Seasonal water storage and replenishment of a fractured granitic aquifer using ASR wells

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Abstract: The Town of Payson is situated in a mountainous region of central Arizona. The Town is totally reliant on groundwater for the needs of over 15,000 people. Groundwater is accessed from a climate-dependent fractured granite aquifer from 42 wells with an annual demand of 3.1 million cubic meters (m^3). As a result of a law, the Arizona Water Settlement Act of 2004, Payson obtained a water right to use 3.7 million m^3 of water stored in the nearby Cragin Reservoir. This additional water supply will be used to offset future groundwater pumping as the Town continues to grow. A pipeline to convey the surface water from the reservoir, a new treatment plant, and aquifer storage and recovery (ASR) wells will be added to Payson's water system. These wells will be used for seasonal and long-term aquifer storage and recovery of the stored surface water and will contribute to a considerable improved management of Payson's water resources. For the ASR operation, a number of existing production wells will be selected and retrofitted for injection. The treated surface water will be delivered to the ASR wells from the Town's potable water distribution system for aquifer storage. Base-Load and On-Call ASR wells and their operation will be automated via a SCADA system. Groundwater in the fractured granitic aquifer is typified as calcium-bicarbonate and so is the water stored behind the Cragin dam. The use of ASR wells as a managed aquifer recharge (MAR) component is a successful solution for providing potable water to a small community in a cost effective manner.

Keywords: fractured rock aquifer; new water source; aquifer storage and recovery; seasonal and long term water storage; ASR wells; managed aquifer recharge

1. Introduction

Payson is situated in central Arizona, 150 km north of Phoenix. Founded in 1882, and first named Green Valley, Payson is known for its scenic beauty below the impressive Mogollon Rim. The Town has grown from its initial humble beginnings of 42 people to a population of over 15,000 in 2015. Payson has experienced significant growth of about 12 percent from the year 2000 to 2013. The population of Payson is expected to double by the year 2030.

Despite the surrounding lush green vegetation and topographic diversity, Payson and other communities within this region of the state are almost entirely reliant on groundwater resources to meet their potable water needs. Groundwater is accessed from fractured bedrock aquifers predominantly from the Payson Granite. Surface soils are feather-thin transitioning abruptly into the weathered granite and underlaying fractured rock with no alluvial aquifers to provide storage. Payson, for many years, has taken a pro-active leadership role in water resource planning, evaluation, development, and active conservation practices. This has included systematic data collection, monitoring, and testing investigations to understand the associated hydraulic characteristics of the hydrogeologic conditions indigenous to the area. Obtaining a long-term sustainable source of renewable surface water has been a primary goal for the Town for many years. The Town's persistent efforts to secure a surface water supply are about to be realized with a new surface water supply set to arrive in Payson in 2018. In preparation for the initial delivery, infrastructure design and construction is ongoing and the Town is developing strategies to most efficiently integrate the renewable source into the Town's water resources portfolio. One of the major challenges is to store this water, for later recovery, in the fractured bedrock aquifer. Successful aquifer storage and recovery testing over the last few years has indicated the Payson Granite as a very favorable component for long-term storage of available surface water resources. Mixing scenarios of the treated surface water also indicate positive results as related to the hydrogeochemical blending of surface and groundwater resources.

1.1 Physiography

Payson is situated south of the Colorado Plateau and north of the Basin-and-Range province in an area known as the Transition Zone physiographic province of Arizona. The Transition Zone, as the name implies, contains remnants of the shallowly northeast-dipping Paleozoic formations of the Colorado Plateau in addition to faulted and tilted sedimentary and volcanic Tertiary rocks of the Basin-and-Range. As a result, the Transition Zone exhibits very diverse geology and a complex hydrogeologic system compared to the other physiographic provinces in the state. The area is roughly bounded by the Mogollon Rim to the north (southern expression of the Colorado Plateau), Fossil Creek and the Verde River to the west, Christopher and Tonto Creeks to the east, and an arbitrary east-west line roughly connecting North Peak in the Mazatzal Wilderness with "Ox-Bow Hill", north of Rye to the south. The Town rests at an elevation of approximately 1,524 m above mean sea level and is completely surrounded by the Tonto National Forest.

Payson is in the Verde River Basin in the Central Highlands Planning Area encompassing a drainage area of approximately 14,662 km^2. The East Verde River is approximately 5.6 km northwest of Payson and is the largest perennial surface water feature in the area conveying flow to a series of regulated reservoirs before its confluence with the Salt River far to the south. This part of central Arizona is classified as Mediterranean (semiarid) with extremes of precipitation and temperature during the year. Payson's precipitation has a historical average of 537 mm per year estimated from 1940 to 2015.

1.2 Water Resources Availability and Challenges

The Town has been utilizing groundwater since the early 1950s as its major supply of municipal water. Groundwater has been pumped from fractures in the granite rock aquifer beneath the Town and water level declines range from 12 m to over 30 m in certain areas over the past 65 years of pumping. Wells tapping these fractures yield varying amounts of water depending on the size and the number of fractures encountered. Considerable field mapping and surface geophysical investigations have been completed as a means to delineate subsurface fractures and future well sites.

Two fractured rock aquifers have been identified by the Town through years of continued monitoring of the groundwater system. Groundwater levels, due to pumping, appear to decline at a predictable rate early in the pumping season until the drawdown reaches a specific depth when the water level seems to stabilize and the decline rate slows considerably. The Town has also identified the presence of a minor change in water quality as the water level decline slows during pumping. This evidence indicates the influence of an upper and lower aquifer within the granite rock aquifer system.

Local rain and snow provide some groundwater recharge to replenish the water that is being pumped from the upper aquifer. Recharge from rain and snow from a more regional area provide the water necessary to replenish the lower aquifer. As the Town grew in population and the water demand increased, more water production wells have been drilled to meet this demand. The newer wells have also been drilled to greater depths penetrating the lower aquifer. Today, the Town owns and operates approximately 42 water production wells.

The Town recognizes that if the water demand continues to increase, their groundwater supply will continue to decline and eventually reach a point where the upper aquifer may not be sufficient to remain sustainable and more reliance will need to be placed on the lower aquifer. Therefore a supplemental water supply will become necessary at some time in the future.

1.3 Water Supply Alternatives and Solutions

In preparation for continued future growth and the possibility of more groundwater mining, Payson acquired approximately 3.7 million m^3 per year of surface water from the nearby Cragin Reservoir. The surface water will be transported by a pipeline to a local water treatment plant to be filtered, disinfected and utilized conjunctively with the groundwater as the Town's municipal water supply. Presently, the 3.7 million m^3 per year is greater than the existing water demand of the Town so the excess surface water will be treated and stored in the fracture rock aquifer.

The 23.3 km transmission pipeline to bring water from the reservoir will connect with the water treatment plant. The reservoir is located at an elevation of approximately 166 m higher than the proposed water treatment plant to be situated at the edge of the Town. This elevation difference provides a significant challenge in handling the pressure head of water in the pipeline when it reaches the water treatment plant. In-line turbine electric generators will be installed at the lower end of the transmission pipeline to utilize the pressure head to generate electrical power to operate the water treatment plant.

Eight of the existing water production wells will be converted to ASR wells. Due to weather conditions at the reservoir site, the surface water is only available 9 months of the year. During those months the ASR wells will be in a recharge mode and will be used to store excess water in the aquifer whereas the other 3 months the ASR wells will produce stored water for municipal use. Of the eight ASR wells, only four will be equipped with a downhole flow control valve and a submersible pump to allow the well to be operated as a dual system well. A systematic plan is being designed to allow the wells to operate according to pre-planned strategy in which the computer operated system will function.

This storage and recovery operation is scheduled to start in 2018 and end around 2034 when the projected increased water demand will exceed the surface water supply and there will no longer be a need for a storage requirement. At which time, the ASR function will then be converted back to solely a water production function.

2. Hydrogeologic Framework

Payson is one of the largest communities in the Transition Zone physiographic province of central Arizona. The Transition Zone is largely a region of bedrock displaying some of the oldest rocks in the state. The structural nature of this province has a direct bearing on developing groundwater resources from the bedrock aquifers common to this area. In essence, this province is one of the most complex hydrogeological areas in Arizona. A knowledge of the regional geology is necessary to understand the source, flow characteristics and storage of groundwater, the only supply of potable water for Payson.

2.1 Regional Geology

The topographic feature known as the Mogollon Rim, the southern edge of the Colorado Plateau, is located 20 km north of Payson. Exposed along the Mogollon Rim are sedimentary rocks of Paleozoic age nearly 900 m thick that attain an elevation in excess of 2,100 m above mean sea level. These rocks are composed of interbedded limestones, sandstones and shales and range in age from Cambrian to Permian (Reynolds 1988; Beus and Morales 1990; Wilson et al. 1959). In some locations basalt flow units of Tertiary age rest unconformably on the units of Paleozoic age. To the south of the Mogollon Rim and all along its northwest to southeast bearing are exposed rocks of Proterozoic age. These rocks range in age from 1740 to 1660 Ma (Anderson 1986). They consist of metavolcanics, and metasedimentary units and plutonic rocks. The igneous intrusives include the older Gibson Creek Batholith and the younger Payson Granite (Karlstrom and Conway1986; Conway et al 1987). Erosional remanants of the Paleozoic rocks rest unconformably on some of the Proterozoic formations. Geologic formations of Mesozoic age are absent in Payson and surrounding areas. Rocks of Tertiary age in this region consist of basalt flows of late to middle Miocene age, some sandstones and conglomerates of Miocene to Pliocene to age and unconsolidated alluvial deposits of Quaternary to Holocene age (Richard 1999).

The rocks of Early Proterozoic age of Payson and immediately surrounding areas originated from and were subjected to two early orogenic episodes: the Yavapai orogeny (1700 to 1690 Ma) and the Mazatzal orogeny (1.65 Ma) (Karlstrom et al. 1991). The 500 km transect across the Early Proterozoic orogenic belt in central Arizona is cut by northeast and north trending shear zones and divides it into eight separate blocks (Karlstrom et al. 1990). The Payson area is located within the Mazatzal block which is bounded on the northwest by the Moore Gulch shear zone and in the southeast by the Slate Creek shear zone. Deformation within the Mazatzal block is compressional and expressed by tight folds, even overturned, and by several thrusts. All rock units in the Mazatzal block exhibit a northeast-striking deformational fabric mostly expressed as foliation and frequently as subvertical cleavage.

Of hydrogeologic relevance is the deformation of the rocks of the Payson region during post Precambrian orogenic events. This is the Laramide Orogeny from late Cretaceous to early Cenozoic and the middle to late Tertiary tectonic events. The latter consists of two periods, an early middle Tertiary magmatism and extensional deformational event and a late Cenozoic block faulting and subsidence event. The Laramide deformation was predominantly a compression and crustal thickening event responsible for most of the folds and thrusts mapped in the mountain ranges of southern and western Arizona and the monoclinal flexures of the Colorado Plateau region (Dickinson 1989). This orogenic episode is most likely responsible for the reactivation of some of the Early Proterozoic faults in the Payson and surrounding areas. However, it is the Tertiary tectonic event that has had a greater impact on the hydrogeology of this region especially the late Cenozoic block faulting episode (Lluria 1988). It is during this event that structural features like the Verde Graben and the Diamond Rim faults were formed and had their full development. Examination of the area extending from south of Payson to the Mogollon Rim and from east of Payson to west of Payson show many high angle normal faults that strike northwest, west-northwest, north and north-northeast (Scarborough et al. 1983). In the Colorado Plateau, in the area immediately north of the Mogollon Rim north striking faults have been mapped. These are late Cenozoic Basin-and-Range faults that resulted from accommodation of east-west extension and possible similar to others in this region that are high angle, down to the west, normal faults (Huntoon 1990).

2.2 Local Geology

The Town and the area containing all its potable water supply wells is approximately 64 km^2. Its surface geology is shown in Figure 1. This area is predominantly underlaid by igneous rocks of Early Proterozoic age which to the northwest are covered by sedimentary rocks of Early Paleozoic age. Small outcrops of Tertiary age rocks rest unconformably on the Early Proterozoic units. Quaternary alluvium deposits cover the drainages. The oldest rocks crop out in the northeast part of this area. It is a gneissic granitoid predominantly a granodiorite that is deeply weathered and poorly exposed. It is intruded by the Payson Granite and fragments of this rock may be contained in the Gibson Creek intrusive suite which is exposed to the southwest of Payson. This geologic unit varies in composition from a gabbro to a granodiorite but is predominatly a diorite. It has an age date of 1,738 $\pm$ 4 Ma, is only moderately foliated and contains numerous intrusive bodies. The Gibson Creek Batholith is host to numerous veins in fault zones that contain sulfide minerals and have been mined for gold, copper and lead. This group of mines form the Green Valley Mining District (Keith et al. 1983). The youngest Early Proterozoic rocks of this area are those of the Payson Granite. It is a hypabyssal intrusive unit that has an age of 1,703 to 1,692 Ma and considered to be a mega sill. It intrudes the Gibson Creek Batholith and its contact with the rocks of this unit dips from 10 to 30 degrees to the southwest. The Payson Granite is predominantly a medium to coarse grain biotite-amphibole granite, but has alaskite and a granophyre phase. It is deeply weathered, is poorly exposed in areas of little relief, breaks up into a grus of quartz and feldspar with very little clay. Foliation is observed only near major Proterozoic faults (Georama 2006). The only other rock formation of considerable extent in the near vicinity of Payson is the Tapeats Sandstone of Cambrian age. Its lithology is that of coarse-grained, cross-stratified arkosic sandstone interbedded with pebble conglomerate.

All the rock units previously described are cut by numerous faults in the Payson area. These are mostly late Tertiary Basin-and-Range faults. There are two dominant bearings; northeast and northwest. The Rumsey Park Fault has been described as a Proterozoic fault that has been reactivated. The northwest trending faults are younger when compared to the older northeast trending faults. The older faults include: Star Valley fault, Goat Camp Canyon fault, Horton Canyon fault, Birch Mesa fault and Summit Canyon fault (Figure 1).

2.3 Hydrogeology

The source of water for the Town and for nearby communities of this region of north central Arizona has been groundwater. This region which is commonly referred to as the Mogollon Rim possesses a very complex interconnected regional aquifer system. Three main aquifers are recognized as the hydrogeologic units that form the regional aquifer. These are: the C aquifer, the RMX aquifer and the X aquifer. The C aquifer occurs within the Paleozoic sedimentary strata principally the Kaibab Limestone, Coconino Sandstone and the Upper to Middle Supai Formation. It is the principal aquifer of the Colorado Plateau Region. The RMX aquifer underlies the C aquifer and is formed by the Redwall Limestone, the Martin Formation, primarily limestone, and the underlying and upper portion of rocks of Proterozoic age which are igneous intrusive rocks and metamorphosed volcanic and sedimentary units. The RMX aquifer is more extensive in the Mogollon Rim area and the lowermost X aquifer further south in the northernmost part of the Transition Zone. There all the rocks of the Redwall Limestone and the Martin Formation have been eroded and only the Proterozoic rocks remain. The flow of groundwater in all three hydrogeologic units of the regional aquifer system is strongly dependent on the secondary permeability of their rocks. In the C aquifer both fracturing of its clastic units and dissolution features of limestone are important. For the RMX aquifer, karstic channel ways in the carbonate rocks and fracturing in the igneous and metamorphic units enhance secondary permeability. For the X aquifer, fault related fracturing and joint systems store and control the flow of groundwater.

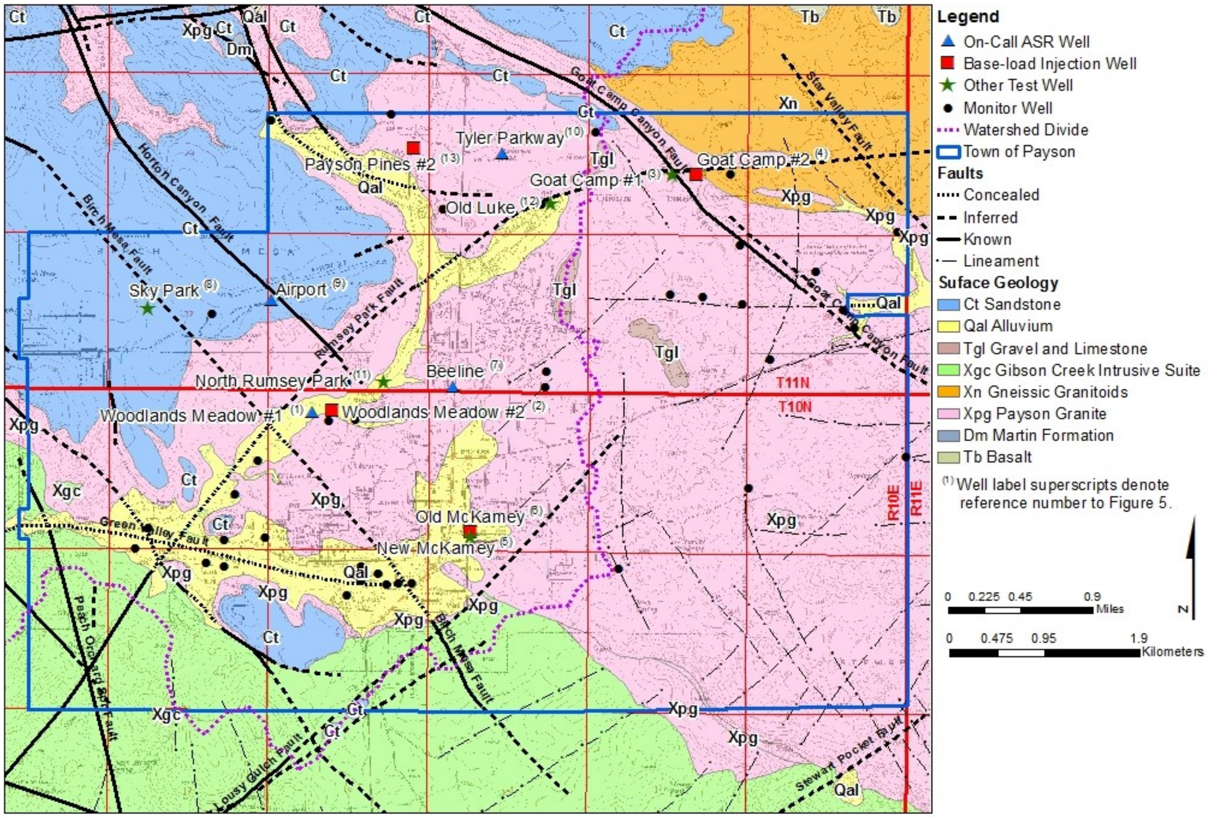

Figure 1. Town of Payson Map Showing Surface Geology and Selected Well Locations.

Groundwater flow in this region follows the topography from the higher elevation of the edge of the Colorado Plateau towards the East Verde River and Tonto Creek. The predominant regional flow is from northeast to southwest. The deep groundwater flow in the region originates in the C aquifer from the snowmelt and more abundant rain that recharges this aquifer in the Colorado Plateau, flows into the lower RMX aquifer and further below into the X aquifer. Structural features, such as the Diamond Rim fault have a strong influence in the direction of groundwater flow of this area modifying the local pathway bearing and its hydraulic gradient (Figure 2). The majority of springs in this region are located on faults and the intersection of faults. All throughout this region local recharge takes place. It ends up in the deep regional aquifer system but also replenishes shallow aquifers. In areas where the fractured Early Proterozoic rocks are exposed some of the igneous intrusive rocks undergo deep chemical and mechanical weathering which can store and transmit the recharge water and become good aquifers with sufficient yield to supply a household and even more. The Payson Granite is deeply weathered, forms this type of shallow aquifer and is cut by many of the Town's deep wells. The shallow wells pumping from these surficial aquifers exhibit significant changes in water levels which correlate well with climatic and seasonal fluctuations. The wells pumping from the deep regional aquifer display less water level variability.

The Town of Payson produces all its potable water supply from 42 wells. The yield from these wells range from 2 to 50 l/sec. The aquifer is mainly the fractured Payson Granite although four of the wells were drilled at the contact with the layered gabbro of the Gibson Creek Batholith. The depth of the wells range from 50 to 310 m. A comparison of the well yield with depth shows that deeper wells have a higher yield (HydroSystems 2012). The fractured density of the granite also influences the yield. The Goat Camp well located at the intersection of Rumsey Park fault and the Goat Camp Canyon fault, drilled to a depth of 287 m, pumps 20 l/sec. The Woodland Meadows Number 1 and 2 wells located near the intersection of the Rumsey Park fault, and two northwest trending faults pump 50 l/sec and 30 l/sec, respectively. Groundwater flows away from Payson to the east, south and southwest. This semi-radial flow pattern suggest that this is an area of local recharge.

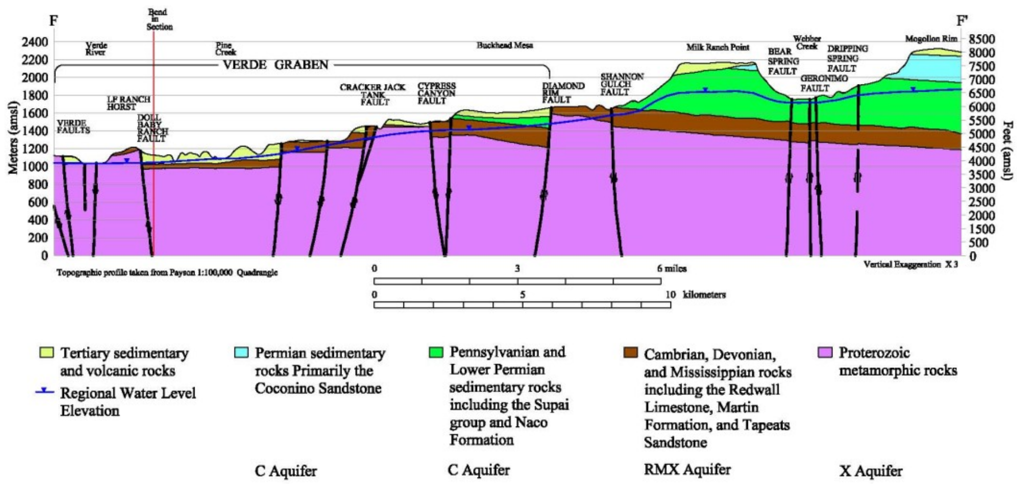

Figure 2. Geologic Cross-Section Displaying Water Level Elevation From the Mogollon Rim to the East Verde River.

3. Hydrogeochemistry

For the managed aquifer recharge project it is important to determine the compatibility of water being stored in the aquifer with the resident groundwater. The chemical aspects are most important since they will determine the final quality of groundwater and other possible impacts such as clogging of the aquifer.

3.1 Cragin Reservoir Water Chemistry

Payson will use the water stored in the Cragin Reservoir as the source to recharge the fractured aquifer. Its storage capacity is 18.5 million m^3 of which the Town will receive 3.7 million m^3 of water for direct use and underground storage (Estes 2011). The Cragin watershed has an area of 260 km^2 all in heavly wooded terrain of the Coconino National Forest within the Colorado Plateau region. The runoff is from precipitation as rain and spring snowmelt from areas with elevations of up to 2,500 m above mean sea level. The geology of the watershed consist of Palezoic sedimentary rocks with a large proportion of carbonate units.

The Cragin reservoir water has a TDS concentration that ranges from 34 to 50 mg/l and a mean of 42 mg/l. It is a calcium bicarbonate type with a mean pH of 7.3. Calcium and magnesium are the cations of higher concentration with a mean of 6 and 4 mg/l, respectively. The anion bicarbonate content has a mean of 25 mg/l and chloride of 2 mg/l. The Langelier Index (LI) has a mean of -1.8 indicating a strong undersaturation with respect to calcite ($CaCO_3$). Arsenic is below the detection limit as are barium, copper, manganese, chromium, and aluminum. Iron had the highest concentration of minor elements with a range of 0.1 to 0.2 mg/l. The total organic carbon (TOC) ranges from 5.5 to 5.8 mg/l. The source of the carbon in this water is derived mainly from the abundant decomposition of vegetation in the forested watershed.

3.2 Spring and Groundwater Chemistry

The groundwater of the Payson area is of a calcium bicarbonate type (Figure 3). Its TDS content is low and ranges from 140 to 450 mg/l and a mean of 266 mg/l. The pH is nearly neutral to slightly alkaline ranging from 6.8 to 8.4 with a mean of 7.7. The highest content component of the groundwater is bicarbonate with a mean value of 203 mg/l and a range of 80 to 390 mg/l. The other two major anions, chloride and sulfate, have lower concentrations with mean values of 23 and 17 mg/l, respectively. Calcium is the cation with the largest content with a mean of 47 mg/l followed by sodium and magnesium with means of 17 and 14 mg/l, respectively. Of the minor elements barium has the highest content in groundwater with a mean of 56 ug/l. Iron was not detected in 45% of the wells and in the remaining 55% it ranged from 0.3 to 5 mg/l. Arsenic had contents below 0.001 mg/l. The chemistry of groundwater in the deep X regional aquifer north and northwest of Payson is more evolved than local recharge having higher concentrations of dissolved solids, mainly as calcium, magnesium, bicarbonate and silica. Three of the wells that pump from the deep regional aquifer had TDS that ranged from 220 to 400 mg/l (HydroSystems 2006). In comparison the TDS of four wells with open boreholes that pump from the local and the regional aquifer ranged from 190 to 230 mg/l. Two wells also in the X aquifer but drilled in fractured diorite/gabbro of the Gibson Creek Batholith south of Payson showed a significantly different chemical composition having a large component of sodium sulfate not seen in any other wells of the Payson region. It is worth observing that it is only in the rocks of the Gibson Creek Batholith that there are veins of copper and lead sulphides in a cluster of small mines near these two wells. A down gradient increase in sodium, potassium chloride and silica in the regional aquifer has been attributed to longer residence time in the igneous rocks of the Early Precambria age. Table 1 shows the chemical composition of groundwater from five candidate ASR wells and provides the U.S. EPA maximum contaminant level (MCL) for regulated species.

There are numerous springs north of Payson especially in the vicinity of the Mogollon Rim (Figure 4). The majority discharge water from the C aquifer and only a few from the RMX aquifer. Their water chemistry indicate that they are of a calcium bicarbonate type the same as the water of the deep X aquifer and the shallow aquifer in the Payson area (Figure 3). Their TDS ranges from 110 to 440 mg/l, and reflects the contribution of local surface recharge to the springs. Those with TDS under 200 mg/l are a blend of groundwater and surface water (Weitzman 2002).

Table 1 Chemistry Data for Selected ASR Candidate Wells

	Primary MCL	Secondary MCL	North Beeline Well	Woodland Meadows #1		Woodland Meadows #2	New McKamey Street		Goat Camp #1		Sky Park Well
POE #			003	007		022	008		031		032
ADWR No.			620867	503323		512429	509870		565426		568624
Well Depth			1004	925		700	860		925		815
Aquifer Geology			X Payson Granite	X Payson Granite		X Payson Granite	X Payson Granite		X Gneissic Granite		X Payson Granite
Water Source			Local + Regional	Local + Regional		Local + Regional	Local + Regional		Deep Regional		Deep Regional
Sample Date			02/09/04	02/09/04	04/21/04	02/09/04	01/06/03	03/16/04	12/18/01	02/11/04	02/12/04
Sample Used in Model			yes	yes	no	yes	no	yes	no	yes	yes
Temperature (°C)					16.5		16.3		16.6		
pH (S.U.)		6.5-8.5	7.1	7.0	7.3	7.2	7.1	7.0	6.9	7.7	7.4
Arsenic (mg/l)	0.01		<0.001	0.0012		<0.001		<0.001		0.0031	0.0017
Asbestos (MFL)	7		<0.2	<0.2		<0.2		<0.2		<0.5	<0.2
Barium (mg/l)	2		0.025	0.035		0.036		0.027		0.13	0.081
Cadmium (mg/l)	0.005		<0.0005	<0.0005		<0.0005		<0.0005		<0.0005	<0.0005
Chromium (mg/l)	0.1		<0.001	<0.001		<0.001		0.0012		<0.001	<0.001
Fluoride (mg/l)	4	2	0.85	0.85	0.86	0.68	1.3	1.3	0.48	0.28	0.44
Mercury (mg/l)	0.002		<0.0002	<0.0002		<0.0002		<0.0002		<0.0002	<0.0002
Nitrate (mg/l N)	10		1	1.4	1.5	1.7	1.6	1.2	0.8	0.79	0.71
Nitrite (mg/l N)	1		<0.1	<0.1		<0.1		<0.1		<0.1	<0.1
Selenium (mg/l)	0.05		<0.005	<0.005		<0.005		<0.005		<0.005	<0.005
Alkalinity (mg/l CaCO3)			114	114	120	103	150	131	270	274	314
Calcium (mg/l)			29	31	28	28	39	36	81	77	73
Chloride (mg/l)		250	10	11	11	11	15	14	12	9.5	19
Copper (mg/l)	1.3	1	0.019	0.0023		0.011		<0.002		0.003	0.0098
Hardness (mg/l)			118	127		111		143		250	298
Iron (mg/l)		0.3	<0.010	<0.010	<0.05	4.9	<0.05	0.098	0.18	0.053	3.0
Langlier Index			-0.7	-0.8		-0.59		-0.59		0.66	0.40
Lead (mg/l)	0.015		<0.0005	0.00089		0.011		0.0097		0.0013	0.0051
Magnesium (mg/l)			11	12	10	10	14	13	14	14	28
Manganese (mg/l)		0.05	<0.002	<0.002		0.0023		0.056		0.0027	0.12
Silver (mg/l)		0.1	<0.0005	<0.0005		<0.0005		<0.0005		<0.0005	<0.0005
Sodium (mg/l)			17	17	16	15	18	18	18	17	19
Sulfate (mg/l)		250	10	15	15	10	13	11	5.3	5.5	5.9
TDS (mg/l)		500	200	210	190	190	230	210	320	300	350
Zinc (mg/l)		5	0.01	0.073		0.15		0.22		0.33	0.32

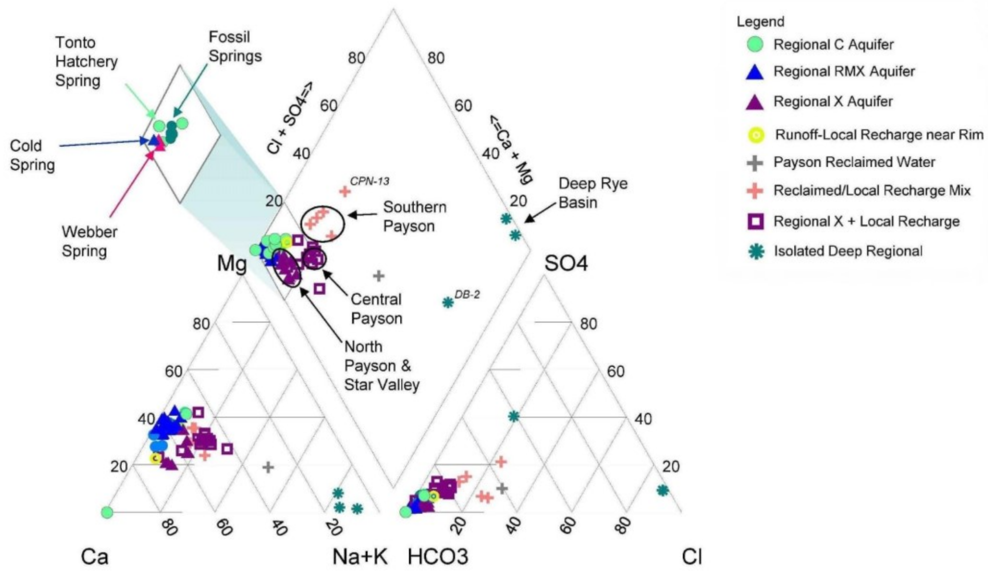

Figure 3. Piper Diagram Indicating Water Chemistry Differences Between Regional Groundwater Aquifers and Local Recharge.

3.3 *Impacts of Blending Reservoir Water and Groundwater in the Aquifer*

Both the Cragin reservoir water and the groundwater pumped by the wells of Payson are of a calcium-biocarbonate type. Their pH is close with a mean of 7.3 for the surface water and 7.7 for the groundwater. The principal difference is in their TDS which have a ratio of 1:6. The very low TDS of the reservoir water renders it very corrosive. A study carried out in 2007 examined the possible effects of placing this water into the existing municipal distribution system and using several blending schemes to mitigate its possible chemical impacts. Among these was blending in the aquifer (HydroSystems 2007). Table 2 shows the saturation indices (SI) for the reservoir water and the groundwater from six wells for the three most common minerals that could precipitate in the fractures of the Payson Granite during an ASR operation. These negative values show that calcite ($CaCO_3$) and gypsum ($CaSO_4$) will not precipitate in the groundwater under present conditions even if the reservoir water is injected and blended in the aquifer. The injected reservoir water will tend to depress the SI of the groundwater of the deep regional aquifer and diminish the precipitation of calcite and gypsum. However, positive values of the SI for both surface water and groundwater indicate the potential for precipitation of Ferrihydrite ($Fe(OH)_3$ in the fractures of the aquifer which could be a concern for clogging. However, the very low iron concentration of the surface water and groundwater does not favor precipitation of hydrous iron oxides in large amounts and in the short time of injection. Nevertheless, aquifer clogging will be monitored during ASR operation.

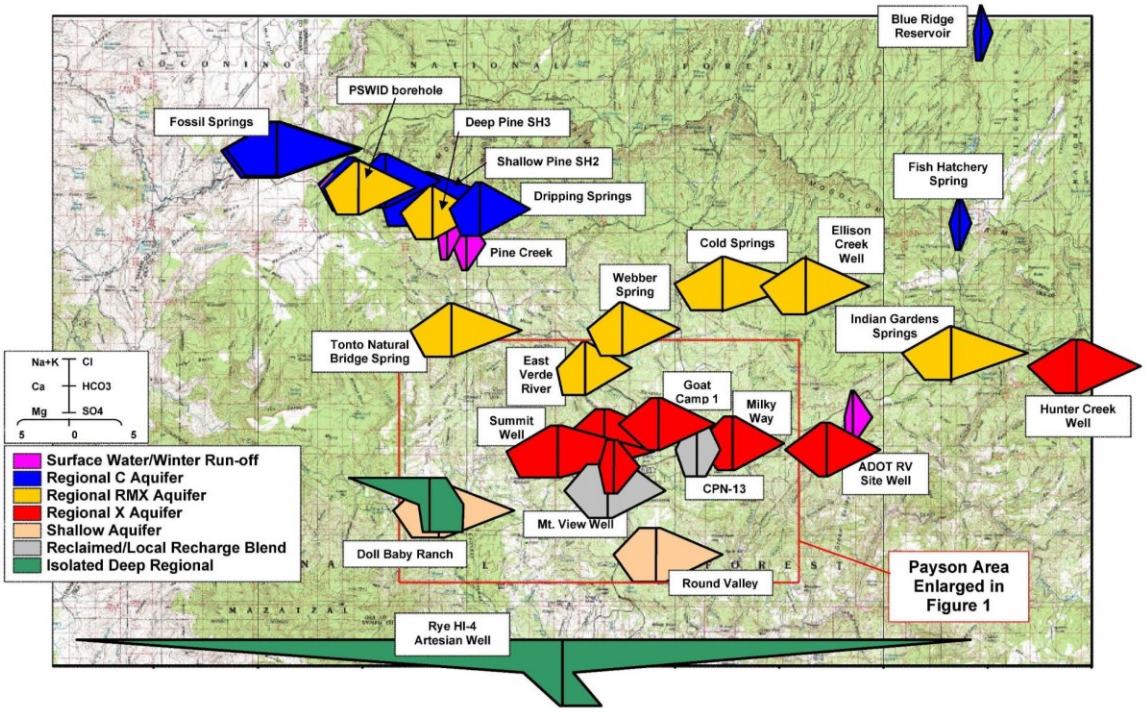

Figure 4. Chemical Variability of Spring, Surface and Well Waters as Shown by Stiff Diagrams.

Table 2
Saturation Indices and Selected Species of
of Cragin Reservoir Water and of Groundwater Concentrations (mg/l)

	Cragin Reservoir	North Beeline	Woodland Meadows # 1	Woodland Meadows # 2	New McKamey	Goat Camp # 1	Sky park
Water Source	Surface Water	Local + Regional	Local + Regional	Local + Regional	Local + Regional	Deep Regional	Deep Regional
Saturation Indices							
Ferrihydrite	1.98	0.11	0.12	3.13	1.19	1.52	2.94
Calcite	-1.37	-0.68	-0.61	-0.63	-0.55	0.24	0.36
Gypsum	-3.95	-2.98	-2.80	-2.98	-2.82	-2.93	-2.96
Aqueous Concentrations							
pH	7.45	7.10	7.15	7.20	7.04	7.30	7.40
Bicarbonate	37.56	137.30	140.90	124.00	168.90	297.00	353.00
Calcium	6	29	30	28	38	79	73

4. Evaluation of Aquifer Storage and Recovery

4.1 Initial Pilot Project Injection Testing and Results

In order to test out the concept of ASR in a fractured rock aquifer an initial pilot injection test was planned. Specific criteria were identified such as casing diameter, pumping rate, location, open borehole, access, monitor points, and long-term static water level trends in order to select wells for pilot injection testing. Each parameter included a numerical ranking where the increase in rank indicated the favorability for injection testing. After evaluating all 42 water production wells only about 1/3 of the wells received a high enough ranking for consideration of injection testing.

For the initial round of injection testing conducted in 2006, only the five highest ranking wells were selected. The Town's requirement of a recharge capacity of 81.7 l/sec was established as the anticipated capacity needed to recharge the excess treated surface water. A downhole flow control valve was used on the larger diameter wells and an orifice plate was used on the smaller wells. The injection testing proved to be very successful by demonstrating a recharge capacity of approximately 149.5 l/sec.

4.2 Follow-up Pilot Project Injection Testing and Results

A second round of injection testing occurred in 2011 and 2012 with eight additional selected wells. The additional testing further expanded the anticipated recharge capacity to approximately 230.9 l/sec (19,950 m^3/day). The positive testing results are exceptional when considering that injection recharge occurred in a bedrock aquifer consisting of the Payson Granite. The initial and follow-up pilot project injection testing utilized 13 wells recharging approximately 34,069 m^3 of water over 470 hours of injection testing. The demonstrated recharge capacity was approximately 3 times the required recharge capacity of the Town.

Figure 5 displays the comparison of injection rates to the pumping rates of each individual well. In most cases, the injection rates were higher than the pumping rates indicating that the fractures exposed above the water table were sufficient to handle the increased flow rates. Similar higher injection than pumping rates were observed in pilot tests carried out in a fractured granite aquifer in the small community of Karkams, South Africa. In three separate tests undertaken respectively in 1999, 2000 and 2001 using two production wells and with filtered water from a nearby stream, the injection rate more than doubled the wells sustainable yield of 2,400 m^3/y (Murray and Tredoux, 2002). Unlike storing water in between sand grains in alluvium, these fractures remain open and are readily available to accept and store water. Fractures are not affected by aquifer compaction once the water has been removed.

4.3 Injection Equipment and Instrumentation

The ASR concept calls for certain wells to be converted from water production wells to ASR wells. The Town's wells are all smaller diameter wells ranging from 20.3 to 25.4 cm and were drilled into fractured granite having varying production and injection rates depending on the density of the fractures that were intercepted by the wells. All wells have steel casing extending the entire depth of the well or are partially cased with the bottom of the well left uncased. The wells that are completely cased have vertical slots in the casing opposite the area where the fractures occur. None of the wells have a gravel pack or formation stabilizer behind the casing.

A specially fabricated downhole flow control valve was developed to fit inside of the 20.3 cm casing. The downhole flow control valve was easily opened or closed as a way to adjust the recharge flow rate going into the well without any air entrainment.

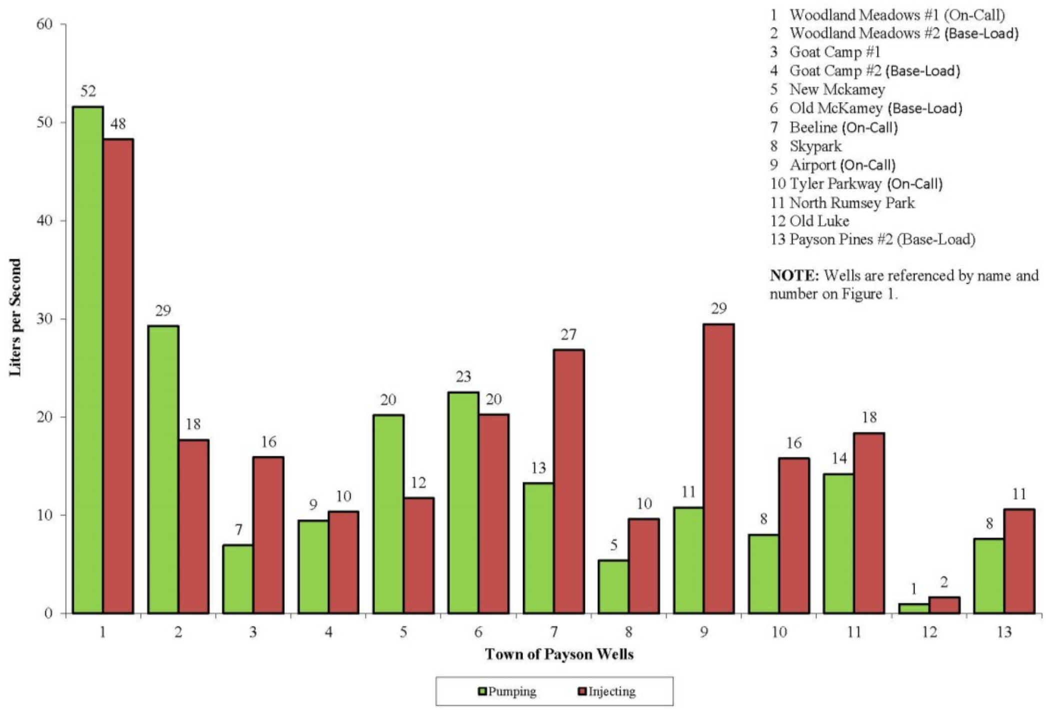

Figure 5. Pumping and Injection Flow Rates for Tested Wells.

Four of the ASR wells will be fitted with a downhole flow control valve and a submersible pump allowing these wells to be used as dual purpose wells. Wells equipped with the downhole flow control valve are considered On-Call wells. Four other ASR wells will be fitted with a downhole orifice plate to regulate flow going into the well. These wells are single purpose wells and can only be used for injection and are considered Base-Load wells. The two types of wells will work together with the Base-Load wells operating continuously handling the major component of the recharge volume whereas the On-Call wells will be used to handle variability in flow volumes during the day.

5. ASR Well Field Operation Plan

The delivery of finished water to customers is the Town's top priority. The second priority for finished water is to maintain full above ground storage reservoirs. The third and final priority for finished water is the underground storage of excess finished water for storage and recovery via ASR recharge wells.

The ASR system allows treated surface water that is not directly used to meet the Town's water demands to be recharged for future use. Flow rates of treated or "finished" water coming into the distribution system are expected to range between 10,975 to 15,140 m^3/d.

The ASR recharge wells were selected to achieve a combined recharge capacity of up to 13,440 m^3/d which includes a combination of a Base-Load recharge capacity of 4,280 m^3/d and an On-Call recharge capacity of 9,160 m^3/d. The Base-Load recharge capacity will likely be fully utilized during the first ten years of operation due to a seasonal surplus of treated surface water available for recharge along with lower customer demands

The conceptual water delivery overview is displayed in Figure 6 which represents the strategy that will be implemented during the operation of the ASR well field. At the start of each recharge season a pipleline flush will occur using the initial flow of surface water from the reservoir that will be discharged on a nearby golf course. After the initial flush the surface water will then be delivered to the water treatment plant where it will be filtered and chlorinated prior to sending it to the Town's water distribution system. Once in the distribution system, the finished water can be used to meet customer demand, go to system storage or go to recharge through the ASR recharge wells.

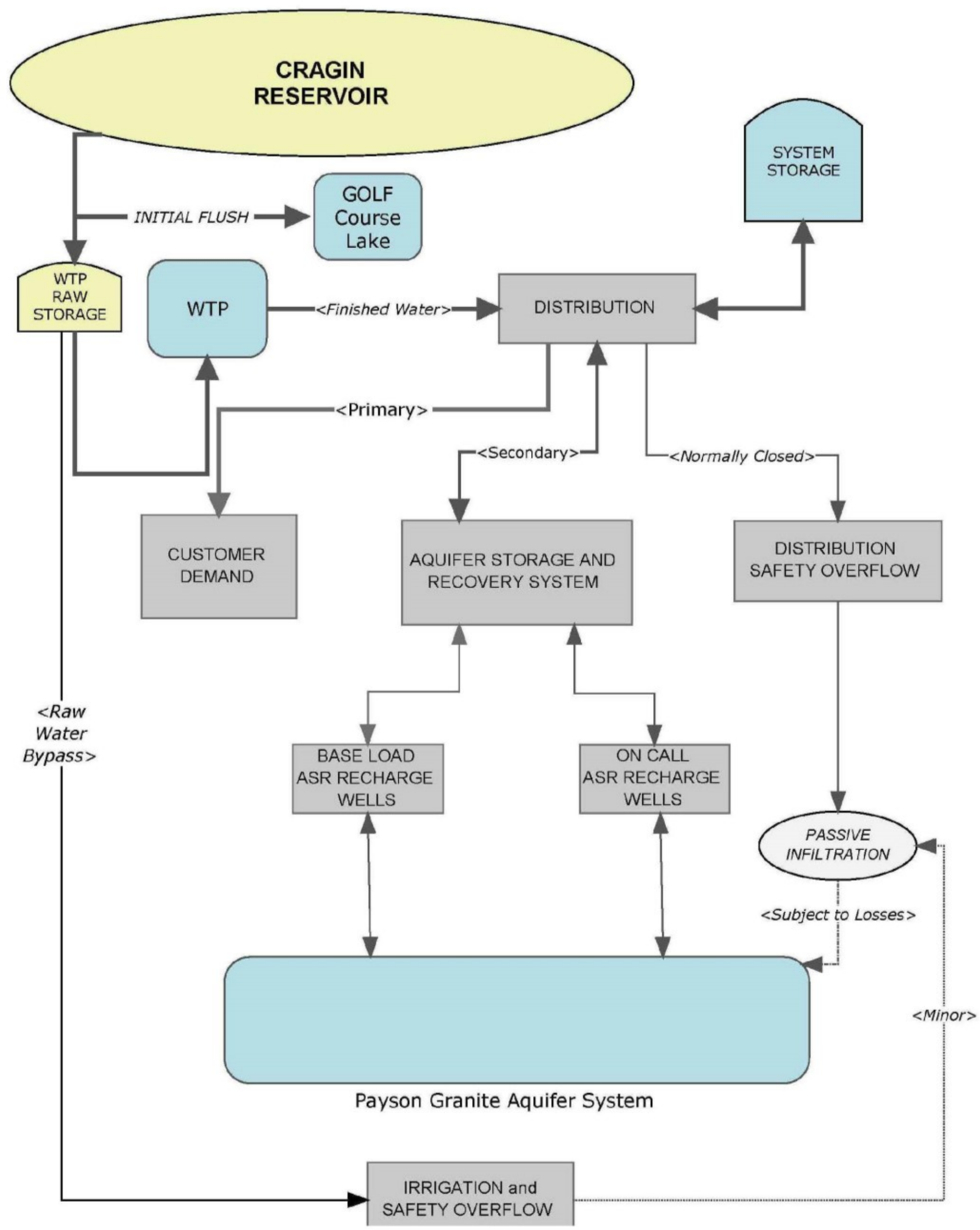

Figure 6. Conceptual Water Delivery Overview.

A Base-Load fixed orifice well when operating, is either on or off and there is no ability to adjust the flow rate without changing the orifice size. A water level transducer will also be housed inside the well casing to measure and report real time water levels within the well. Should the water level rise beyond a maximum upper level, the transducer will record that level, trigger an operator alarm and then have the well shut off.

On-Call ASR recharge wells incorporate a downhole flow control valve for flexibility to adjust the flow rate from 0 to 47.3 l/sec depending on how far the valve is opened. The opening of the valve will be controlled through a computerized hydraulic pump in a control cabinet. The flow rate will depend on the amount of water in the distribution system that is available for recharge and the performance of the ASR On-Call recharge well.

The water level transducer in the recharge well will also be used to control the water level rise in the well. This operation allows the computer to close the downhole flow control valve slowly reducing the flow rate until the water level in the well drops back into the operating range.

The On-Call ASR recharge wells are very important to operate in conjunction with the Base-Load ASR recharge wells (Figure 6). An example as to how these two types of wells could work together would be as follows. The finished water flow rate coming into the distribution system is a normal flow of approximately 175.3 l/sec. The customer's water demand is only approximately 96.5 l/sec leaving 78.7 l/sec going to either system storage or to recharge. Once the system storage capacity is full then the ASR wells will need to be put into operation to recharge the remaining flow. The ASR System Operator realizes that the Base-Load recharge wells can only provide recharge capacity of 73.8 l/sec so an On-Call well will need to be operated to make up the difference which is 4.9 l/sec to match the inflow.

The On-Call ASR recharge wells also provide important backup capacity should operational problems occur with one or more of the Base-Load wells. The On-Call ASR recharge wells can also be set to operate at a fixed flow rate if the need arises therefore, one or more Base-Load wells can be taken out of service without affecting the Town's ability to recharge the available surface water.

The On-Call ASR recharge wells have an advantage over the Base-Load wells because of their ability to be back flushed. Perdiodically, these wells will be placed in a pumping mode to reverse the flow in the aquifer. The reversing of flow helps to minimize the plugging effects caused during recharge.

There are several recharge methods that can be used to replenish the aquifer however, it is very important that the chosen recharge method complements the hydrogeology from a cost and efficiency standpoint. In the case of the Town of Payson, installing recharge basins in the shallow alluvium is less costly than ASR wells. However, the efficiency of the recharge water reaching the groundwater table in the aquifer could be lower and potentially risky due to evaporation and the lateral movement that could take place when the water encounters the top of the granite aquifer.

From a cost standpoint, the capital cost for two fully equipped ASR wells is approximately US$500,000. This assumes that the wells maintain an average annual recharge capacity of 18.9 l/sec equaling approximately 600,000 m^3/year. The annual operation and maintenance cost is estimated at US$30,000. The average life of an ASR well is about 15 years and over this time 9 million m^3 of water can be recharged, and 100% of this water reaches the water table. Assuming a discount rate of 4%p.a. over a 15 year project life, these capital and operating costs in a present value analysis yield a levelized unit cost of additional groundwater of US$0.12/$m^3$. Levelized unit cost is simply the annual cost of supply (the sum of the annual operating and maintenance costs and the annuity that amortises capital costs over the project life) divided by the annual supply volume.

If the same 9 million m3 of recharge was applied to an infiltration basin project, then a total of 162,000 m^2 of basins is required accounting for the wetting and drying cycles. The capital cost would be US$400,000 for the land plus US$120,000 for initial construction. The annual operation and maintenance cost is likely US$20,000. However it is estimated here that only approximately 70% of the applied water actually reaches the groundwater table. Again assuming a 15 year project life and the same discount rate, the levelized unit cost of cost of additional groundwater would be US$0.16/$m^3$.

6. Conclusions

ASR projects performed over the last several years for the Town of Payson has been a huge success. Injection testing of the selected Town wells exceeded the 2006 recharge capacity of 81.6 l/s with 149.2 l/s in 2011 and 2012 having a remarkable combined total recharge capacity of approximately 230.5 l/s or 20,060 m^3/d. The positive testing results are exceptional when considering that injection recharge occurred in a bedrock aquifer consisting of the Payson Granite. In other geologic environments, the general rule of thumb is to expect the recharge capacity to equal approximately one-half of the normal pumping capacity of the well. Figure 5 compares the pumping and injection flow rates experienced at the 13 wells tested for the Town. The injection rate at more than 50% of the Town sites exceeded the pumping rate.

At this time, groundwater is the sole source of potable water for the Town accessed from 42 water production wells. Drought and large seasonal demand can burden the limited groundwater supply particularly in the summer months. In 2011, the Town had approximately 16,000 residents having an estimated water demand of 2.0 million m^3. The Town desires to maintain water usage below what is replaced on a long-term basis by rain and snowfall within the watersheds that recharge or re-fill the aquifer upon which it relies. Maintaining groundwater usage below this amount is considered Safe Yield (Town of Payson 2011). The groundwater cap (as enumerated in the Town of Payson/SRP Cragin Surface Water Agreement of 2008) is set at 3.1 million m^3 within the Safe Yield of approximately 3.3 million m^3. As additional growth is experienced in the Town with a commensurate rise in water demand, additional water supplies are required if sustainability is to be achieved. Implementation of Payson's part of the Arizona Water Settlements Act of 2004 with completion of the Cragin Pipeline Project will provide 3.7 million m^3 of surface water for use by Payson. Once undergoing treatment in a newly constructed water treatment facility, imported water will enter the distribution system. Water that is not required to meet the operational demand will be directed through the main distribution system and stored underground through ASR wells. Groundwater production areas that were once over pumped are now planned for seasonal recharge of surface water through ASR wells. The use of ASR wells will meet seasonal needs while helping to restore previously depleted groundwater production areas. Groundwater resources can then be restored as a primary reserve for drought and meeting future demand. In essence, long-term water sustainability is very much a possibility for Payson through the ASR project (Ploughe and Paski 2012).

Acknowledgments

The authors of this paper wish to recognize the Payson Water Department as a leader in fractured rock ASR technology for municipal use and a group to be recognized for practical and creative water resource implementation. Mr. Buzz Walker is the visionary individual, who has always recognized the value and importance of protecting and planning the Town's most precious commodity, which are its water resources. Mr. Walker has spent his entire career, as an overseer of this water resource to meet the water needs for future generations. Mr. Michael Ploughe acted as the Town's hydrogeologist for several years and provided the technical expertise to study and understand the hydraulic conditions indigenous to the bedrock aquifer. Mr. Ploughe was instrumental in developing testing and ongoing monitoring of the Town's water resources and keeping the public informed through various communication formats. Mr. Mark Keeney is responsible for the nuts and bolts of the Town's water system, providing capable staff oversight to meet the water needs of the community. Mr. Keeney works closely with hydrogeologists and engineers as the practical component of the water delivery operation and delivery system. Without the continued commitment, talent, insight, and dedication of these three individuals, ASR in the Payson Granite at the municipal level would not be possible.

Abbreviations

mm:	millimeters	Ma:	Million years ago
cm:	centimeters	mg/l:	milligrams per liter
m:	meters	TDS:	Total dissolved solids
m^3:	cubic meters	l/sec:	Liters per second
km:	kilometers		
km^2:	square kilometers		

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