Groundwater Technical Memorandum No. 4
2015 Laramie Master Plan, Level I – Appendix 440

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City of Laramie
WWC Engineering

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FUTURE GROUNDWATER DEVELOPMENT AND USE

This technical memorandum is the last of a series of four regarding the groundwater supply of the City of Laramie. Companion memoranda discuss the history of City groundwater development and current groundwater production facilities, hydrogeology of the Casper Aquifer, and water quality and related City programs to protect and monitor the Casper.

This memorandum presents discussion that supports recommendations regarding the management and development of the City groundwater supply to meet future supply objectives. We begin with a review of the relevant considerations in development and expansion of a groundwater supply, summarize the conditions and opportunities at the three existing wellfields, and conclude with discussion of future potential locations for groundwater evaluation/development. This technical memorandum relies on and is developed from information provided in the previous three technical memoranda. References cited in this technical memorandum are listed in the "References" chapter of the main report.

I. Groundwater Supply Development Considerations

A groundwater supply can be thought of as a water reservoir. Like a surface reservoir, the groundwater aquifer has a storage volume, inflow rate, and discharge capacity. A small water reservoir, like a constructed storage tank, is used in municipal water systems to allow the steady daily production of a water treatment plant or wellfield to meet the instantaneous peaks in demand over the course of a day. A large tank may have sufficient capacity to meet a multi-day peak in excess of contemporaneous production capacity or to meet demands for a short period of time while the source is unavailable. Surface impoundments provide much larger storage capacity, and are commonly used in the same manner, to even out water supply from a stream that produces excess water in the spring, but insufficient water in the summer and fall. In some cases, surface reservoirs are large enough to provide multi-year leveling of demand, storing in high-water years and releasing in low-water years. The Casper Aquifer is most analogous to the latter type of surface reservoir, providing sufficient storage to accommodate multi-year drawdown and refilling cycles.

A water reservoir is limited by the rate of inflow. No matter what the storage volume, if the demand on the reservoir exceeds the inflow for a long enough period of time, the reservoir will be depleted. As presented in Technical Memorandum No. 2, the long-term average recharge to the relevant portion of the Casper Aquifer is on the order of 2.3 billion gallons per year.

Finally, a water reservoir is constrained by its discharge capacity. In the case of a surface reservoir, that capacity is controlled by valves and pipes. In the case of an aquifer, the discharge capacity is determined by the permeability of the aquifer – a highly permeable aquifer can produce large volumes of water quickly – and of the installed pumping capacity. In the case of the Casper Aquifer, certain locations have proven to be extremely permeable (e.g. the Spur Wellfield), leaving instantaneous discharge capacity constrained primarily by pumping and transmission facilities.

Table TM 4-1 provides a qualitative summary of relevant development factors for the existing wellfields. Factors summarized in the table can be used to evaluate wellfield development options. Terms used in the table are defined below.

"Availability" refers to the aquifer production characteristics and the existing groundwater production facilities at that location. Aquifer production depends primarily on permeability, which is quantified by transmissivity (T) and specific capacity (gpm per foot of drawdown) values. Availability may also be constrained by water rights and/or related production agreements. For example, the Spur Wellfield has the most transmissive aquifer (specific capacities of 440 – 580 gpm/ft) and a large installed pumping capacity (3,100 gpm), but also has production limits established by agreement.

The construction and design of City production wells are primarily the result of being located near existing or historical springs, immediately west of the contact between the Satanka Shale and the Casper Formation, and in areas of high permeability and geologic structure. Consequently, the wells are flowing or have a depth to water of less than 32 feet and have total depths that are less than half the saturated thickness of the aquifer. The notable exception is the Spur Wellfield which is not located near a spring or other surface water feature. In particular, Spur No. 2 is located approximately 1 mile west of the Satanka-Casper contact, which results in a considerable amount of artesian head (i.e. 227 feet) that can be pumped down if need be. This more westward location for a production well is highly desirable due to the increase in available drawdown (i.e. the pumping water level will not reach down into the aquifer) that significantly enhances well production potential and operation.

Availability is the result of a wide variety of variables, some of which can be manipulated to maximize instantaneous production and expand short-term supply. Well location and construction, pumping equipment, and aquifer hydrology affect the production capacity and run-time of a well or wellfield. For example, the casing diameter limits the size/capacity of the pump, and the static water level, pump set depth, and specific capacity of the well will determine the magnitude of available and actual drawdown (see Table TM 1–2). When the pumping water level approaches to within approximately 10 feet of the pump intake, the pump is set to automatically shut off. Ultimately, these engineering elements are shaped by aquifer hydraulics and long-term aquifer management objectives to define the final availability of the groundwater supply.

"Efficiency" refers to the energy (i.e. expense) of withdrawing water from the aquifer and delivering it into the municipal water supply. The Soldier No. 1 well is ideal in this regard, as the artesian flow from the well is approximately 1,300 gpm and there is sufficient elevation drop from the wellhead to the low-level reservoir to provide free flow into the municipal system. Least efficient in this sense are wells with lower specific capacities (e.g. Turner No. 1 and Turner No. 2) from which water must be pumped to the surface from greater depth. As shown on Table TM 1-2, the depth to water during pumping in City production wells is typically less than 50 feet, with a maximum of approximately 75 feet. In practical terms, all of the City wells are efficient, but relative comparisons between wells can be made and dollar differences added up.

"Conflicts" refers to other uses of the aquifer with which City groundwater production may conflict. The Turner and Soldier-Pope wellfields are located at the site of historical springs. Aggressive production at these wellfields reduces the volume of water flowing from natural springs that feed local streams. This can be both a water-rights issue, e.g. if there are downstream senior rights that must be satisfied, and an aesthetic/environmental issue, as it would be undesirable to reduce streamflow to the point of impacting habitat or recreational values. Additional City production may generate concern from local groundwater users (e.g. domestic wells) that water levels will decline and affect their ability to extract groundwater efficiently. The Spur Wellfield Use Agreement is a manifestation of such concerns. For the most part, the water-production characteristics of the Casper Aquifer and the water-rights configuration for the associated springs/streams/wells are such that these concerns can be accommodated without significant limitation of municipal groundwater production.

"Quality Issues" refers to aspects of a wellfield and wellfield management that may impact water quality. Of particular concern here is the relationship between springs and wells, in that natural springs represent communication between the aquifer and surface sources of bacteriological and other potential contaminants. At Turner (City Springs) and Soldier Spring, for example, it would be desirable to maintain sufficient discharge facilities to prevent groundwater from surfacing and thus eliminate the potential to introduce contaminants into the aquifer when the wells are pumped at high rates. The Groundwater Under the Direct Influence of Surface Water section in Technical Memorandum No. 3 provides a discussion of this issue.

A relative ranking of the four wellfields using Table TM 4-1 depends on management priorities and objectives. The current dependence on the Soldier No. 1 well is an obvious first rank given its productivity and efficiency under free-flow conditions and its relatively low potential for use conflicts. If the long-term potential of the Spur Wellfield can be verified (discussed further below), it may be the "best" of the pumped production options due to its very high productivity, small drawdown and relatively undeveloped

Table TM 4-1: Groundwater Development Factors and Conditions at Existing Wellfields			
Wellfield	**Factor**	**Advantages**	**Disadvantages**
Spur	Availability	very high aquifer T; high-capacity wells	
	Efficiency	small drawdown	no free flow
	Conflicts	no streamflow impact	Use Agreement constrains daily and annual max. prod.
	Quality Issues	no concern with surface influence; minimal development in recharge area	
Turner	Availability		Relatively low aquifer T; production limited by well design
	Efficiency	some artesian flow from Turner No. 2	relatively low
	Conflicts		Potential impacts to Spring Creek
	Quality Issues		concern with surface influence; in area of urban development
Pope	Availability		hydraulic connection with Soldier Spring
	Efficiency		no free flow
	Conflicts	no streamflow impact	
	Quality issues	no concern with surface influence	downgradient of I-80
Soldier	Availability	high aquifer T	pipeline capacity limited
	Efficiency	high artesian flow	
	Conflicts		minor streamflow impact
	Quality issues		potential concern with surface influence

recharge area and the complete absence of surface-water conflicts.

II. Opportunities for Expanded Production and Improvement of Existing Wellfields

Table TM 4-2 presents an approximate comparison between the overall groundwater flow through the Casper Aquifer in the study area (data from Table TM 2-1) and the current

Table TM 4-2 Groundwater Total and Current Development (average mgd)						
Area			Groundwater Withdrawals		Remaining Available	Notes
	Total Groundwater Flow		Municipal	Other users		
Spur			0.07	Included below	1.0	2003-2014 avg City production
	Springs/wells	0.07				No springs
	Leakage discharge	0				No streamflow
	Underflow	1.0				
City Springs / Turner			0.74	Included below	1.0	2003-2014 avg City production
	Springs/wells	1.6				
	Leakage discharge	0.16				Spring Creek
	Underflow					Included below
Soldier-Pope			1.82	Included below	0.3	2003-2014 avg City production
	Springs/wells	1.82				
	Leakage discharge	0.3				Soldier Creek
	Underflow					Included below
Simpson Springs			0	(small)	??	
	Springs/wells					Simpson Creek
	Leakage discharge	0.28				Simpson Creek
	Underflow					Included below
General			0	0.97	??	Subdivisions, institutions, and commercial fac.
	Springs/wells	0.97				
	Leakage discharge	??				unknown
	Underflow	0.53				All but Spur area
TOTALS		**6.73**	**2.63**	**0.97**	**2.3**	

state of groundwater development. The listed values are a combination of careful measurements (e.g. City production) and general estimates (e.g. underflow), with a bias toward lower values to be conservative.

It is impractical and perhaps undesirable (e.g. Spring Creek flow) to capture the entire groundwater flow of the aquifer, but the table indicates substantial additional development potential. The "available" column suggests three quantities worthy of consideration and perhaps further investigation: 1) the underflow in the Spur area; 2) the unused flow of City Springs (leaving the subsidiary flow feeding Spring Creek through the springs discharging from the Satanka Shale/Forelle/Chugwater); and 3) the remaining streamflow at Soldier Spring. In all cases, there is installed pumping capacity to increase production were such increases determined to be compatible with other water-supply management objectives.

The groundwater development factors identified in Table TM 4-1 and the quantity of "available" water specified in Table TM 4-2 are used in the following sections to explore additional water supply options at the Spur, Turner, and Soldier-Pope wellfields. The reader should recognize that the following discussion on groundwater development is in the context of the physical availability of the resource. Water rights pertaining to the administration and limitations of groundwater use by the City are discussed in Appendix 400 and may require adjustment/expansion to accommodate future development of the resource.

Spur Wellfield

The Spur Wellfield is the most productive wellfield in terms of large available production rates, small drawdown, and total available drawdown. Although the currently installed pumps produce a combined discharge of 3,100 gpm, the aquifer is clearly capable of several times that much on a short-term basis were sufficient additional pump and pipeline capacity installed. With their high specific capacities, neither of the two Spur wells uses a significant portion of the available drawdown at their design 1,560 gpm discharge rates (see Table TM 1-2).

The Spur wells experience so little drawdown at production rates of 1,560 gpm that the pumping water levels in both wells are significantly above the pump intakes. These wells can be pumped simultaneously for as long as needed. A favorable design element of Spur No. 1 is that the bottom of the casing is set 37 feet into the top of the Casper Aquifer (i.e. into the epsilon sandstone which is 64 feet thick) thereby allowing even more drawdown, if needed.

Spur No. 2 is perhaps the ideal Casper Aquifer well. It not only has a very high specific capacity (440 gpm/ft), but it is located far enough west that the Casper Aquifer would remain fully saturated even if drawdown in the well was 227 feet. All other municipal wells are located where the top of the Casper Aquifer is much closer to the ground surface. The drawdown available at other City production wells before beginning to de-water the aquifer ranges from 22 to 103 feet.

Particularly in fracture-dominated aquifers, specific capacity values typically decline with increased discharge rate. However, the specific capacity at the Spur No. 2 well could be reduced by 90% and the well would still be capable of producing over 10,000 gpm before beginning to de-water the aquifer.

Instantaneous production capacity at the Spur Wellfield is presently constrained only by the size of the installed pumps, the diameter of the well casings (16-inch will only accommodate a certain size pump), the number of wells (2), and the capacity of the 18-inch transmission line into Laramie which can accommodate approximately 4,200 gpm.

Additional short-term production, if desired, is available through an increase in production/transmission line capacity. Larger capacity pumps could be installed in both existing wells to "max out" the transmission line capacity of 4,200 gpm, providing an additional 1,100 gpm (1.6 mgd) production capacity. Production could also be enhanced by additional wells, but only if the transmission line capacity were also increased. Any additional wells in the Spur Wellfield should be located along the western extrapolation of the Spur geologic structure (i.e. anticline) to take advantage of the larger available drawdown in that direction.

Long-term average production at the Spur Wellfield is constrained by estimated values for groundwater flux westward into the basin and aquifer recharge rates. As discussed in Technical Memorandum No. 2, this aspect of the Spur Wellfield has not been thoroughly evaluated. Basic recharge and groundwater flux calculations suggest a sustained physical availability of approximately 474 - 550 mg/yr (1.3 - 1.5 mgd average).

Unfortunately, the initial period of Spur Wellfield operation, from 2001 to 2009, occurred during a pronounced period of drought and low aquifer recharge, with an associated decline in water levels. During this time period, wellfield production was believed to have significant and long-lasting effects on water levels in the Spur area. Concerns with the lack of full water-level recovery following the initial testing of the wells and following the large production of 2002 are legitimate, but appear to have been confounded by significant natural declines in water levels over the same time period. Climatic and water level data over the last five years indicate that the perception of hyper-sensitivity of the Spur area to production is probably not correct (see Technical Memorandum No. 2).

At present, the Spur Wellfield is legally constrained to a maximum of 391 mg/yr, to be withdrawn at a maximum rate of 4.0 mgd, and both of these values are reduced if drawdown at specified monitor wells exceed threshold values. The agreement stipulates that these constraints can be re-examined and potentially adjusted in 2020.

Given the present situation of historically high aquifer water levels (see Technical Memorandum No. 2) and the impending re-examination of the Spur Wellfield Use Agreement, we recommend an aggressive program of aquifer evaluation at the Spur over the next few years to better define the response of the aquifer to pumping and to prepare for agreement re-examination. In coordination with other water-supply priorities, an extended period of maximum allowable production from the Spur wells into the municipal supply system, accompanied by continued monitoring of water levels using the existing monitor wells and equipment, would be ideal. The 4.0 mgd daily production limit would allow 90 days production within the annual volumetric cap.

The current relatively high natural water levels in the aquifer are particularly well suited to this type of exercising of the Spur Wellfield without triggering Use Agreement-based reductions in wellfield production. Recognizing the limitations of theory-based projections of wellfield performance, the solid, empirical evidence from an extended period of production is critical to an improved understanding of the potential of this water-supply asset.

Turner Wellfield

Of all the City wellfields, the Turner Wellfield is the most problematic, with potential for improvement and/or reconsideration. Operational issues associated with limited run-times are caused primarily by well design, high pumping rates, and limited aquifer hydraulics. Water quality concerns are associated with the wellfield's location near the springs, the periodic recycling of surface water back into the aquifer during pumping, and breaches in enclosure[1] security by wildlife. The wellfield is also located within the City limits and is the most vulnerable wellfield to contamination from existing and future land use and development.

For the Turner Wellfield to remain viable into the future, local land use decisions should take into account potential water quality impacts (i.e. aquifer protection), enclosure security should be improved, and production from the Turner wells and the subsurface drainage system should be modified to better eliminate/control the discharge of groundwater to the surface within the enclosure.

The Turner wells, individually and in combination, are operated at high pumping rates despite their relatively low specific capacity. Drawdown during pumping reaches the available drawdown threshold and the wells are shut off after an extended pumping period, with reduction in run-times of subsequent pumping periods as a result of incomplete aquifer recovery. Run times could be extended if the well casings were set deeper into the aquifer, the pumps lowered, and the available drawdown thus increased. Turner No. 2's casing and pump are set 24 feet into the epsilon member, thereby maximizing available drawdown at this well. Were the bottom of the Turner No. 1 well casing also set at the middle of the epsilon member (i.e. to a depth of approximately 135 feet) and the pump lowered accordingly, the available drawdown would be increased by 45 feet (a 49% increase), and run-times at current production rates would be significantly increased. This redesign of Turner No. 1 would require the installation of a new well offset from the existing well.

[1] The "enclosure" refers to the fenced area around the Turner No. 2 well, the low-level reservoir, and the historical City Spring. In the absence of pumping, groundwater emerges at the surface in this area.

An alternative wellfield operation strategy using the existing wells would be to reduce and/or modify the pumping rates of the Turner wells. Rather than "maxing out" production from the wellfield, an alternative approach would be to pump at rates that 1) allow longer periods of simultaneous well operation and 2) eliminate the discharge of groundwater to the surface within the enclosure. Any reduction in peaking capacity of the Turner Wellfield under this operation strategy could be supplemented by the Spur Wellfield.

Alternatives designed to protect water quality and maintain viable production at the Turner Wellfield are listed below.

- Install variable frequency drive (VFD) motor controls in the Turner wells. Pumping rates in the Turner wells could be adjusted to extend simultaneous run times and to maintain the head in the aquifer below ground surface. At a minimum, the pumping rate at Turner No. 1 would probably be reduced.

- Install a wet well adjacent to Turner No. 2 at an elevation low enough to prevent groundwater surfacing in the vicinity of the well (i.e. analogous to the Soldier No. 1 completion). A small booster pump could deliver water flowing from the well into the low-level reservoir, thus taking full advantage of the free flow of the well without having to operate the primary, high-capacity submersible pump in the well.

- Install shallow pumping wells distributed in the enclosure designed to lower the head in Casper below ground surface and provide additional wellfield operation flexibility as described by WWC Engineering (2006).

- Install a passive system designed to prevent the discharge of groundwater to the surface that may include:
    - a new subsurface groundwater collection system
    - elevate the grade in the enclosure using imported fill
    - modify Turner No. 2 to enhance artesian flow from the well

These alternatives are not evaluated in this Master Plan study, but are presented here as initial considerations in a subsequent study that would thoroughly evaluate how to protect water quality and optimize production from the Turner Wellfield. Issues that would need to be resolved in a subsequent study are: 1) what to do with excess water from the Turner Wellfield, 2) how best to maintain the head in the Casper below ground surface, and 3) optimal operation strategy in consideration of the overall water supply.

As discussed in Technical Memoranda No. 1 and No. 2, the annual extraction of groundwater from the Turner wells is substantially less than the natural discharge of City Springs. Additional groundwater from this wellfield is available for extraction by the City. However, under the current condition of low demand, and in particular very low demand during the late-fall/winter/early spring, there is little demand for additional groundwater for much of the year. Operating the Turner well(s) at some low rate continuously may achieve the objective of maintaining the aquifer head below the ground surface and eliminate the discharge of groundwater from the pipe-springbox collection system and reduce the potential to recycle water between the ground surface and the wells. However, this may generate a surplus of supply during the winter and require adjustments in production from other elements of supply (e.g. surface water treatment plant, Soldier No. 1) to prevent the perception that water is being wasted.

An operational scheme to consider is seasonal operation of the Turner Wellfield. For example, do not pump the Turner wells during the late fall/winter/early spring. During this period the Turner No. 2 well flows into the low-level reservoir and the pipe-springbox collection system discharges surface and near-surface groundwater from the enclosure into Spring Creek. Because the wells are not pumped, there is no potential recycling of surface water back into the aquifer during this period. In the spring or early-summer, the Turner wells are turned on and remain on continuously throughout the high demand summer season. Pumping rates could be adjusted using VFDs to eliminate any discharge of groundwater from the pipe-springbox collection system. In the late-summer or early-fall, the Turner pumps are shut off and remain off until next spring. In this manner, there is only one period during the year that surface water in the enclosure is potentially recycled back into the aquifer (i.e. when the area is first "dried up" in the spring or early-summer). Although this is still not optimal, it is an improvement and may be considered more practical than the current operation.

A series of controlled tests should be conducted whereby the pumping rates of the Turner wells are altered to address two production-rate questions: 1) what is the minimum sustained pumping rate necessary to eliminate discharge from the pipe-springbox collection system; and 2) what is the maximum pumping rate that can be sustained within the available drawdown of the existing wells. VFDs would still allow currently available short-term maximum production, if needed, although the suggested operational approach would emphasize the use of the Turner Wellfield as a continuous supply rather than as a peaking supply. Evaluation of sustained production from the Turner wells as a way to minimize the potential for surface water/groundwater communication would also provide opportunity to observe the impact of such an operation on the downstream flow of Spring Creek.

<u>Soldier-Pope Wellfield</u>

As discussed in Technical Memorandum No. 1, the Soldier No. 1 and Pope wells are in close hydraulic connection. The Pope wells have the advantage of having no significant contact with surface water and some of the wells have relatively modest specific capacity. Production (or run time) from the Pope wells could be increased through reconstruction to provide modest increases in available drawdown as described above for the Turner No. 1 well. However, given the hydraulic interaction between the Pope and Soldier wells, in terms of both the aquifer and the transmission pipeline, and the high-production of the Soldier No. 1 well, it may not be cost effective to invest in additional production capacity at the Pope wells.

The primary advantage of the Soldier No. 1 well relative to other components of the groundwater supply system is the availability of substantial artesian flow. As presently operated, the well captures a substantial percentage of the natural artesian flow. Pumped production is avoided in order to prevent occurrence of a non-flowing or reduced flow period during recovery after pumping. Primary use of artesian flow ensures a continuous delivery of water to Laramie without the expense of pumping and risk of supply interruption due to a power failure.

When pumped, Soldier No. 1 produces 2,300 gpm with approximately 12 feet of drawdown (i.e. specific capacity of 191 gpm/ft). Given the location of the well screen at 44 feet, current pump setting at 40 feet, and transmission pipeline capacity limitations, there is no apparent reason to enhance production capacity by modifying or lowering the pump. Soldier No. 1 capacity and operation appears to be optimum.

The performance of Soldier No. 1 clearly identifies an area of highly favorable aquifer permeability, indicating the opportunity for additional production capacity through construction of additional wells. There is a modest opportunity of increased long-term average production at Soldier Spring if the City were to capture the entire flux through the aquifer in that area. Such an approach would have to be weighed against the obvious advantages of the current artesian flow system in the context of overall municipal water demands, alternatives for increased supply, and the condition and capacity of the Soldier-Pope transmission pipeline.

The continuing discharge of the Casper Aquifer to the natural spring location at Soldier Spring clearly demonstrates the availability of additional groundwater from this site, but development of that potential would have to be coordinated with a host of related operational and water right related issues, so is currently a low priority.

<u>Aquifer Storage and Recovery</u>

Aquifer storage and recovery (ASR) involves the storage of surplus water in an aquifer by injection and the later retrieval of the water by pumping. ASR is an innovative and potentially powerful tool for aquifer management in response to temporary supply/demand imbalance. The Laramie Water Management Plan (WWC Engineering, 2006) introduced the potential use of ASR for injecting surplus water from the Turner Wellfield (e.g. were a continuous operation established to achieve water-quality goals or simply to capture all available groundwater) into the Spur Wellfield, for subsequent retrieval during peak use periods.

The ASR concept at the Spur Wellfield was further investigated by Jehn Water Consultants (2010) by a 5-day injection test that indicated no adverse changes in water quality as a result of the test. Modeled predictions of water level rises from injection were noticeably less than water level rises actually measured in wells outside of the immediate test area. Recommendations were provided regarding improvement of the MODFLOW model should there be interest in further development of this concept.

Both drawdown (WWC, 1997c) and injection (Jehn Water Consultants, 2010) tests demonstrated that large volumes of water can be removed from or injected into the Casper Aquifer in the Spur Wellfield with small changes (less than 5 feet) in aquifer water level. Infrastructure at the Spur Wellfield is conducive to the application of ASR. For example, TW-1 (see Figure TM 1-5) could serve as a well-positioned up-gradient injection well, Spur No. 2 could serve as a downgradient withdrawal well, and there is an extensive network of monitor wells in place to document hydraulic responses. The Spur pipeline would allow water from the City to be conveyed to and from the Spur Wellfield.

The element of a successful ASR project which has not yet been evaluated is the recovery efficiency of the overall injection/pumping cycle. Two extremes illustrate the point: 1) if the storage vessel were a steel tank, it would readily accept water and one could count on all the water added being available at some later time of demand; and 2) if the storage vessel were a river, it would readily accept water, but the water would be long gone before some later time of demand. Given the very high transmissivity of the Spur area, we have some concern that the Casper Aquifer may behave somewhere between the two extremes with a tendency towards the latter. The recovery efficiency issue should be addressed in any future evaluation of ASR potential at the Spur.

Current high water levels in the Spur area and the absence of a need to maximize the recovery of groundwater to meet demands greatly reduces the immediate need to implement or further develop the ASR concept. However, there may be other water system management objectives that ASR could facilitate. For example, the Spur Wellfield could receive system water in the winter in an effort to reduce the water age in the distribution system. With ASR being used to address a distribution system water quality issue, a lower efficiency in the subsequent recovery of that water may be justified.

III. Aquifer Management Strategy

At present, the general approach to aquifer management has been to capture the artesian flow from Soldier No. 1 on a continuous basis, then add pumped production from the Turner and Soldier-Pope wells as needed to supplement production from the surface water treatment plant. The Spur Wellfield is rarely used. The overall philosophy is to maintain aquifer storage as high as possible as insurance against a sustained deficit in surface water availability; understanding that this approach allows substantial quantities of available groundwater to escape capture. This is a conservative approach that ensures maximum groundwater availability when and if needed.

The previous sections discussed the conditions and opportunities for expanded production at the existing wellfields. "Expanded production" could take the form of either increased instantaneous production capacity, increased run times with existing equipment, and/or increased long-term average groundwater withdrawal (i.e. gal/yr). With respect to long-term average groundwater withdrawal, an additional 2.3 mgd appears to be available for development beyond the current level of City groundwater production. With respect to instantaneous production, opportunity for increase through additional well construction is virtually limitless with infrastructure construction decisions contingent on the economics of increasing capacity when there may be little or no increase in current demand.

As developed in this series of Technical Memoranda, the Casper Aquifer has enormous reservoir capacity and large quantities of groundwater are available for extraction. This large storage capacity provides the opportunity to “average out” year-to-year variations in aquifer recharge to maximize the sustainable capture of available groundwater if needed. As discussed in Technical Memorandum No. 2, the estimated aquifer discharge in the area of the Laramie supply system is 6.7 mgd. As discussed in this memorandum and presented in Table TM 4-2, an estimated 2.3 mgd over the current rate of average annual municipal groundwater extraction is available for extraction.

IV. Supply Expansion – New Municipal Wellfields

As discussed in Technical Memorandum No. 1, the history of groundwater development in Laramie has been a sequence of passive collection of spring flow, then drilling wells to more effectively and efficiently capture spring flow, and finally, drilling wells to capture groundwater in areas without historical spring flow. The focus on spring areas is based on the observation that natural conditions have created local concentrations of groundwater discharge at those locations. Extension to new areas has been guided by the understanding that folds and faults offer the potential for locally enhanced permeability even in the absence of historical discharge to the surface.

The accumulating evidence for the importance of horizontal (or bedding plane) fractures or openings suggests an additional targeting criteria, but thus far no physical model has been proposed that would guide exploration to one area versus another in search of these potentially important features. Thus, the contribution of horizontal features to groundwater exploration is primarily to document the possibility (probability unknown) of substantial production from virtually any location.

When the potential for additional groundwater production from the existing wellfields and their existing infrastructure has been exhausted, there is additional groundwater development opportunity in new areas. Groundwater exploration concepts to guide future development efforts are listed below.

- Expand targeting criteria to consider the potential for large production in the absence of natural springs (e.g. Spur) and water-quality and water rights issues (i.e. negative) in spring areas.
- Do not target production wells in the recharge area due to limited saturated thickness and the potential to dewater productive fracture zones in the upper part of the aquifer.
- Maximize available drawdown and saturated thickness by targeting production wells in areas west of the Satanka/Casper Formation contact.

- Maximize the potential capture of basinward “underflow” by targeting major geologic structures (with assumed potential for high permeability) west of the Satanka/Casper Formatin contact such as the Laramie Fault and the westward extension of faults mapped in Casper Formation outcrop areas. Recognize, however, that exploration programs to evaluate these targets will be expensive because of greater drilling depths and associated well construction costs.

- Allow for critical, highly localized variations in aquifer characteristics and associated productivity by provision of multiple exploratory boreholes.

<u>Laramie Fault Prospect</u>

The Laramie Fault has been identified in numerous studies as a feature with substantial potential for a high yield well. The Laramie Fault is a major geologic structure that trends for over 30 miles: from Red Buttes to the south, through the center of Laramie, and northward beyond the Spur (Plate I). The fault is largely expressed in the Chugwater Formation which means that the fault displaces the Casper Formation, Satanka Shale, Forelle Limestone, and lower half of the Chugwater Formation. The fault’s north-south orientation and location west of the Satanka/Casper contact provides the opportunity to capture groundwater underflow in the Casper Aquifer that is presently not being captured by the Turner and Soldier-Pope wellfields and potentially provides far greater available drawdown than any of the existing wellfields. Because the fault runs through the center of Laramie, transmission pipelines from a successful in-City production well to storage facilities would be short.

Aside from the City’s high-yield irrigation well (i.e. Hunziker Well) completed in the Satanka Shale (Plate I) and a low-yield well drilled in the Casper Aquifer for the South Laramie Water and Sewer District, the Laramie Fault is currently unexplored and unevaluated. Given its attractive, but largely undefined, characteristics as a target for groundwater development, the Laramie Fault in the vicinity of Laramie is considered here to be an excellent prospect for groundwater investigation(s) at such time as an additional area of groundwater development is needed for potable purposes.

<u>Simpson Springs Prospect</u>

The Simpson Springs area has been identified in numerous studies as a potential location for a new City wellfield. The occurrence of natural springs, possible faulting, and documented high-capacity wells in that area suggest production potential from the Casper on a par with the existing municipal wellfields. Simpson Springs has received initial exploration attention as presented by Weston Engineering (2013a) and discussed in Technical Memorandum No. 2. The groundwater development potential at Simpson Springs is not yet defined nor has the development been considered in view of the above concepts regarding targets for groundwater development.

Given the current balance of supply and demand for the Laramie municipal water system and the need for a 6-mile pipeline if the area were developed for municipal supply, there is no urgency to develop additional groundwater supplies at Simpson Springs. Similarly, the absence of potentially competing development pressure suggest little need for immediate exploration and development to establish a water right priority position at Simpson Springs.

Continued water-level and streamflow monitoring at Simpson Springs is appropriate to establish hydrogeologic conditions, but the additional hydrogeologic investigations necessary to complete development designs for this resource may best be deferred pending greater need for additional municipal water supplies.

V. Supply Expansion – Non Potable Irrigation Supplies

There is a growing awareness that groundwater from redbed aquifers - Satanka Shale, Forelle Limestone, and Chugwater Formation - is available for development for non-potable uses such as the irrigation of parks and golf courses. Use of a redbed aquifer will depend on finding acceptable water quality (e.g. total dissolved solids) and production for the intended purpose. The following sections summarize wells and projects that demonstrate the potential for development of redbed aquifers in the Laramie area.

Hunziker Well

The Hunziker Well (U.W. permit No. 628) was drilled in 1940 and is located on the surface trace of the Laramie Fault in the northeast quarter of Section 28 on the Monolith Ranch. The well has a pump rated for 800 gpm which provides water for flood irrigation. The well was drilled to a total depth of 336 feet but caving of the open hole has reduced the well depth to 145 feet. The well was drilled into the Satanka Shale but probably obtains most of its water from the Chugwater Formation (i.e. current open interval).

LaPrele Park

A municipal groundwater supply study in 1997 (WWC, 1997b) identified significant production in the Chugwater Formation, Forelle Limestone, and Satanka Shale at the east end of LaPrele Park. The potential to use redbed aquifers for the irrigation of City parks was discussed in the 2006 Master Plan (WWC Engineering, 2006) and later in a report to the City in 2010 (WWC Engineering, 2010).

The City Parks and Recreation Department is conducting an on-going study on the development of non-potable raw water for the irrigation of LaPrele and Washington Parks using a combination of groundwater from the Casper Aquifer and the Satanka Shale (Wester-Wetstein, 2013). Appendix 490 – Irrigation Water Use - provides a discussion of the irrigation of City parks using treated and non-treated raw water.

Simpson Springs

A hydrogeologic study at Simpson Spring identified a “channel deposit” in the lower part of the Satanka Shale with potential use for municipal or irrigation purposes (Weston

Engineering, 2013a). The high permeability zone in the Satanka is in direct hydraulic connection with the underlying Casper. Like the LaPrele Park study, the high permeability zone at Simpson Springs illustrates that one should not ignore the potential to find significant quantities of groundwater in the redbeds.

University of Wyoming

University of Wyoming (UW) campus landscape/recreation areas are currently irrigated using water from two wells completed in the Forelle Limestone and water from the City of Laramie. The Fine Arts well was drilled in 1939 and has provided a reliable supply of up to 450 gallons per minute (gpm). The West Campus well was drilled in 2003 and produces up to 150 gpm, but excessive sediment production has forced UW to discontinue use of the well. Given the age of the Fine Arts well and the loss of production from the West Campus well, the irrigation system is vulnerable to supply disruptions and increased reliance on the more expensive City water supply.

In 2013 and 2014, two test borings and two test wells were installed into the redbeds near the Central Energy Plant (CEP TB #1 and CEP Well No. 1) and the Visual Fine Arts facility (VAF TB #1 and VAF Well No. 1) on the UW campus with the objective of developing additional groundwater irrigation supply (Weston Engineering, 2013b; Weston Engineering, 2014; Weston Engineering, 2015). Adequate water production and water quality for irrigation purposes occurred at both locations in a 20-foot thick thinly-bedded limestone in the lower part of the Chugwater Formation. The wells have the following production and water quality characteristics:

- Tested production rates of 130 to 150 gpm at CEP Well No. 1 and 220 gpm at VAF Well No. 1
- Specific capacity values of 3.3 gpm/ft at VAF Well No. 1 and 0.8 gpm/ft at CEP Well No. 1
- Total dissolved solid concentration of 481 to 501 mg/l

The general water quality in the lower limestone of the Chugwater Formation is a noticeable improvement over the water quality in the Forelle Limestone which has a total dissolved solids concentration of approximately 1,100 mg/l (Weston Engineering, 2013b; WWC, 1997b). It appears likely that the two test wells completed in the Chugwater Formation will be suitable for irrigation purposes on the UW campus. UW submitted an application to the WWDC in August 2015 to consider funding a study to evaluate the irrigation of the Red Jacoby Golf Course using groundwater resources such as the redbeds and perhaps the Casper Aquifer.

VI. Wellfield Loss or Failure Contingency

During this Master Plan study, City staff expressed concern about the potential permanent or semi-permanent loss of a wellfield. This could happen, for example, from a gradual deterioration of water quality, a catastrophic contamination event, or an infrastructure failure. For example, the Turner Wellfield is vulnerable to water-quality deterioration associated with nearby subdivisions, existing commercial development, future land-use development (e.g. the proposed expansion of the Red Jacoby Golf Course into the area north of the Turner Wellfield in 2006), and accidental spills along the Grand Avenue traffic corridor. The Soldier-Pope wellfield could be compromised by highway accidents and spills along the I-80 corridor. (The Union Pacific railroad tracks cross over the Satanka/Casper contact, i.e. off the Casper recharge area, just north of Simpson Springs such that the only City-owned groundwater resource area that could be contaminated by a train derailment would be at Simpson Springs.)

Infrastructure failures can be repaired in a relatively short time frame. Aquifer contamination, however, is unlikely to be mitigated within a time frame acceptable to the operation of a municipal water supply. For example, if there was a spill or contamination event involving dense non-aqueous phase liquids (DNAPLs), e.g. chlorinated solvents, reaching the aquifer, the water supply to a particular wellfield could be permanently impaired or rendered unusable without special treatment. An aquifer contaminated by DNAPLs is virtually impossible to "clean up" and compliance concentrations are so low that water treatment would be inevitable (e.g. City of Cheyenne Borie Wellfield).

The response of the City to the loss or impairment of a wellfield would be complex depending on the wellfield affected, type of contaminant, location and magnitude of spill, and local hydrogeology. In general, the City is well-positioned to maintain a viable water supply in the event that a single wellfield is lost permanently or for an extended time period. The four groundwater extraction facilities are spread over a large north-south area (i.e. Spur-Turner-Pope-Soldier) which provides considerable operational and supply flexibility. In the event that any one of the central and southern facilities (Turner, Pope, and Soldier) is lost, the Spur Wellfield can serve as a replacement wellfield from which production can be expanded as needed.

Previous sections in this memorandum described potential additional opportunities for development of a new wellfield(s) and expansion of existing wellfields that can be executed in the event of a permanent or semi-permanent loss of a wellfield.

VII. Casper Aquifer Research and Cooperative Relationships

For the past 37 years, paradigms regarding the permeability and flow characteristics of the Casper Aquifer have been largely guided by the work of Lundy (1978) and Dr. Peter Huntoon (Huntoon and Lundy,1979a; Huntoon, 1993). These original research efforts have since been supplemented by numerous Laramie-area water supply studies funded by the WWDC and the City such that our understanding of the Casper Aquifer continues to improve. There is, however, much more to be learned about the hydrodynamics of the Casper Aquifer. A better understanding of aquifer permeability and the role of geologic structure and stratigraphy in groundwater production and flow will pay dividends in developing better working models for the exploration, development, protection, and monitoring of the Casper Aquifer.

The City's implementation of the Casper Aquifer Protection Program and Casper Aquifer Monitor Well Network Program are positive steps towards greater public awareness and understanding of the importance of the aquifer to the City and Albany County community. These programs should continue to be supported and implemented.

The development of cooperative aquifer research between the City and the University of Wyoming is particularly important. As part of the Laramie Monitor Well Installation Project (Hinckley Consulting and Wyoming Groundwater, 2015), the Wyoming Center for Environmental Hydrology and Geophysics (WyCEHG) provided near-surface and downhole geophysical surveys to assist in the evaluation of the Sherman Hills Fault at Imperial Heights Park. The geophysical data helped to properly locate monitor wells and provided unparalleled digital and visual data on permeability features in the Casper. Combining standard hydrogeologic field data with sophisticated geophysical techniques proved to be a very powerful tool for aquifer evaluation. There are a number of City-owned or potentially City-available wells with open hole completions that are not hindered by pumping equipment (e.g. Spur TW-1, 41T2, 41T3, LaPrele No. 1, LAPCA-1, Simpson Test Well No.1, Simpson Test Well No. 2, and LCCC IW #1) such that the wells can easily be evaluated by WyCEHG to expand our understanding of the permeability characteristics of the Casper Aquifer.

Future drilling and investigative efforts in the Casper by the City should attempt to take advantage of "enhanced services" that may be available from the University of Wyoming as listed below.

- WyCEHG
- Geology Department research projects
- Engineering Department research projects
- Master's and Ph.D thesis topics related to hydrogeology in vicinity of Laramie

Whenever possible, cooperative aquifer-related projects and relationships between the City, County, and University of Wyoming should be fostered. Albany County is an important player because of its jurisdiction over the vast majority of the aquifer recharge area and the University of Wyoming has tremendous academic and research capabilities.

VIII. Recommendations

Based on information and analysis provided in Technical Memoranda No. 1 - 4, the following recommendations are provided for consideration by the City of Laramie.

1. When additional water is needed, groundwater expansion opportunities are available on a short-term peaking basis and on a long-term sustainable production basis through more aggressive operation, particularly of the Turner and Spur wellfields. An additional 2.3 mgd beyond current average annual groundwater production is available for extraction without adverse impacts to long-term aquifer water levels.

2. Meet with the State Engineer's Office (SEO) to define information that the SEO will need to consider modification of the Spur Wellfield Use Agreement in 2020. It is assumed that the response of the Casper Aquifer to Spur Wellfield production will be a primary factor in the modification of the agreement such that we recommend:

- In 2016 and over successive summers, the Spur Wellfield should be pumped at maximum allowable production rates for extended time periods to empirically test the aquifer's response to sustained pumping. A Spur Wellfield testing plan should be developed prior to testing.
- In 2020, present data collected at the Spur Wellfield over the previous 20 years, including production records, the monitoring well hydrographs, and the results of testing per the previous recommendation, to the State Engineer's Office for consideration to modify the agreement.
- Revision of either the baseline water levels used to define "drawdown" or development of trigger-points that distinguish natural from wellfield production-induced impacts on monitor well water levels.
- Revision of production peak rates to reflect the points at which short-term drawdown impacts have a significant impact on domestic wells.

3. Conduct pump tests at the Turner Wellfield that empirically define pumping rates at the Turner No. 1 and Turner No. 2 wells that eliminate/control surface discharge at City Springs and that allow extended periods of simultaneous pumping of the wells. A Turner Wellfield testing plan should be developed prior to testing.

4. Conduct an engineering study to evaluate alternatives designed to improve the operation and infrastructure of the Turner Wellfield to achieve water quality objectives within the limits of desired water production.

5. Conduct a study to evaluate the condition and performance of the existing buried groundwater collection system in the City Springs enclosure. If determined to be in poor condition or inefficient, alternatives (including replacement) should be considered.

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6. Improve or replace the security fence at the City Springs enclosure to prevent unauthorized access by wildlife and humans.

7. Conduct bi-annual sampling and analysis of water from the Turner and Soldier wellfields for Microscopic Particulate Analysis and fecal coliform.

8. When additional groundwater is needed beyond what can be developed through modified management/construction at the existing wellfields, the next

groundwater development prospect to evaluate for drinking water supply replacement or expansion is the Laramie Fault where it occurs within the corporate limits of the City.

9. Update the Casper Aquifer Protection Plan in 2016 with new information on the aquifer and program implementation improvements.

10. Work with Albany County towards the development of a consistent delineation of the western boundary of the protection area and the implementation of City and County Casper Aquifer Protection programs.

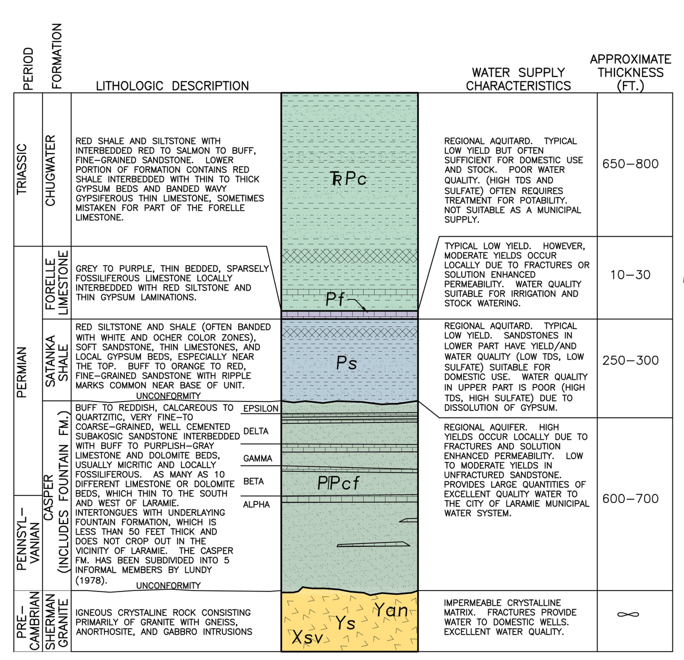
11. Expand the Casper Aquifer Monitoring Program to include the installation of monitor wells in areas contributory to the Soldier-Pope Wellfield and in areas that provide baseline water quality data.

12. Prepare a Casper Aquifer Monitoring Program document that defines program objective(s), the location of existing and proposed monitor wells, water level measurement and water sampling procedures, water quality analytes, sampling frequency/schedule, and the creation of water level and water quality databases that facilitate data presentation and interpretation.

13. Develop cooperative data-based Casper Aquifer research efforts with the University of Wyoming and WyCEHG.

List of Tables (embedded in text)

SOURCE: VER PLOEG (2007) AND VER PLOEG AND McLAUGHLIN (2009)



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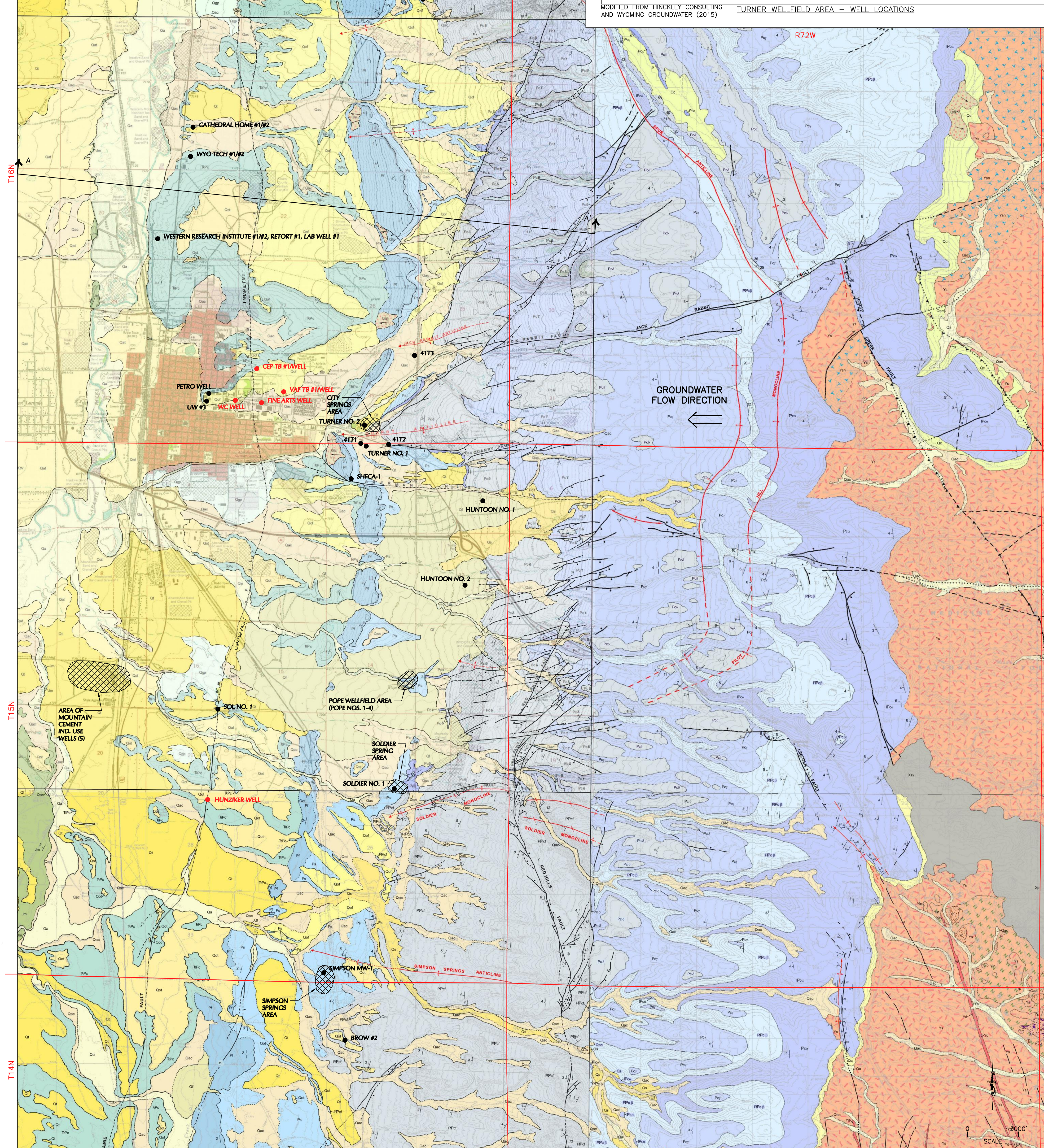
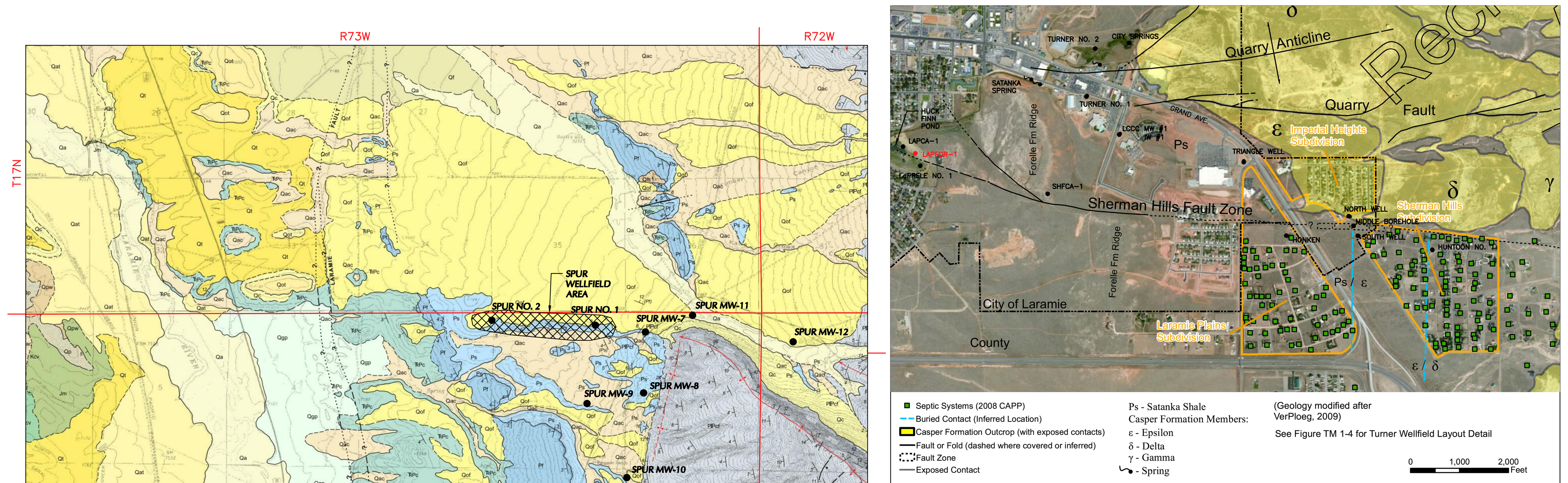
LITHOLOGIC DESCRIPTION FROM VER PLOEG (1998, 2007, 2009)

LARAMIE AREA HYDROSTRATIGRAPHY

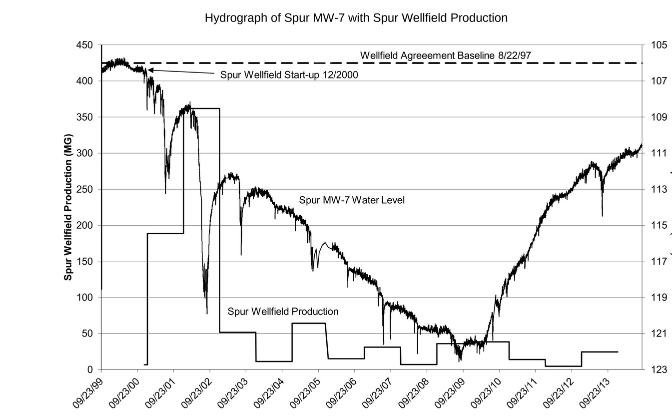


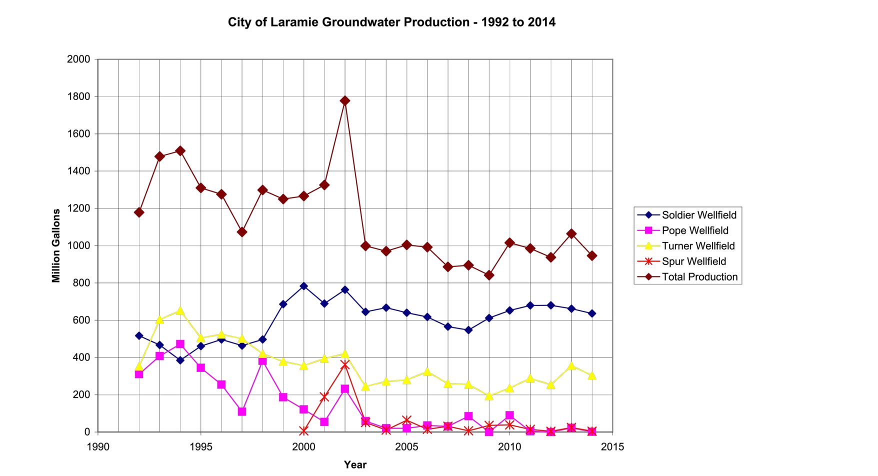
COMPILED AND MODIFIED FROM VER PLOEG (1996, 2007, 2009) AND VER PLOEG AND McLAUGHLIN (2009)
BLACK WELLS ARE COMPLETED IN THE CASPER AQUIFER, RED WELLS ARE COMPLETED IN THE REDBEDS.



MODIFIED FROM HINCKLEY CONSULTING AND WYOMING GROUNDWATER (2015)

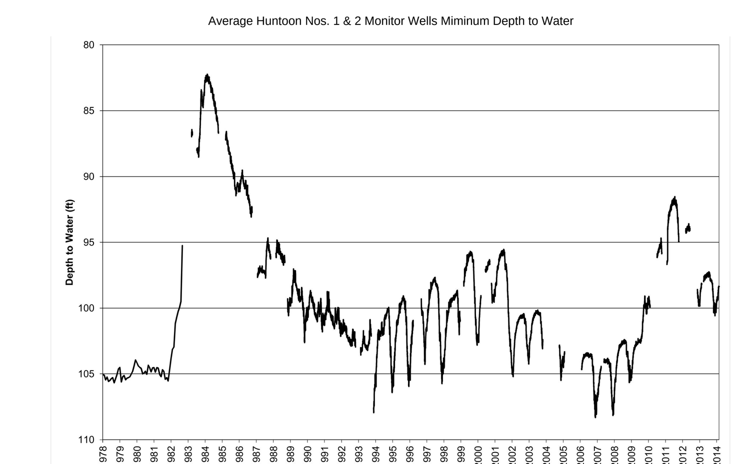
TURNER WELLFIELD AREA – WELL LOCATIONS





Laramie Municipal Supply Well Completion Data. 2015 Laramie Master Plan, Level I

Well Name	Year Drilled	Total Depth, ft.	Cased Interval, ft.	Casing OD, in.	Open Hole Interval, ft.	Well Pumping Rates, gpm	Casper Members Penetrated, ft.
Spur No. 1	1997	305	0 - 91	16	91 - 305	1,560	epsilon, delta, gamma; 251
Spur No. 2	1997	323	0 - 255	16	255 - 323	1,560	epsilon; 84
Turner No. 1	1982	240	0 - 98.4	16	98.4 - 240	2,200	epsilon, delta; 136
Turner No. 2	1982	350	0 - 100	16	100 - 350	1,700	epsilon, delta, gamma, beta; 274
Pope No. 1	1937	156	0 - 64	8	64 - 156	475	epsilon, delta; 95
Pope No. 2	1938	162	0 - 64	8	64 - 154	650	epsilon, delta; 95
Pope No. 3	1939	158	0 - 66	15	66 - 158	994	epsilon, delta; 95
Pope No. 4	1982	350	0 - 100	16	100 - 350	1,935	epsilon, delta, gamma, beta; 285
Soldier No. 1	1997	289	0 - 79.5	16	79.5 - 289	1,300 flowing 2,300 pumping	epsilon, delta, gamma; 248



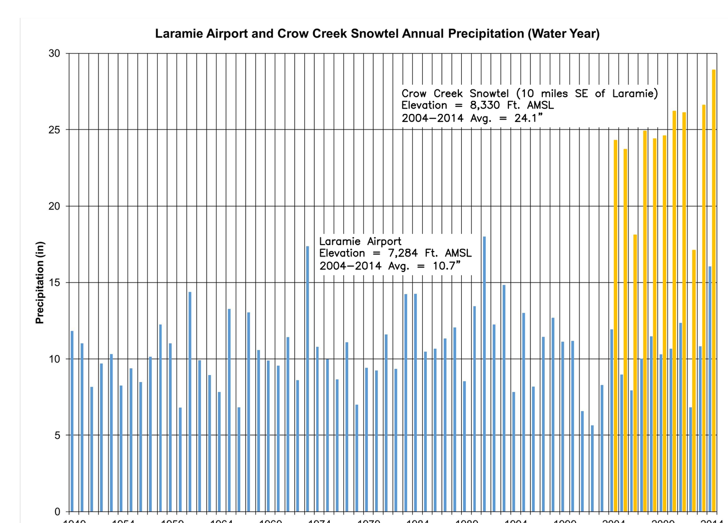
Production Characteristics of the Casper Aquifer. 2015 Laramie Master Plan, Level I

High Permeability Conditions in Casper (horizontal and vertical openings/fractures/bedding plane/karst features)

Municipal Well Name	Approx. Depth to Water, ft.	Test Duration, days	Test Pumping Rate, gpm	Drawdown End of Test, ft.	Well Specific Capacity gpm/ft.	Current Max. Well Pumping Rate, gpm	Data Source
Spur No. 1	32	6.0	2,000	3.4	580	1,560	WWC, 1997c
Spur No. 2	12	5.0	2,000	4.5	440	1,560	WWC, 1997c
Turner No. 1	0	6.9	2,030	30.5	66	2,200	WWC, 1996a
Turner No. 2	+6	1.4	1,730	47	36	1,700	This study
Pope No. 1	11	1.0	475	12	40	475	
Pope No. 2						650	
Pope No. 3	15	1.0	994	16	62	994	
Pope No. 4	31	2.0	1,500	12	125	1,935	
Soldier No. 1	+2	5.8	1,800	9.4	191	2,300	WWC, 1997a
41T2	39	0.4	490	7.5	65		WWC, 1996a
North Well	89	2.0	400	19	21		HC and WG, 2015

Low Permeability Conditions in Casper (absence of horizontal and vertical openings/fractures/bedding plane/karst features)

Well Name	Approx. Depth to Water, ft.	Artesian Flow, gpm	Test Duration, days	Test Pumping Rate, gpm	Drawdown End of Test, ft.	Well Specific Capacity gpm/ft.	Data Source
LaPrele No. 1	45 ft. above grd	30 - 40	2.8	200	308	0.6	WWC, 1997b
Petro Well	65 ft. above grd	5				0.08	Weston, 2013b
SOL Well No. 1	2.0		1.0	30	367	0.08	Weston, 2012
Huntoon No. 1	121.5		0.46	8	12.6	0.6	Lundy, 1978
Simpson Test Well No.1	17 ft. above grd		5.0	125	142	0.9	Weston, 2013a



Groundwater Quality of Casper Aquifer at Municipal Wells and Springs. 2015 Laramie Master Plan, Level I

All units in mg/l with the following exceptions: pH in standard units, Hardness in mg/l $CaCO_3$; Gross Alpha and Radium in pCi/l

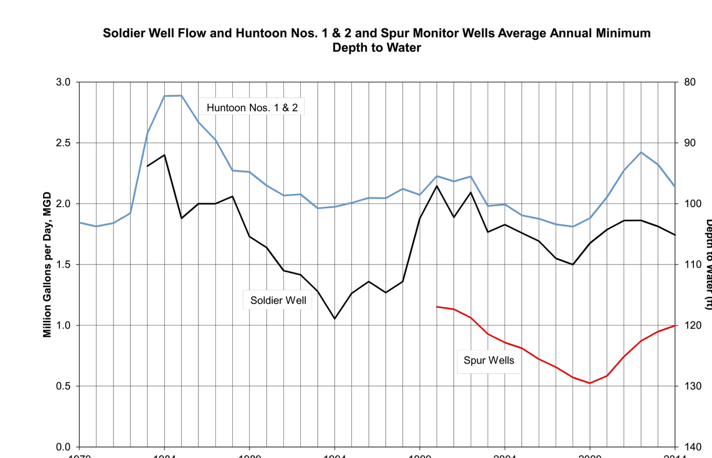
			Major Cations				Major Anions				Other Key Parameters						
Well	Sample Year	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3 as N	F	Fe	U	TDS sum	Hardness	Gross Alpha	Radium 226+228
Spur No. 1	1997	8.0	52	16	2.6	<1.0	215	1.1	6.0	1.6	0.2	<0.05	0.002	300	196	<1.0	<1.0
Spur No. 2	1997	8.0	52	16	1.9	<1.0	216	<1.0	5.0	1.5	0.2	<0.05	0.001	298	196	<1.0	<1.0
Spur No. 1	2014	8.0	47	17	2.6	0.7	220	1.6	5.9	1.5	0.2	<0.02		301	187	2.8	-0.02
Spur No. 2	2014		48	17	2.3	0.7	220	1.4	5.3	1.4	0.2	<0.02		301	190	2.8	-0.02
City Springs	1973	7.8	52	17	2.1	0.9	233	1.8	6.6	1.4	0.2	0.03		320	200		
City Springs	2008	8.0	49	17	2.4	0.9	240	2.7	8.3	1.4	0.1	<0.02		326	192	2.7	0.1
Turner No. 1	1981	8.2	49	22	2.0	0.7	240	1.5	9.1	0.6	0.2	<0.1		327	213		
Turner No. 2	1981	8.3	35	20	2.0	0.2	210	1.4	6.6	0.2	0.2			276	170		
Turner No. 2	2014	7.5	53	17	2.9	0.9	240	4.0	11.0	2.0	0.1	<0.02	0.001	338	202		
Pope Wells	1973	8.2	54	13	2.1	0.7	222	1.8	5.8	1.6	0.2	0.04		306	188		
Pope No. 4	1981	8.2	51	19	2.0	0.2	230	1.8	0.0	0.8	0.2			308	205		
Soldier Spring	1973	7.9	50	16	3.7	0.9	220	1.8	8.2	1.7	0.7	0.04		308	191		
Solder No. 1	1997	8.1	58	17	1.9	<1.0	218	3.5	12.0	2.0	0.2	<0.05	<0.001	313	215	<1.0	<1.0
Soldier No. 1	2014	7.6	54	16	3.3	0.9	230	6.4	11.0	2.1	0.1	<0.02	0.001	331	201	1.8	0.4
EPA MCL		*6.5 - 8.5*						*250*	*250*	10	4.0	*0.3*	0.030	*500*		15	5

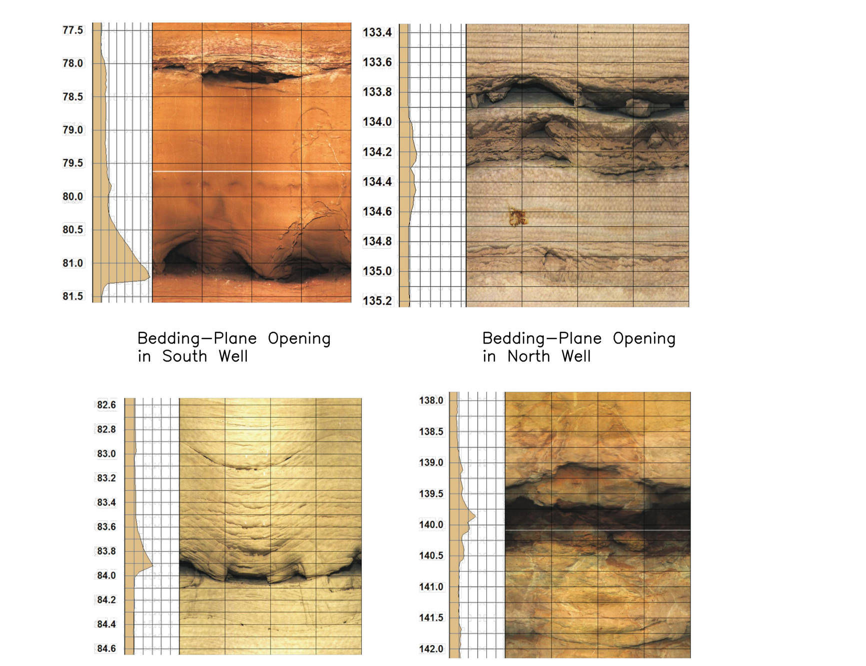
Groundwater Quality of Redbed Aquifers in Vicinity of Laramie. 2015 Laramie Master Plan, Level I

All units in mg/l with the following exceptions: pH in standard units, Hardness in mg/l $CaCO_3$; Gross Alpha and Radium in pCi/l

Well/Spring	Formation	pH	Ca	Mg	Na	K	HCO_3	Cl	SO_4	NO_3 as N	F	TDS sum	Hardness	Data Source
Honken Well	Satanka	8.2	56	19.3	3.3		249	5.1	10.3	6.3		371	219	Weston, 1995
Satanka Spring	Satanka		49	25	4.7	1.3	230	11	19	2.2		350	225	WWC, 1994a
B-7	Satanka		40	36	8.5	3.4	240	9.2	47	2		393	248	WWC, 1994a
B-12	Satanka		35	36	7.2	2.9	240	12	28	3.9		378	235	WWC, 1994a
LAPFOR-1	Forelle	7.8	231	65	8.9	2.2	180	10	660	1.1		1,162	844	WWC, 1997b
Fine Arts Well	Forelle	7.6	190	50	19	1.8	341	28	430	1.1	0.2	1,065	680	Weston, 2013b
LAPCA @ 40'	Chugwater	8.0	260	71	9.6	3.1	150	9.5	720	2.6		1,235	941	WWC, 1997b
VAF TB#1	Chugwater	8.7	67	38	20		71	48	192	6.3		464	323	Weston, 2014
CEP TB#1	Chugwater	7.9	124	62	9.1		246	1.3	244	5.1		709	564	Weston, 2014
CEP Test No. 1	Chugwater	7.6	101	54	7.1	1.2	235	7.6	223	4.4		648	474	Weston, 2014
VAF No. 1	Chugwater	7.7	100	43	11.2	1.4	302	13	134	9.4		646	426	Weston, 2015

Notes: Ca: Calcium; Mg: Magnesium; Na: Sodium; K: Potassium; HCO_3: Bicarbonate; Cl: Chloride; SO_4: Sulfate; NO_3: Nitrate; F: Fluoride; Fe: Iron; U: Uranium
TDS: Total Dissolved Solids
EPA MCL: Maximum Contaminant Level as established by the EPA for drinking water standards. Enforceable primary standards in bold type. Nonenforceable secondary standards in italics.
*: Radium 226 was not analyzed in most samples, but when analyzed it is non-detect.



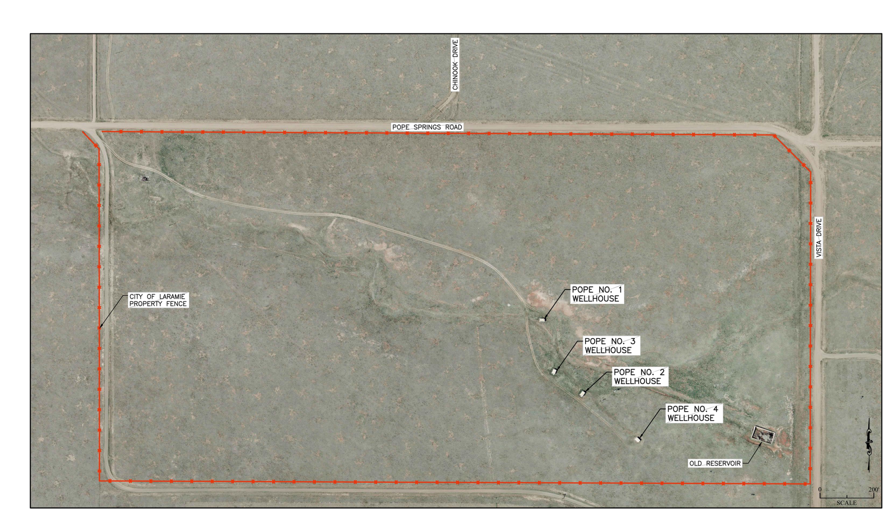


Bedding-Plane Opening in South Well

Bedding-Plane Opening in North Well

Bedding-Plane Opening in Triangle Well

Shale Layer in Middle Borehole



POPE WELLFIELD LAYOUT

CASPER AQUIFER OVERVIEW

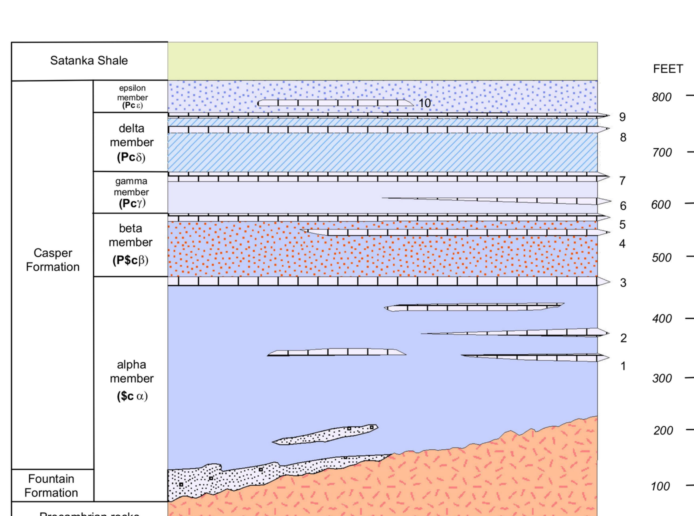
In the vicinity of Laramie, the Casper Formation provides a classic Wyoming range-front aquifer system. Interbedded sandstones and limestones exposed on the west flank of the Laramie Range receive precipitation/snowmelt recharge. Groundwater flows east-to-west, from the range crest to springs at the foot of the range and on into the interior of the Laramie Basin. The Casper is underlain by the Precambrian Sherman Granite and overlain by the Satanka Shale, both of much lower productivity. Numerous faults, folds, and associated fractures within the Casper enhance aquifer permeability, modify groundwater flow, and serve to hydraulically integrate sandstone units by disrupting the intervening limestones. Horizontal and sub-horizontal fractures and openings in the sandstones and at contacts between sandstone and limestone units also locally enhance aquifer permeability and facilitate rapid lateral groundwater flow. The inter-granular pore space of the sandstones store tremendous quantities of groundwater and the interconnected fracture system transmits large volumes of groundwater to wells and springs at favorable locations.

The Casper is a continuous aquifer from north-to-south (Spur Ridge to Simpson Springs) and from east-to-west (range crest to the Casper/Satanka contact). Water levels at monitor wells and groundwater discharge at range-front springs respond to multi-year precipitation patterns and periodic intense recharge events. Recharge mechanics are dynamic, complex, and vary locally within the general pattern of the recharge:discharge process.

By all standards, the Casper Aquifer provides an extraordinary municipal water supply. Municipal wells that penetrate fractures/openings have specific capacity values ranging from 36 to 580 gpm per foot of drawdown and instantaneous yields ranging from 475 to 2,300 gpm. Municipal wells are located adjacent to natural springs, penetrate only 12% to 41% of the 700-feet thick aquifer, and have total depths ranging from 156 to 350 feet. The four municipal wellfields are located within 6 miles of Laramie and immediately west of the recharge area. Water quality complies with EPA drinking water standards by wide margins and requires no treatment. These attributes result in a relatively simple, efficient, productive, high-quality, and low-cost water supply.

The City of Laramie began using groundwater from the Casper Aquifer in 1868. After 148 years of municipal use, the Casper Aquifer remains undepleted by municipal or commercial use. This is a result of low extraction pressure, relatively few commercial/industrial users, and conjunctive development of a surface water supply (Laramie River). In the area defined by Spur to the north and Simpson Springs to the south, there is an estimated 6.7 million gallons per day (mgd) of groundwater potentially available for sustainable extraction from the Casper. This is an additional 2.3 mgd estimated to be available beyond current levels of production. More aggressive use of the aquifer is possible by taking advantage of the storage/reservoir capacity of the aquifer.

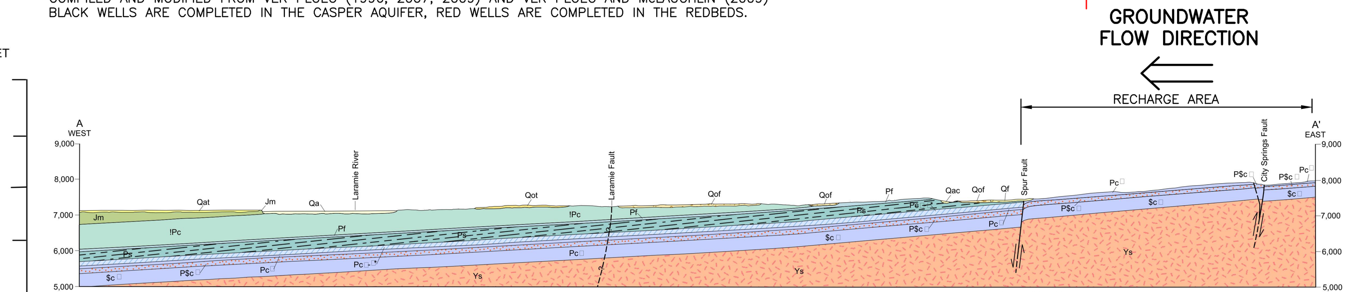
Current relatively high aquifer water levels provide the opportunity for empirical confirmation of production potential through aquifer testing at the Spur, Turner, and Soldier wellfields. Within our general understanding of the Casper Aquifer important details are not well-defined. Topics that could be usefully refined include: permeability type/distribution, recharge mechanics, hydraulic relationship with underlying/overlying units, how to best capture/utilize basinward flow and vertical flow into overlying units, and vulnerability to contamination. The better we understand and appreciate this remarkable resource, the better that the Laramie-area community can use and protect its water supply.



SOURCE: VER PLOEG (2009)

CASPER FORMATION MEMBER DIAGRAM

GROUNDWATER FLOW DIRECTION



SOURCE: VER PLOEG (2007)

WEST TO EAST GEOLOGIC CROSS SECTION A–A'

SIMPSON SPRINGS AREA

SOLDIER WELLFIELD LAYOUT

PLATE I

GROUNDWATER TECHNICAL MEMORANDA 1–4
HYDROGEOLOGY AND
WELL/WELLFIELD INFORMATION

2015 LARAMIE WATER MASTER PLAN, LEVEL I
WYOMING WATER DEVELOPMENT COMMISSION

REVISED BY:	DATE:

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