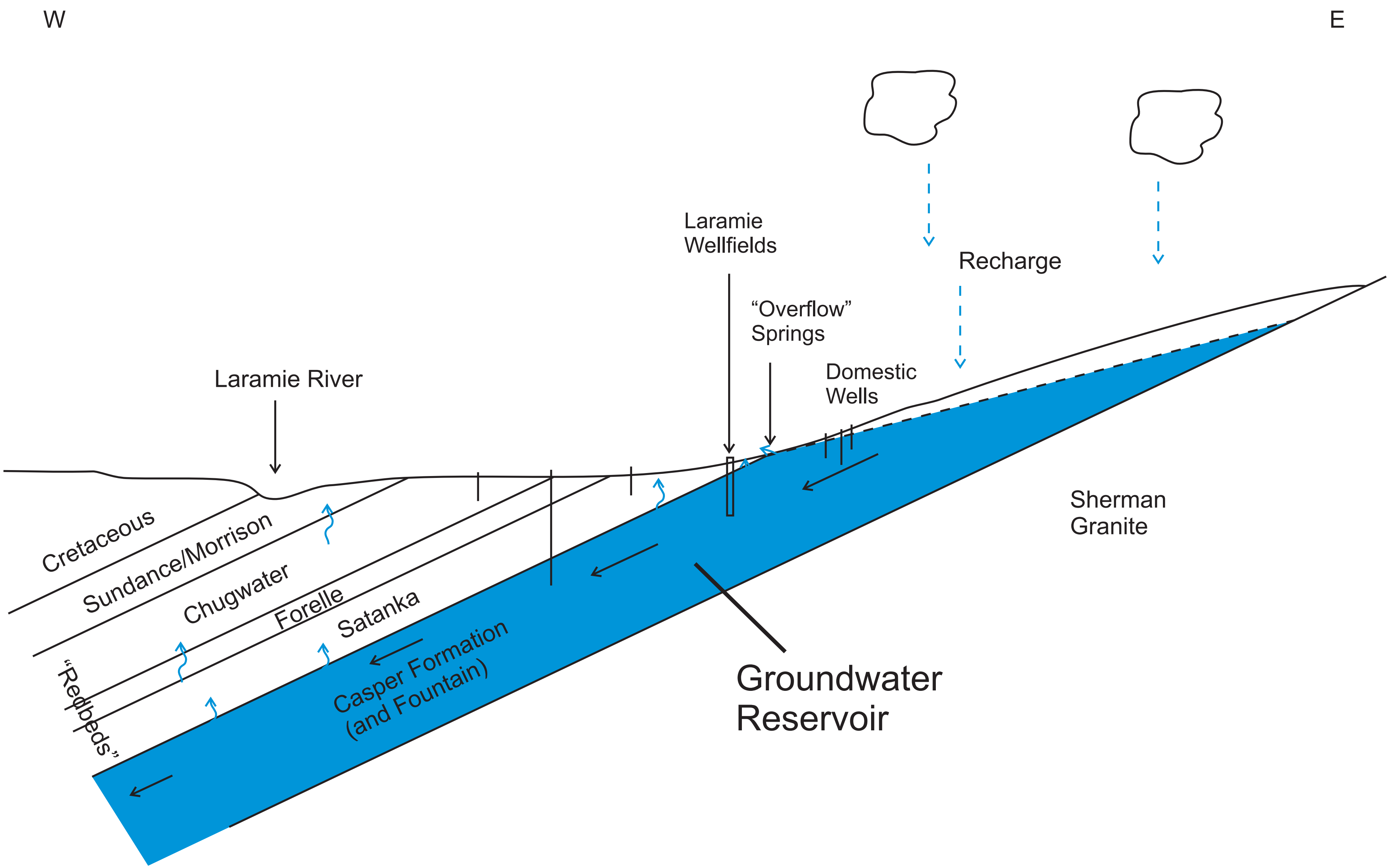


Figure TM 2-2; Casper Aquifer Schematic.
2015 Laramie Master Plan, Level I

Figure TM 2-3; Average "Huntoon Nos. 1 & 2" Monitor Wells Annual Minimum Depth to Water and Laramie AP Precipitation (Water Year). 2015 Laramie Master Plan, Level I

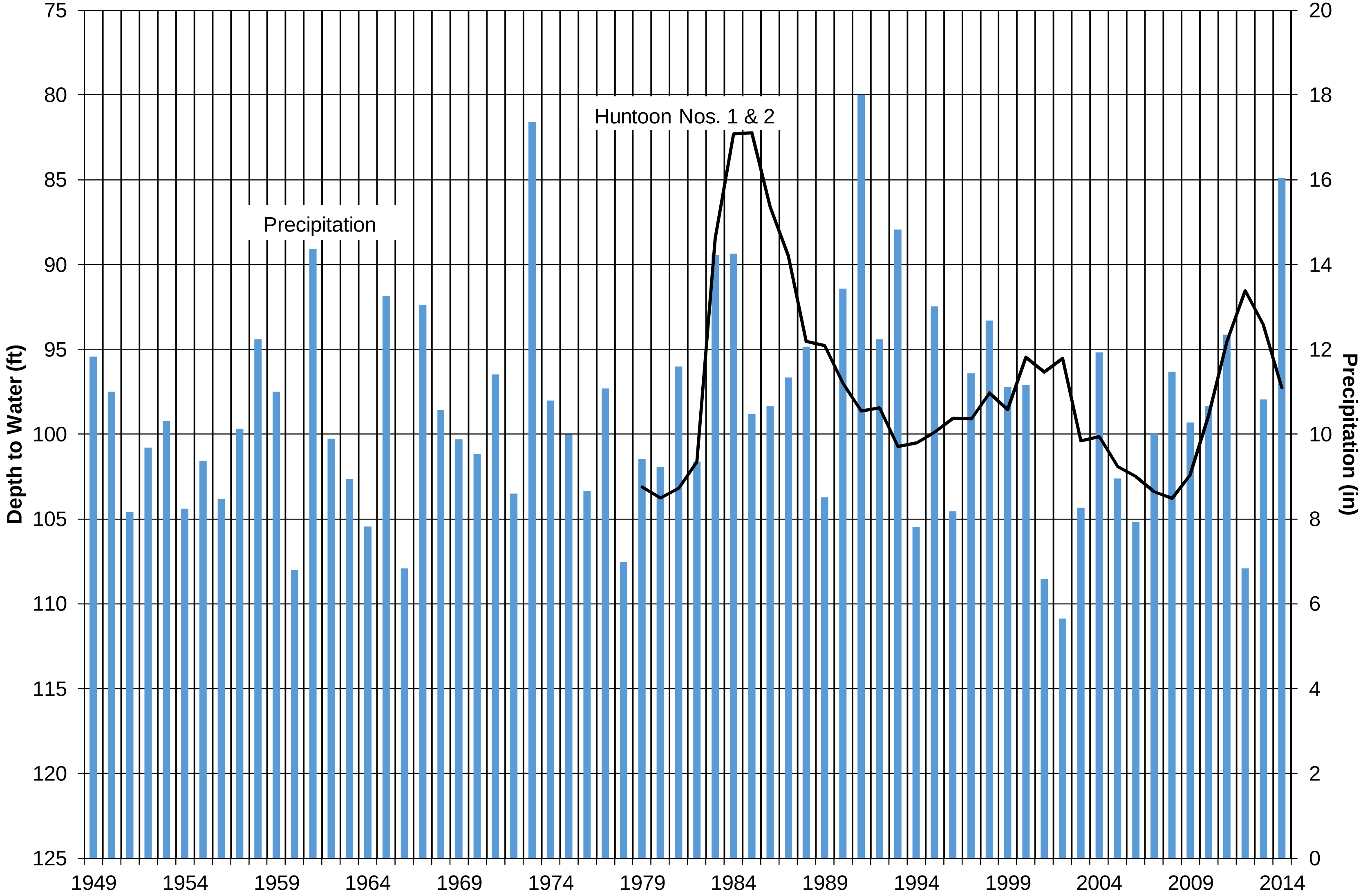


Figure TM 2-4; Average "Huntoon Nos. 1 & 2" Monitor Wells Annual Minimum Depth to Water and WY Division 10 PDSI (Water Year). 2015 Laramie Master Plan, Level I

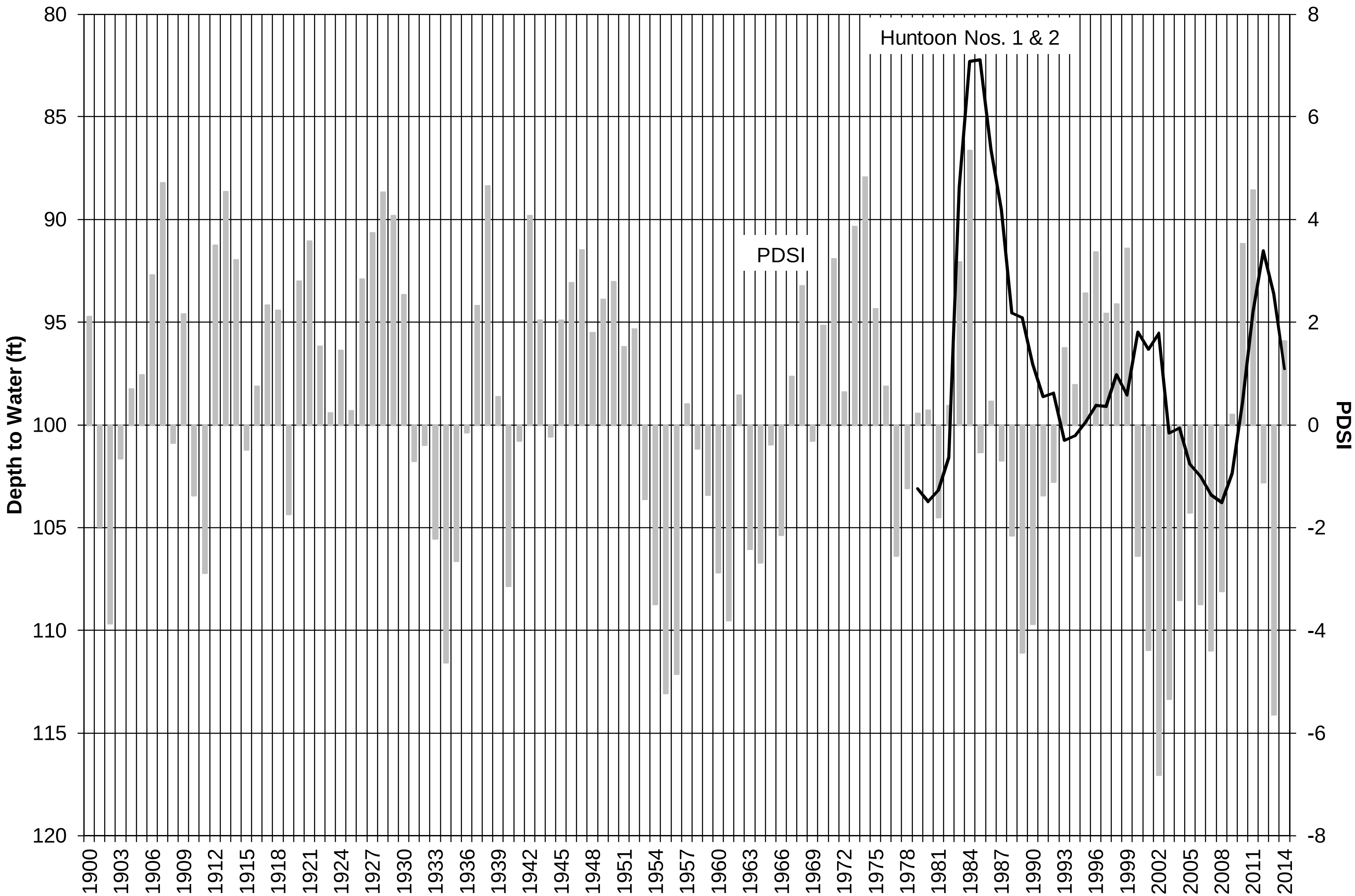
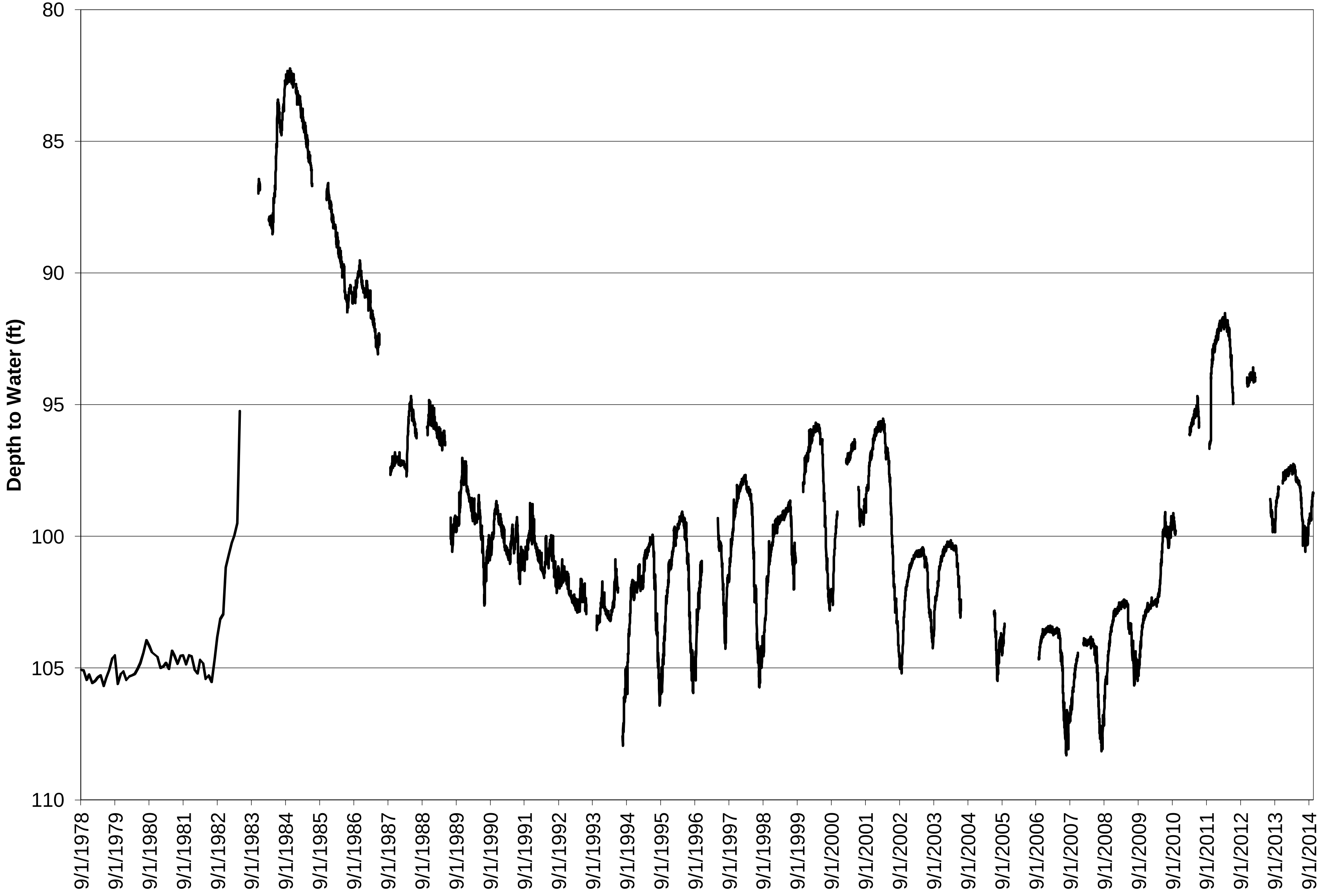


Figure TM 2-5; Average "Huntoon Nos. 1 & 2" Monitor Wells Minimum Depth to Water.
2015 Laramie Master Plan, Level I



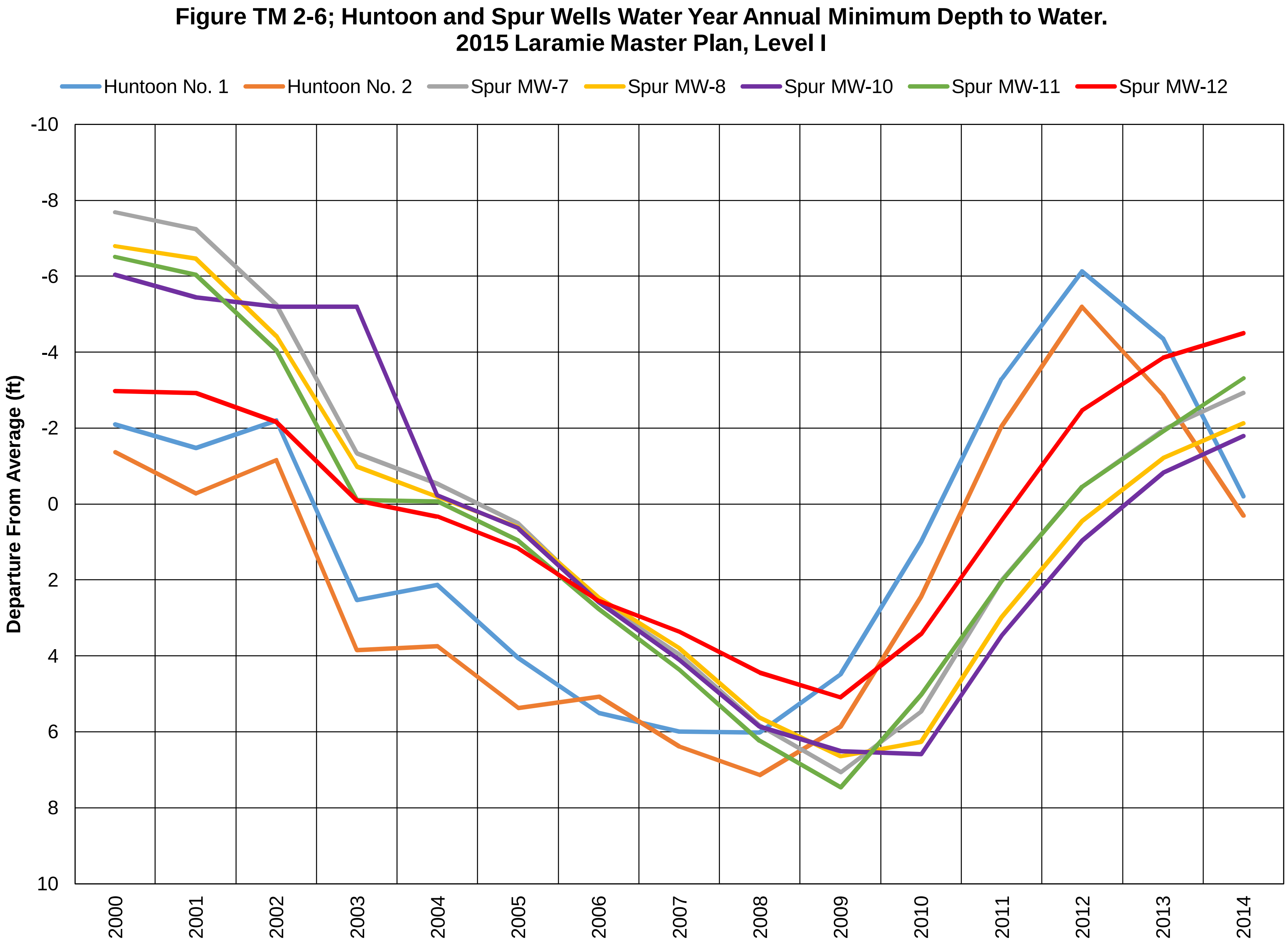


Figure TM 2-6; Huntoon and Spur Wells Water Year Annual Minimum Depth to Water.
2015 Laramie Master Plan, Level I
Huntoon No. 1
Huntoon No. 2
Spur MW-7
Spur MW-8
Spur MW-10
Spur MW-11
Spur MW-12
Departure From Average (ft)
-10
-8
-6
-4
-2
0
2
4
6
8
10
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014

Figure TM 2-7; Soldier Well Flow and Average "Huntoon Nos. 1 & 2" Monitor Wells Annual Minimum Depth to Water.
2015 Laramie Master Plan, Level I

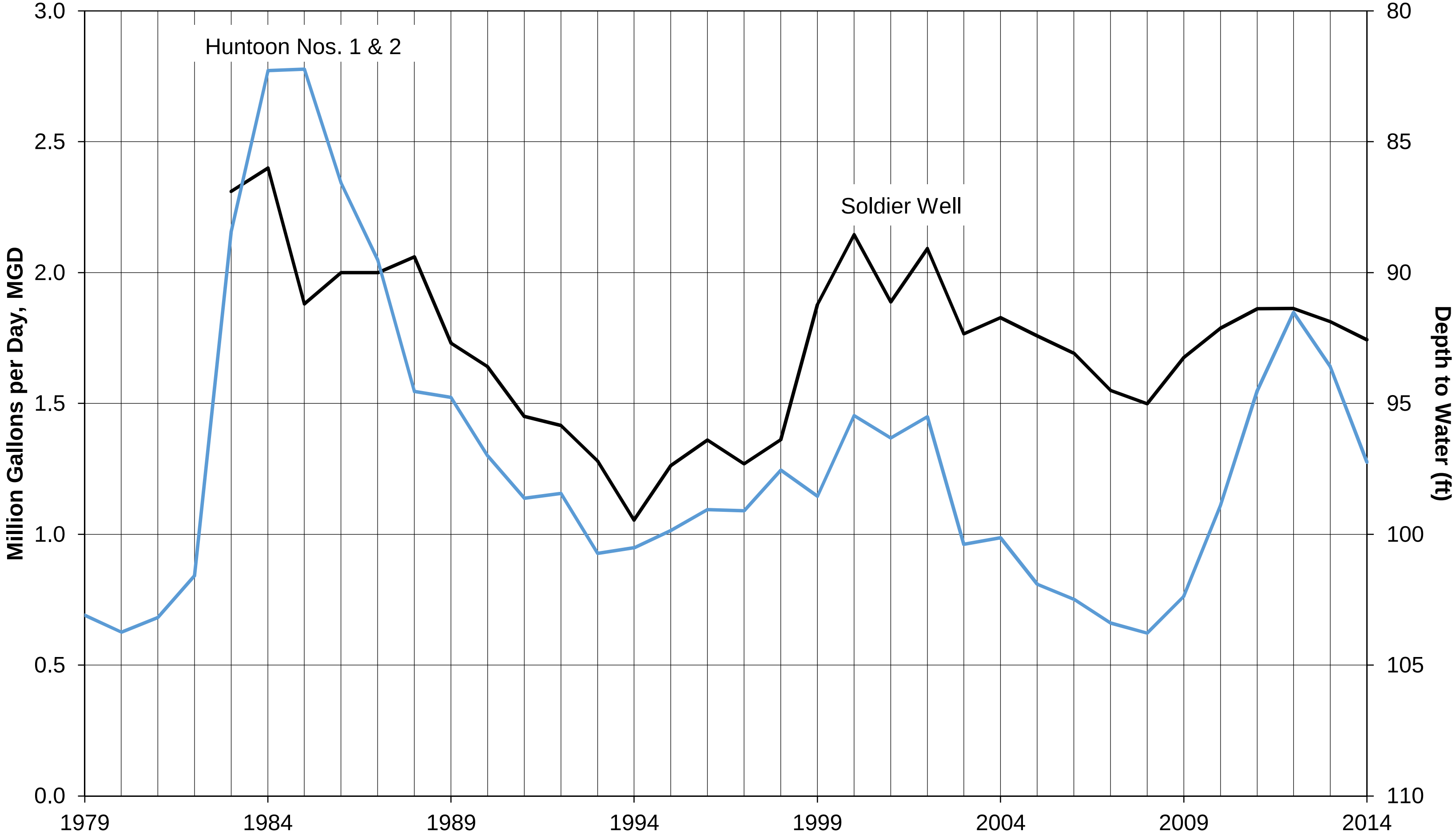
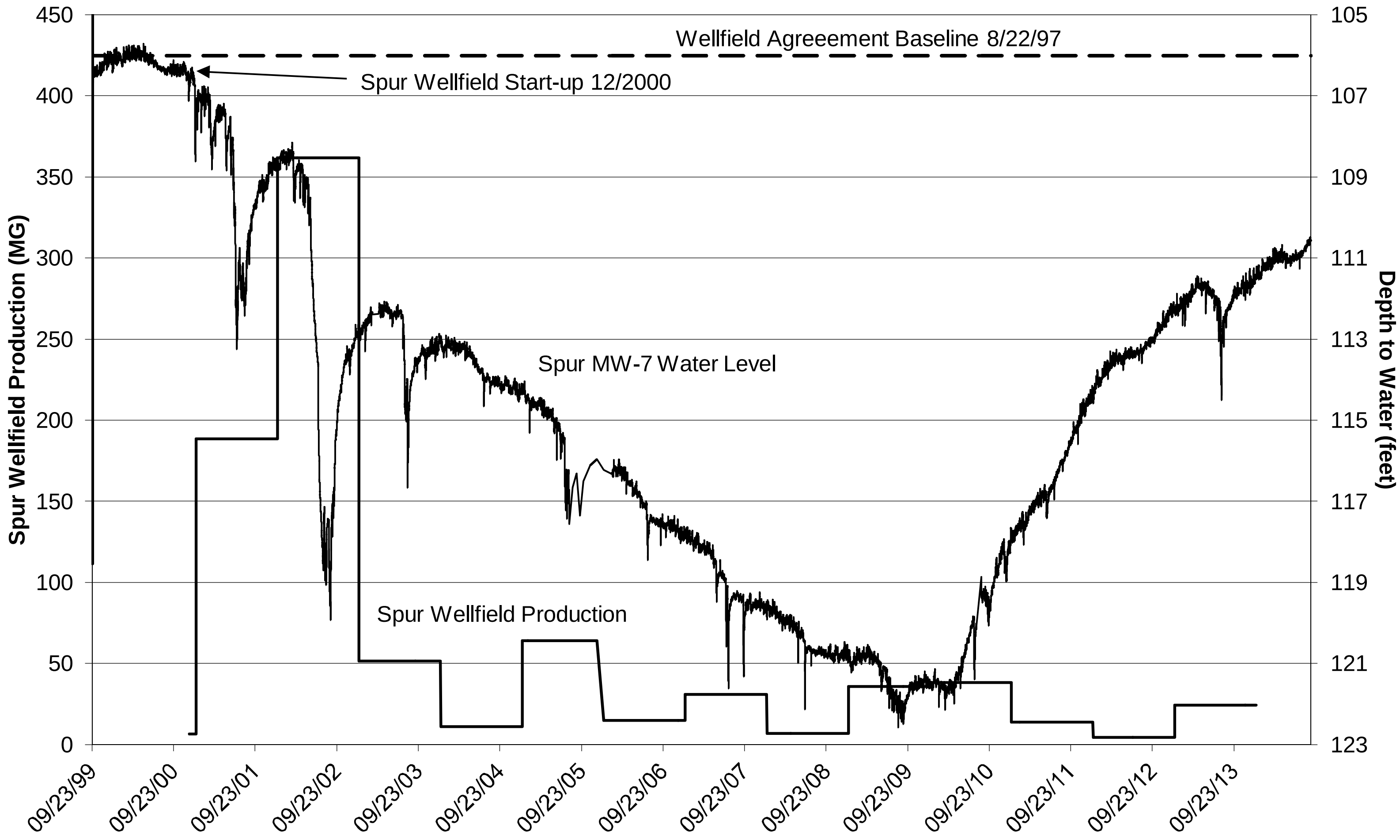
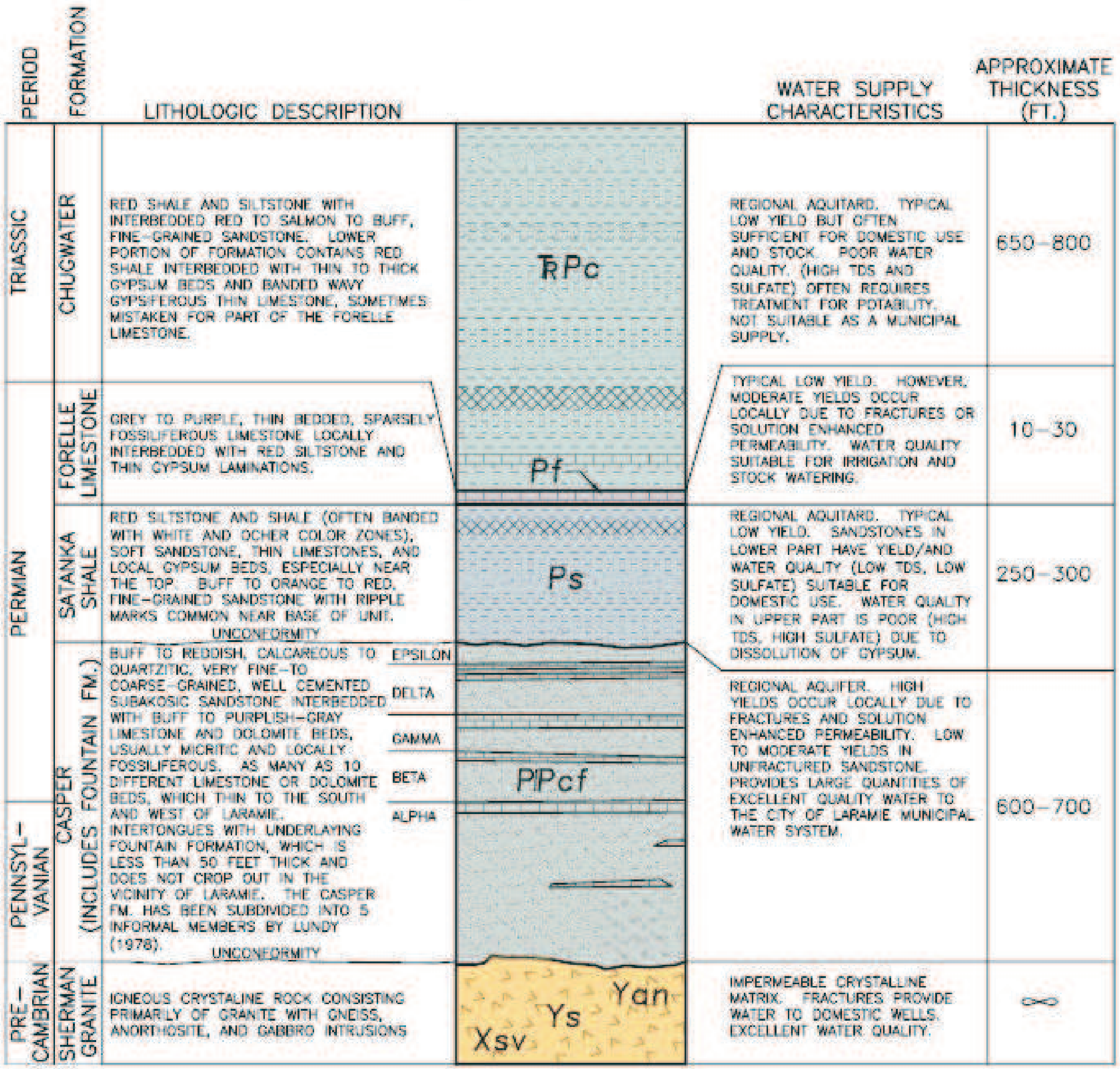


Figure TM 2-8; Hydrograph of Spur MW-7, 9/1999 to 9/2014.
2015 Laramie Master Plan, Level I



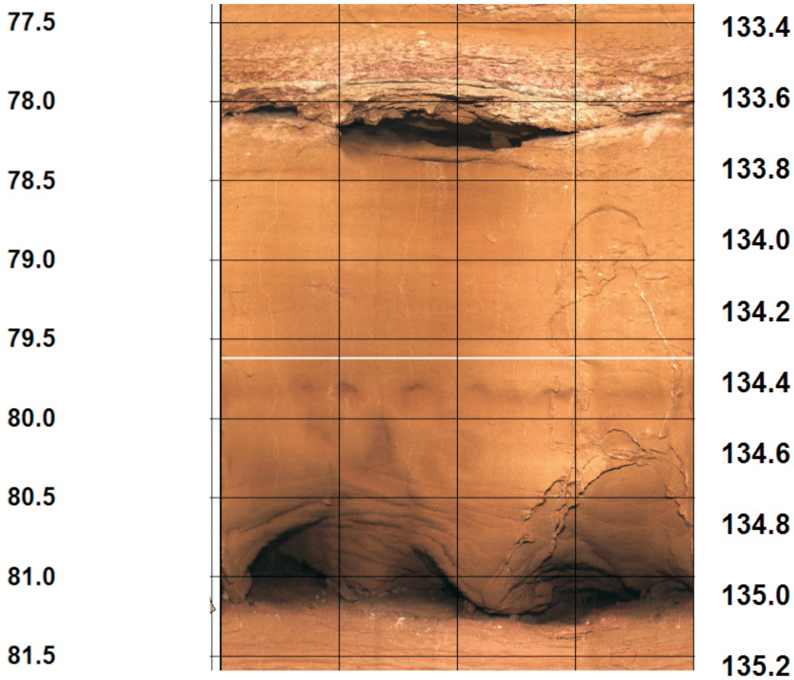


VERTICAL SCALE: 1"=300 FT.

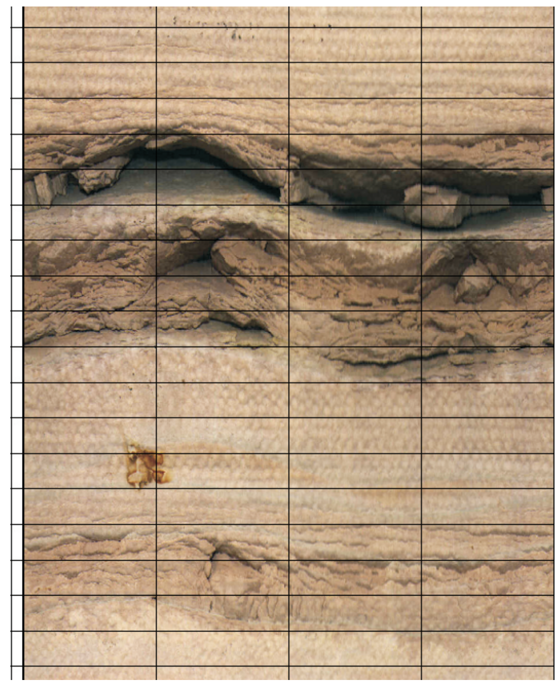
(WWC, 2006; Plate 10-1)

MODIFIED FROM LUNDY (1978)
LITHOLOGIC DESCRIPTIONS FROM VER PLOEG (1995, 1996, 1998)

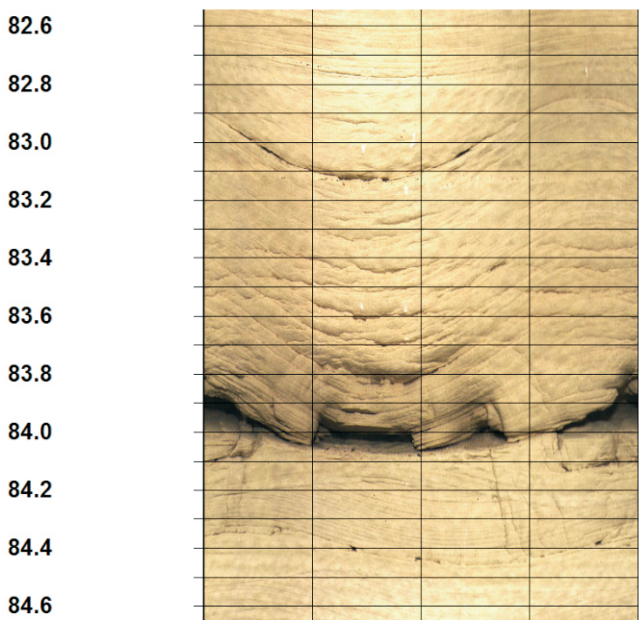
Figure TM 2-9; Generalized Geologic Column.
2015 Laramie Master Plan, Level I



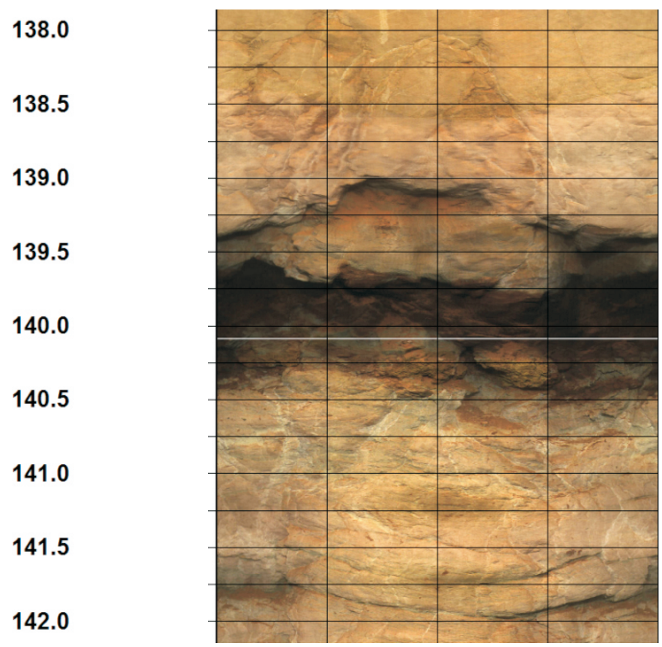
Bedding-plane opening
in South well



Bedding-plane opening
in North well



Bedding-plane opening
in Triangle well



Shale layer
in Middle borehole

Figure TM 2-10: Down-hole images from Laramie Monitoring Well Project - June, 2015 (vertical scale in feet)

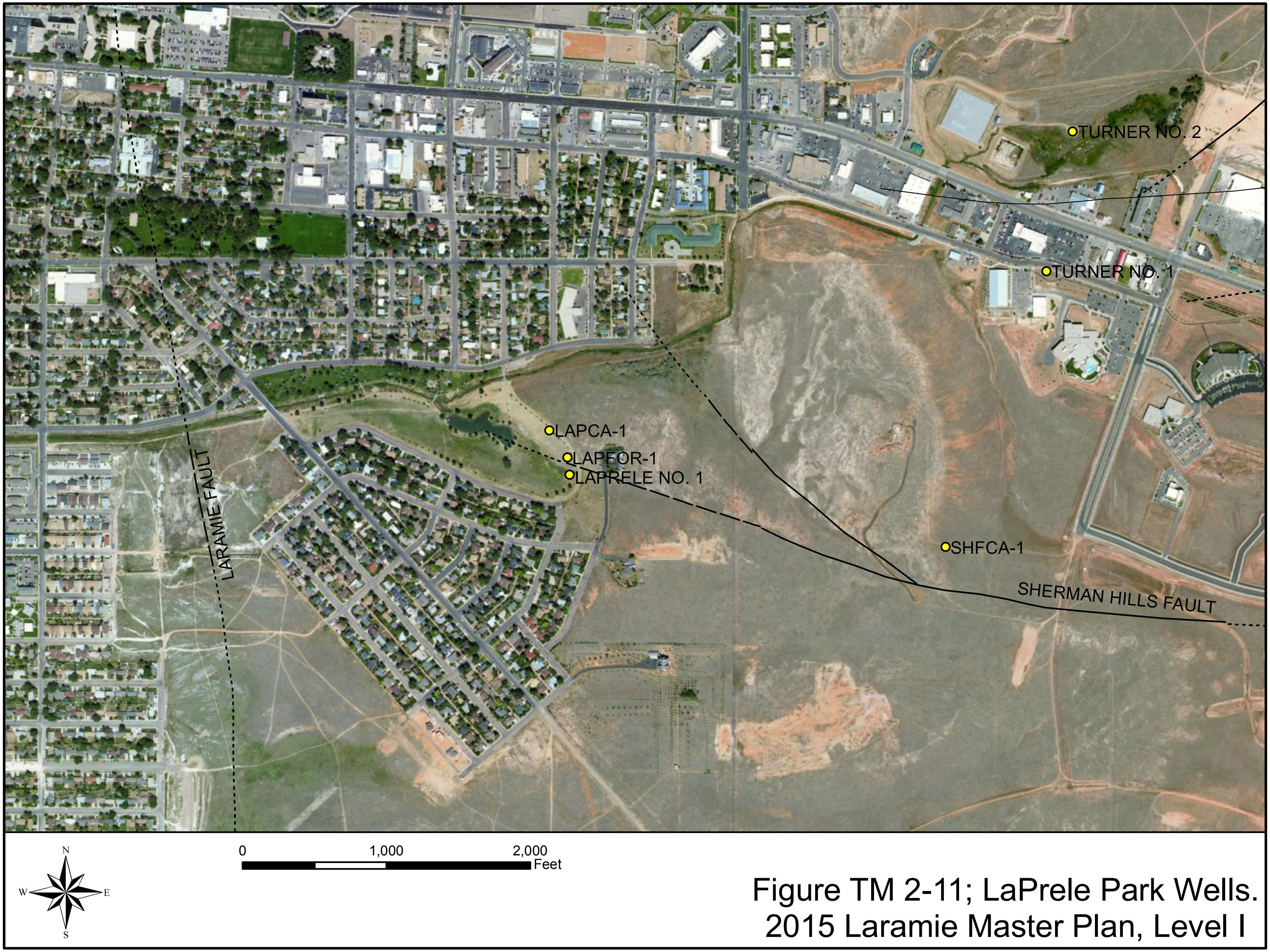


Figure TM 2-11; LaPrele Park Wells.
2015 Laramie Master Plan, Level I

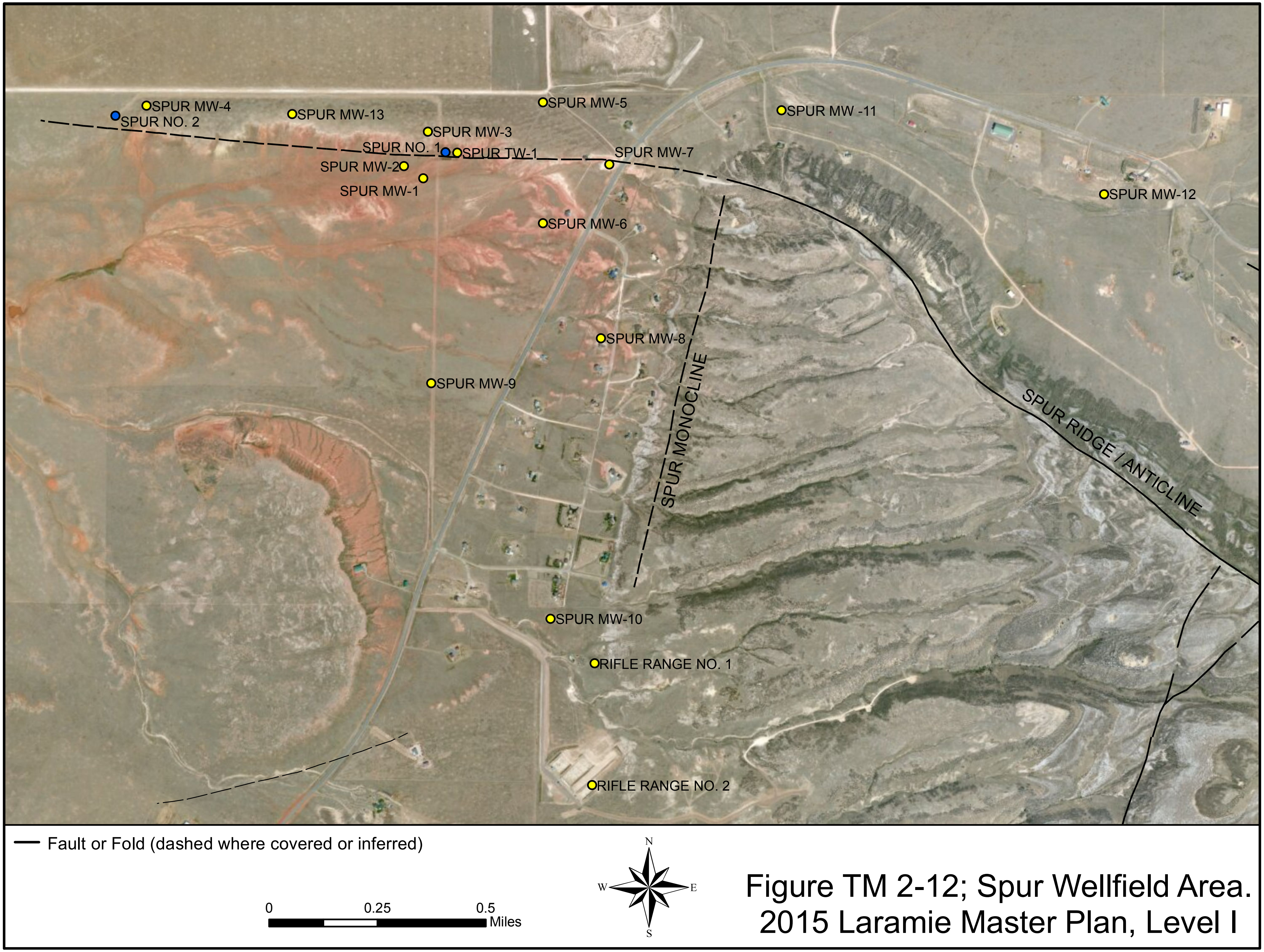


Figure TM 2-12; Spur Wellfield Area.
2015 Laramie Master Plan, Level I

Figure TM 2-13; Spur Wellfield Seasonal Production Distribution 2001 to 2014.
2015 Laramie Master Plan, Level I

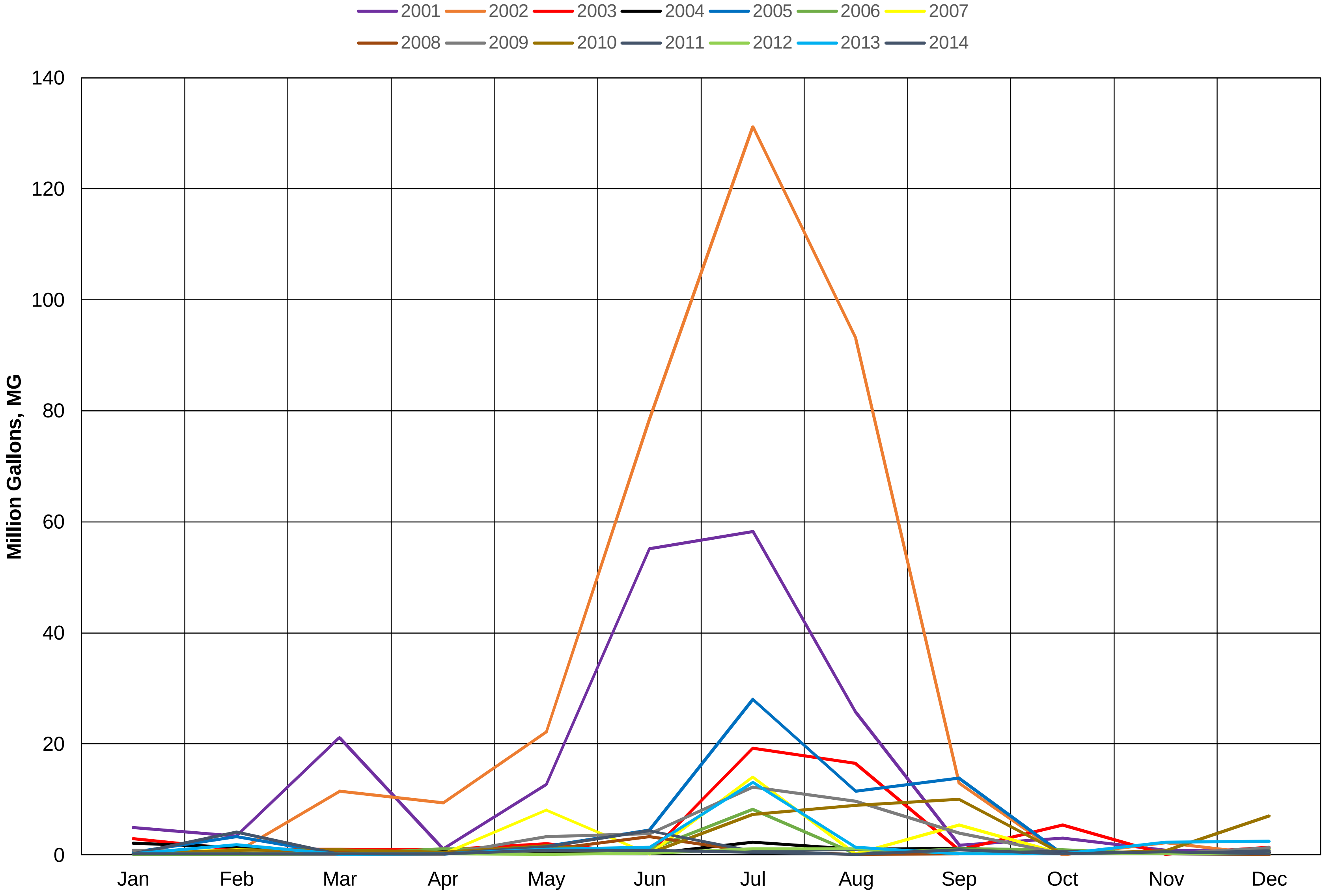
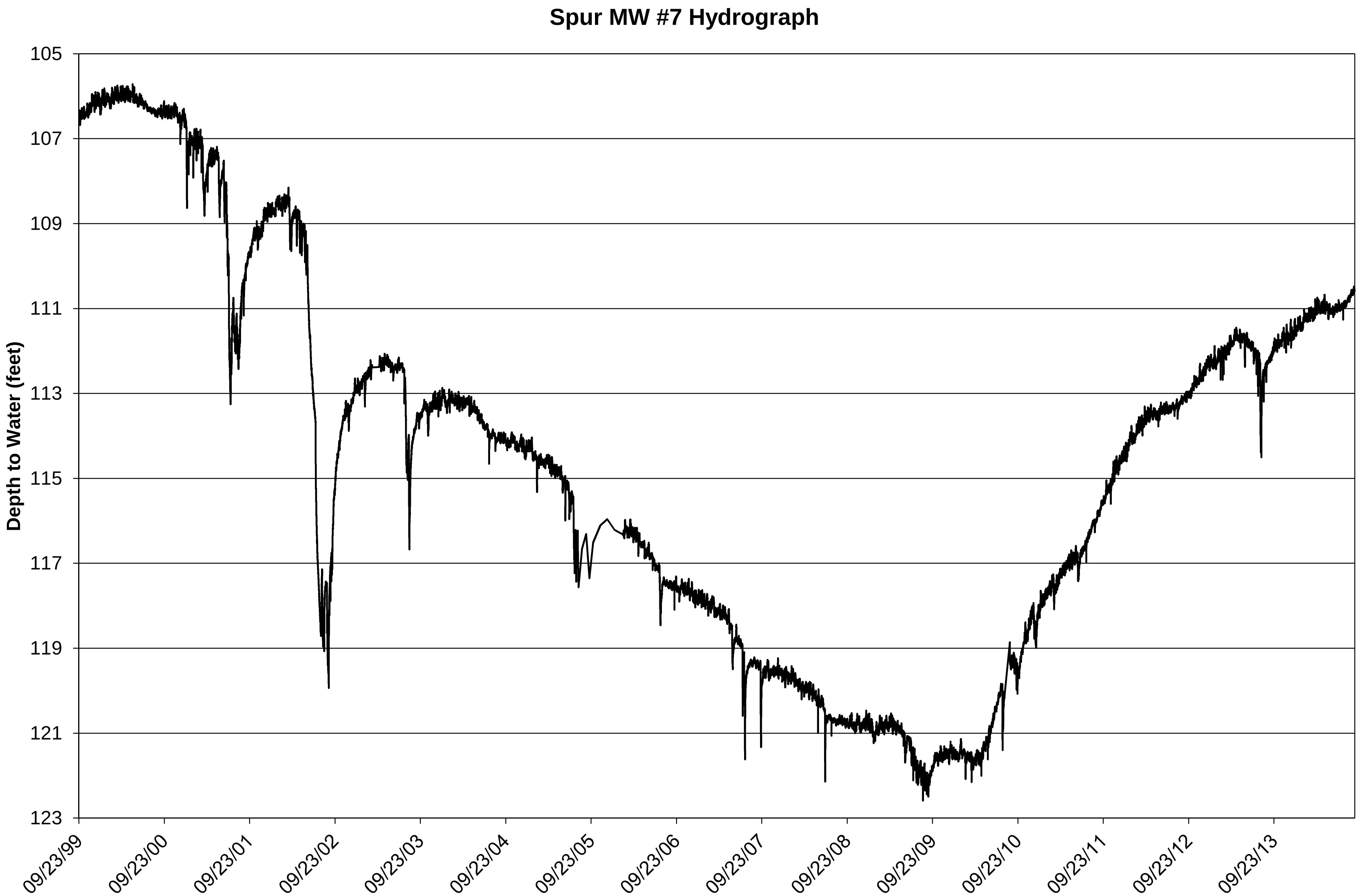


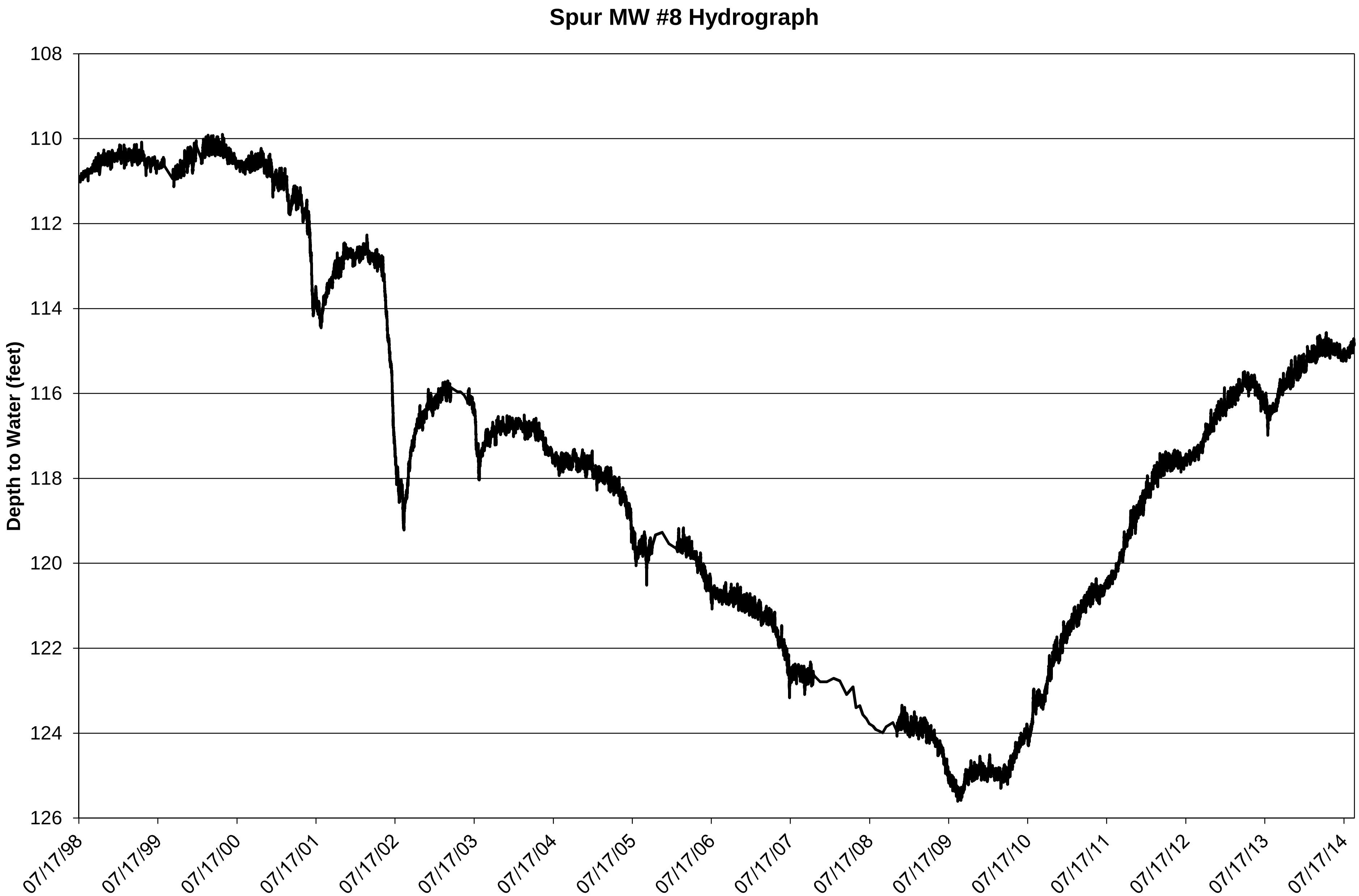
Figure TM 2-14; Simpson Wellfield Area.
2015 Laramie Master Plan, Level I

TECHNICAL MEMORANDUM NO. 2

ATTACHMENT 1

SPUR MONITOR WELL HYDROGRAPHS


Spur MW #7 Hydrograph
Depth to Water (feet)
105
107
109
111
113
115
117
119
121
123
09/23/99
09/23/00
09/23/01
09/23/02
09/23/03
09/23/04
09/23/05
09/23/06
09/23/07
09/23/08
09/23/09
09/23/10
09/23/11
09/23/12
09/23/13



Spur MW #8 Hydrograph
Depth to Water (feet)
108
110
112
114
116
118
120
122
124
126
07/17/98
07/17/99
07/17/00
07/17/01
07/17/02
07/17/03
07/17/04
07/17/05
07/17/06
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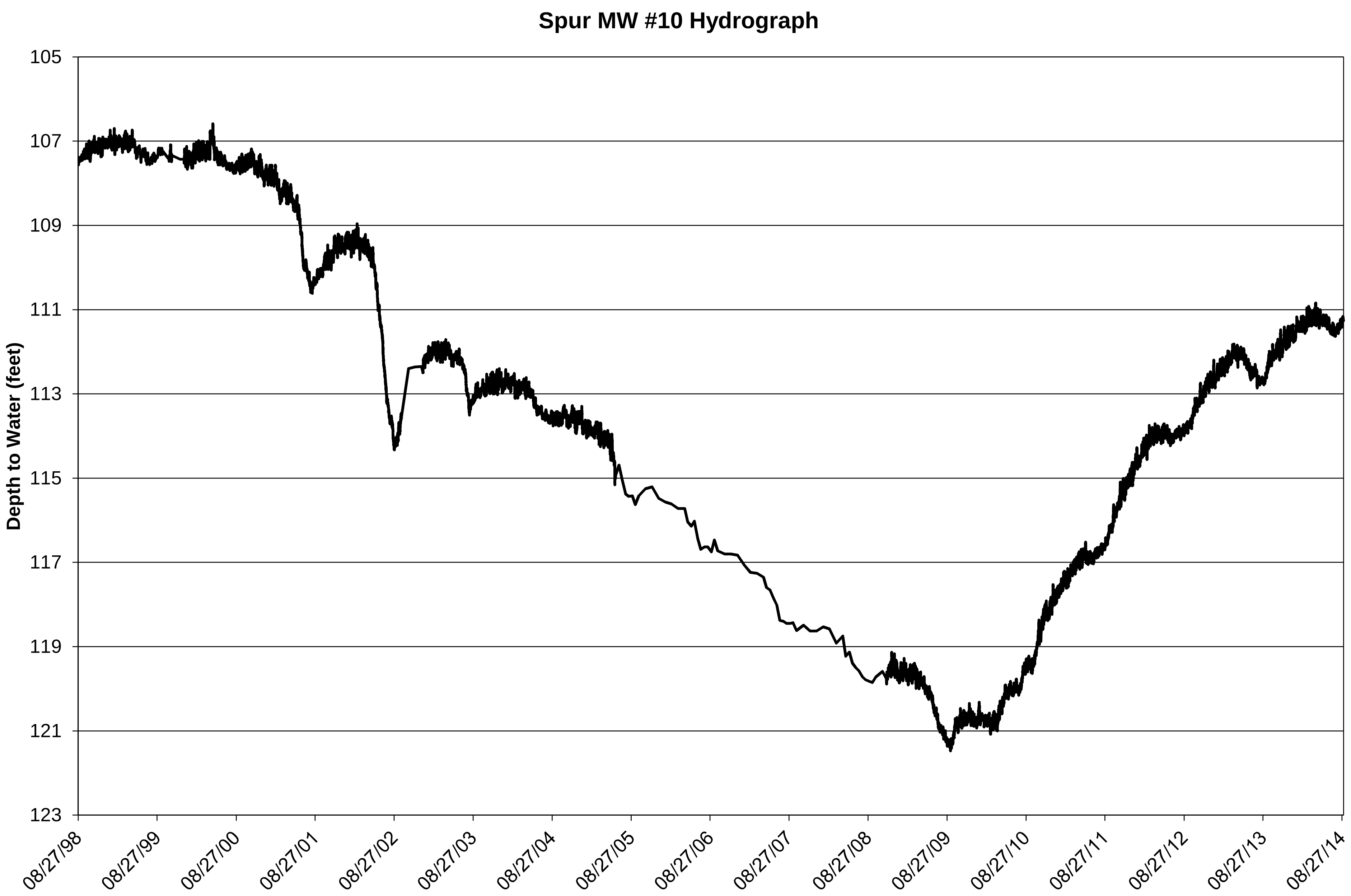
07/17/13
07/17/14



Spur MW #10 Hydrograph
Depth to Water (feet)
105
107
109
111
113
115
117
119
121
123
08/27/98
08/27/99
08/27/00
08/27/01
08/27/02
08/27/03
08/27/04
08/27/05
08/27/06
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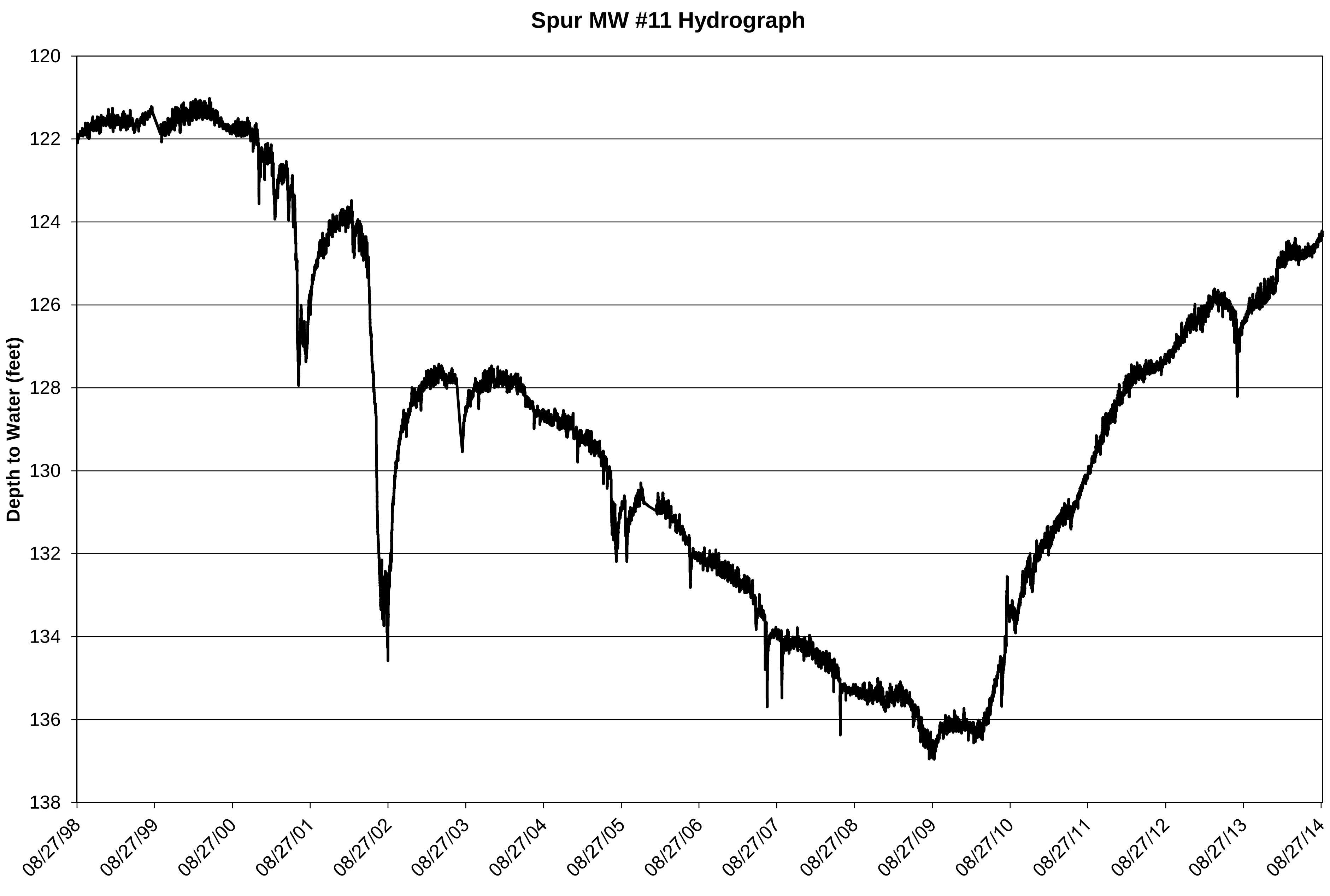
08/27/12
08/27/13
08/27/14


Spur MW #11 Hydrograph
Depth to Water (feet)
120
122
124
126
128
130
132
134
136
138
08/27/98
08/27/99
08/27/00
08/27/01
08/27/02
08/27/03
08/27/04
08/27/05
08/27/06
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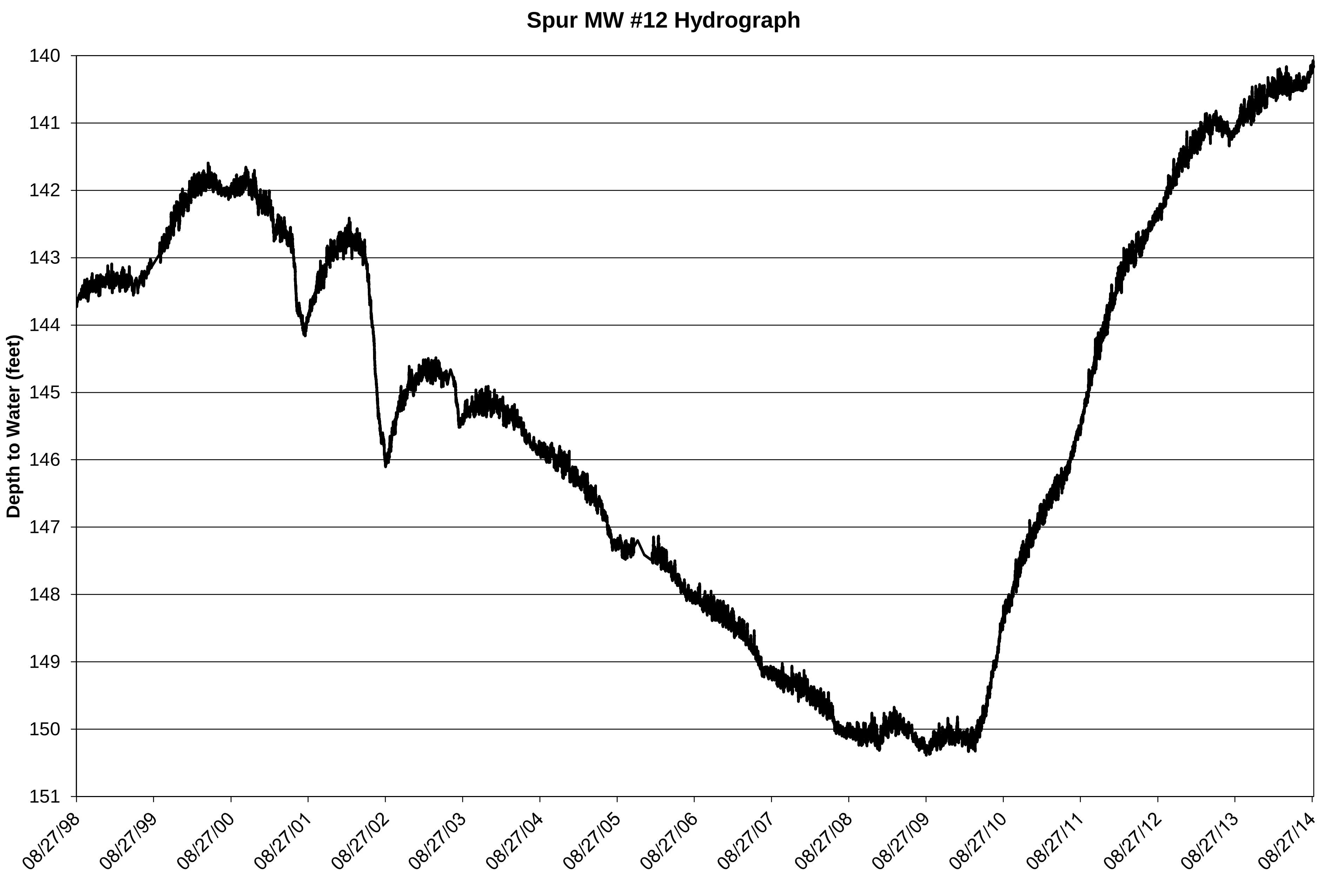
08/27/12
08/27/13
08/27/14


Spur MW #12 Hydrograph
Depth to Water (feet)
140
141
142
143
144
145
146
147
148
149
150
151
08/27/98
08/27/99
08/27/00
08/27/01
08/27/02
08/27/03
08/27/04
08/27/05
08/27/06
08/27/07
08/27/08
08/27/09
08/27/10
08/27/11
08/27/12
08/27/13
08/27/14