Sedona Waste Water Treatment Plant
Groundwater Recharge Feasibility Evaluation

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1.0 BACKGROUND

Since at least 1995, the City has examined several alternative options to dispose of treated wastewater: (1) the creation of wetland treatment systems, (2) piping treated effluent to currently dry washes which, in turn, would enhance riparian development, (3) discharging wastewater to an existing sinkhole, and (4) consumptive reuse which would utilize the existing irrigation of Coconino National Forest land to produce feed crops (or a combination of alternatives) (Burgess and Niple, 2008). Each of these alternatives has been analyzed and compared by previous contractors with respect to the factors mentioned above. All of these options possess some disadvantages that make long-term viability difficult. As a result, the City has recently looked into a fifth option: the possibility of using surface or well recharge as a means of both disposing of treated effluent and providing a means to recharge the local groundwater.

In the Sedona Wastewater Project Interagency Meeting Summary (April 8, 1996) five separate areas of concern were identified in the implementation of any of the alternatives mentioned above: (1) general environmental/ecological, (2) hydrologic, (3) technical/operational, (4) financial/administrative, and (5) community benefit. This report addresses the hydrogeologic aspects related to the possibility of well recharge. It takes into consideration the following hydrologic goals and objectives as expressed in the Interagency Meeting Summary:

- Avoid negative hydrologic impacts
- Meet or exceed aquifer water quality standards
- Meet the requirements for ‘unique water’
- Protect or enhance the quality/integrity of Oak Creek

2.0 PURPOSE

2.1 Purpose

The purpose of this study is to determine if a recharge method can be employed on or near the WWTP property that satisfies the five concerns stated above as well as provides a viable long-term option with competitive costs when compared to the costs of the four previously studied alternative methods of disposing of treated effluent.

2.2 Method of Study

For this feasibility evaluation the available consultant's reports related to the hydrogeology in and around the WWTP were obtained from the City and evaluated. All available primary hydrologic and geologic information was acquired from their original sources (ADWR, AZGS, USGS) and evaluated for comparison. HSI personnel conducted an onsite visit of the WWTP on May 6, 2009 for purposes of locating and observing the available wells in the area and observing the local geology and soils. All of this information has been evaluated and assimilated into the following summary.

3.0 GEOLOGY

3.1 Geology Beneath the Site

At least six geologic maps are available that include the area of the WWTP (Twenter and Metzger, 1963; Levings, 1980; Owen-Joyce and Bell, 1980; Weir et al, 1989; House and Pearthree, 1993; DeWitt et al., 2008). Each is a different scale and each shows the geology in and around the WWTP site differently. There are similarities between them, however. The site rests on a gently southwest-sloping plain that is covered in patches by alluvial deposits up to several tens of feet thick. These alluvial deposits were mostly derived from the weathering and erosion of the older rocks in the area and in part from the influx of wind-blown silt and clay. The deposits are composed of a wide variety of materials including clay, silt, sand, and cobbles. Most of the material exposed at the surface is composed of fine-grained silt and clay, and this material forms much of the matrix of the coarser-grained conglomerate deposits in the subsurface. Protruding through this cover in places are light tan-colored outcrops of the Verde Formation. The Verde Formation in this area is composed of interbedded limestone, limy siltstone, and minor sandstone that were deposited in quiet waters when the Verde Valley was a closed lake basin several million years ago. Much of the Verde Formation was removed by erosion in this area. Outcrops of dark gray basalt form most of the surface exposures near the WWTP. These basalts were erupted as hot lava flows that flowed across the landscape. The Verde Formation appears to fill ancient channels that were cut into the underlying basalts by stream erosion long after the basalt flows had cooled and solidified. All together the alluvial cover, Verde Formation, and basalts are about 140 feet thick as interpreted in Monitor Well 4A (55-526825). For the location of this well see *Figure 1*.

The well log for well 55-600125, drilled in cadastral A(17-4)25bba, indicates that fine-grained red sandstones of the Supai Formation underlie the basalt to a depth of 460 feet. The Supai Formation forms most of the strikingly rusty red landscape for which Sedona is famous. It is composed almost solely of very fine-grained red quartz sandstone and siltstone. This is the same unit from which the City of Flagstaff obtains most of its groundwater. Because the Supai Formation is so fine-grained specific capacities (a measure of a formation's ability to transmit water into a well) are typically less than 1 gallon per minute per foot of drawdown—which means water flows very slowly through the Supai Formation. Where successful wells have been drilled, the wells characteristically penetrate fractures within the formation. Fractures are direct paths for groundwater and flow rates through fractures can be much higher than through the formation itself.

Below the Supai Formation from 460 feet to 878 feet the log of well 55-600125 shows interbedded sandstone, mudstone, and limestone of the Naco Formation. The abundance of mudstone layers means that the Naco Formation is even less able to transmit water and in most areas is considered an impermeable layer, or 'aquitard'. Below 878 feet to the bottom of the borehole at 920 feet is the Redwall Limestone. Limestone deposits are typically very finely crystalline and contain few pore spaces, but they are also susceptible to dissolution by fresh water over time. As a result, since its uplift above sea level more than 300 million years ago, the Redwall Limestone has developed a network of solution cavities that have been partially filled with reddish clay-rich insoluble residue. The remaining open cavities are prime places for groundwater flow. Although not penetrated in well 55-600125 and not exposed in the region, the

Redwall Limestone is underlain by the Martin Formation (dolomite) and the basal Tapeats Sandstone. Below these units are Precambrian granitic and metamorphic rocks that extend to great depths.

3.2 Surface Soils

Engineering-Science (1991) DEI Professional Services (1995), and CH2MHill (1998) all examined the geology and hydrology at the WWTP itself in detail. Their reports agree reasonably well when describing the surface material at the facility. They subdivide the material into two separate deposits: a shallower soil described as relatively loose silty sand from the surface to depths of about 2 to 11 feet, overlying a deeper soil composed of harder, more clay-rich conglomerate down to a depth of 68 feet. Dames and Moore (1998) also drilled three soil borings to depths of 500 feet. They described "fault gouge" composed of clayey gravel down to 210 feet, which is likely conglomerate as well. The thickness of this material is highly variable and pinches out close to zero where basaltic bedrock is exposed. HSI personnel also witnessed these clay-rich soils exposed on the surface, in small road-cuts, and in the excavated material used to construct the impoundment basins. ***The presence of so much clay-rich material near the surface constitutes a significant barrier to infiltration.*** This is supported by the observation that the Rapid Infiltration Basins (RIB's) onsite are no longer used because they have become 'clogged' (from personal correspondence with City personnel).

In 1995 DEI Professional Services (1995) drilled 34 soil borings between four and 68 feet deep in Area 2 of the WWTP, in what is now the three impoundment reservoirs. The logs of these borings were examined and a cumulative grain-size distribution graph was created for their tabular data (*Figure 4*). DEI also dug 15 shallow test pits between 5.5 and 15 feet deep. Their goal was to observe and characterize the composition of the materials close to the surface to help estimate recharge rates. As mentioned above, nearly all of the borings and test pits revealed clay-rich sedimentary deposits from the surface down to depths of at most 68 feet. Perched groundwater was encountered in ten of the borings between depths of 9 and 34 feet. These shallow water levels correspond to areas that were recently used as infiltration basins. ***These data indicate that the surface soils at the WWTP are not conducive for surface recharge.***

3.3 Structure

The geologic maps discussed in Section 4.1, show several small faults between Sedona and the WWTP (*Figure 2*). All of the faults have a northwest-southeast strike and all have been mapped as down-to-the-south normal faults. Unlike the Verde fault which dips to the northeast and has rotated rock units down to the southwest, these smaller faults dip to the southwest and have acted to rotate the geologic units back to the northeast. As a result, many of the sedimentary beds visible between the WWTP and Sedona are nearly flat-lying. The contact between the Supai Formation and the Coconino Sandstone on the north side of House Mountain about 3 miles southeast of the WWTP appears to dip very gently to the southwest, as does the contact between the Supai Formation and the basalt in the immediate vicinity of the plant site itself. The gentle dip is probably the reason why the groundwater contours in *Figure 3* are so widely spaced in the area of the WWTP.

The cross-section drawn by Paul Lindberg in Burgess and Niple (2008) (*Figure 5*) shows about 200 feet of displacement on the Page Springs fault located about 3 miles south of the

WWTP. On the cross-section, the fault is shown to cut the Paleozoic rocks and the younger Tertiary basalts. Only one of the six published geologic maps of the area shows the existence of the Page Springs fault. The map that does show the fault is DeWitt et al., (2008) (*Figure 2*) and it shows the fault as a dashed line which denotes uncertainty in either its location or its existence. ***Understanding whether or not this fault exists is an important point.***

Burgess and Niple (2008) concluded that any direct recharge from the area in or near the WWTP will flow south-southwestward and then be preferentially funneled laterally southeastward along the fault until it reaches the surface at Page Springs where the water could then enter Oak Creek. The fact that none of the geologic maps of the area show a definite fault, combined with what appears to be abundant obscuring soil cover at the surface along the surmised fault, probably means that there is not enough exposure at the surface to clearly identify a fault. ***Additional field mapping and surface geophysics would be required to better define the presence and location of this fault.***

4.0 HYDROLOGY

4.1 Groundwater Levels

HSI created a groundwater flow contour map (*Figure 2*) using the latest available groundwater level information derived from the ADWR-GWSI database showing a general groundwater flow direction to the southwest. HSI also modified an existing Dames and Moore (1998) groundwater contour map by adding recent depth to water measurements of the existing wells in and around the WWTP collected by City personnel on May 14, 2009 (*Figure 1*). Groundwater level beneath the site is about 450 feet below the surface. The current groundwater contour map (*Figure 2*) agrees reasonably well with other groundwater contour maps produced by previous contractors showing groundwater flowing to the southwest under the WWTP. ***This means that not much change to the groundwater level beneath the WWTP has occurred over the years. If recharge could occur at the WWTP, there would likely not be any obvious threat to Oak Creek due to the groundwater flow direction.*** However, some of the unknowns involve the direction and extent of lateral groundwater flow which can be controlled by either the characteristics of the sedimentary beds or by faults themselves.

As mentioned above Burgess and Niple (2008) reported that recharged water might be diverted southeastward to Page Springs by the inferred Page Springs Fault. Burgess and Niple (2008) also made a similar conclusion for the Spring Creek fault, located about 1.5 miles to the southwest of the inferred Page Springs fault (according to Paul Lindberg's cross-section in *Figure 4*). They cautioned that recharged water would be preferentially diverted southeastward along the Spring Creek fault and resurface at springs along Spring Creek. Besides being shown on the cross-section, this fault has also not been shown on previous geologic maps, except on the map by DeWitt and others (2008) where it is again dashed and given the name Sheephead fault (see a discussion of this fault in Recharge Options). Burgess and Niple (2008) also surmise that groundwater eventually makes its way downward into the Redwall Limestone where it flows through dissolution cavities and eventually surfaces at Page Springs.

4.2 Available Infiltration Data

Engineering-Science (1991) also drilled numerous soil borings within Area 2 of the WWTP, and a few in Area 1. Their observations of the geologic materials are comparable to those of DEI's (1995) and revealed surface alluvial deposits up to tens of feet thick overlying basalt. Engineering-Science also performed six falling-head tests within some of the borings and 14 cylindrical infiltrometer tests. Their tests concluded that the hydrologic conductivity of the surface alluvium (the clay-rich material down to a depth of at most 68 feet) has a value of about 5.92 feet per day. These tests were all of relatively short duration—less than 8 hours per test for the infiltration tests and less than 1.5 hours for most of the falling-head tests.

Infiltration tests performed by HSI in other areas, typically show much higher rates at the beginning of the tests and decrease dramatically over longer time intervals of days and/or weeks, and in some cases by more than an order of magnitude. This reduction in infiltration rate occurs as water that has infiltrated deepest encounters material with even lower infiltration rates, and the water above slows down. In effect, the entire water column becomes perched to some extent on this less transmissive material. ***This is very important because although previous reports of the***

WWTP site estimate relatively rapid rates of recharge (Dames and Moore, 1998) these rates are based on data obtained from the short-term tests and the conclusions are thus not likely realistic.

The previous tests also concluded by DEI showed that the basalt, mostly buried beneath the alluvium, has a much lower average hydrologic conductivity of 0.6514 feet per day. Even though the exposures of basalt at the surface appear to be extensively fractured, DEI observed that the fractures within the basalt in the subsurface are 'extensively infilled'. An infiltration test performed by Hydrometrics (2001) within Boring 4-A showed a comparable infiltration rate of between <1 and 3 gallons per minute. ***These were also short-term tests. Therefore, the long-term infiltration rate will likely be even less than 0.6514 feet per day and could be much less.***

A 4-hour constant-rate pumping test performed by Engineering-Science (1991) within MW-1 provided an estimate of the hydrologic conductivity of the underlying Supai Formation sandstones at 50 feet per day, corresponding to a transmissivity of about 19,000 gallons per day per foot. The Supai Formation thus has a hydrologic conductivity one order of magnitude greater than the alluvium and two orders of magnitude greater than the basalt. The fine-grained nature of the Supai Formation suggests that the hydrologic conductivity should not be that much higher than the alluvial sediments. The discrepancy may be resolved by the observation that the well log indicates zones within the Supai Formation that contain abundant fractures. ***Therefore, the hydrologic conductivity value of the Supai Formation without fractures may be significantly less.***

A 6-hour pumping test was performed on well 55-501470, cadastral A(17-4)25baa, in March, 1982 when the well was deepened by Earl Huggins, Consultant and Myers Drilling Company. The 5-inch diameter steel casing allowed only a 5-hp pump, which was set at a depth of 618.8 feet. The static water level was 471 feet. The 5-hp pump allowed a maximum pumping rate of 22 gpm and showed 2 feet of drawdown. This corresponded to a specific capacity of 10 gpm/ft. Engineering-Science (1991) also reported a specific capacity of 20 gpm/ft from a well on the northwest side of the WWTP with cadastral A(17-4)25bbc (well number unknown). The specific capacity is a measure of how much water a well can produce in a sustained manner. The specific capacity can be calculated very easily by dividing the pumping rate (in gallons per minute) by the drawdown of the water level (in feet). For example, a well pumping water at a rate of 100 gpm that shows a drawdown of the water level of 100 feet has a specific capacity of 1 gpm/ft. A better well that is able to pump twice as much (200 gpm) with the same amount of drawdown (100 feet) has a specific capacity of 2 gpm/ft. Since most of the wells in the Flagstaff area that penetrate the Supai Formation have relatively low specific capacities, the two relatively high specific capacities of 10 and 20 gpm/ft obtained from the Supai Formation are most likely reflecting water flow through fractures. In support of this conclusion Dames and Moore (1998) obtained a Specific Capacity of 6 gpm/ft from a 3-hour pumping test at 30 gpm in 'Well No. 1' (apparently in the same location as MW-4A), where no fractures were described.

4.3 Influence of Sinkholes

According to Burgess and Niple (2008) drill-hole records in the Sedona area reveal an extensive cave system in the subsurface within the Redwall Limestone and Martin Formation. Four known sinkholes in the area are visible a few miles south of the WWTP along Oak Creek at Page Springs and Spring Creek. Most springs are within the Verde Formation, though the

'Devils Kitchen sinkhole' is within the Supai Formation at the surface and all have been interpreted to have formed as the result of cavern collapse within the underlying Redwall Limestone (Burgess and Niple, 2008). Interestingly, the formation of the Devils Kitchen sinkhole was apparently almost witnessed in the early 1880's. There are no visible collapse features closer to the WWTP. However, since most of the surface is covered with basalt and alluvium, it is possible that any collapse features may have been filled in. As mentioned in Burgess and Niple (2008, Appendix 10) it is also possible that there are sizeable caves within the Redwall Limestone beneath the site that could act as conduits for recharged groundwater. In the absence of any other information, however, there is at present no viable way to evaluate this possibility. The hydrologic conductivity of the sinkholes is not known, nor is the direction of groundwater flow. Appendix 10 within Burgess and Niple (2008) contains a report that states that all five sinkholes in the Sedona region lie along prominent northwest-trending joints. This suggests that water may flow more easily in a northwest-southeast direction.

4.4 Groundwater Flow

Burgess and Niple (2008, Appendix 10, Paul Lindberg consultant report), surmised that water recharged on the southern Colorado Plateau above Sedona percolates downward through the Supai Formation and eventually makes its way into dissolution caverns in the Redwall Limestone (*Figure 6*). They concluded that water passes out of the Redwall Limestone where it is cut by the Page Springs fault and is in contact with more permeable sedimentary deposits of the Verde Formation. While this is certainly possible it is difficult to verify with the existing data. Twenter and Metzger (1963, p. 83) speculated that most of the discharge from Page Springs originates from the Supai Formation. Page Springs discharges more than 15 million gallons of water per day at 68° F (20° C)(Burgess and Niple, 2008). Twenter and Metzger (1963) reported the flow was more than 23 million gallons per day in 1959. The spring discharge at Spring Creek was also measured at 20° C (Levings, 1980). ***Based only on the temperature data, the water issuing from both Page Springs and Spring Creek, therefore, appear to have originated from the same source, postulated to be the Redwall Limestone.***

Engineering-Science (1991) included a driller's report about the deepening of the Dells Water Well No. 1 (well 55-501470) that stated that, when drilling below 800 feet (into the Naco and Redwall Formations), some zones encountered water as warm as 30° C. Subsequent mixing of the warm water and the rest of the water in the borehole resulted in a temperature of 22° C. If there is a source of geothermal heat near well 55-501470 then its effects may be measurable as elevated water temperatures in the subsequent boreholes drilled to those depths down-gradient across the WWTP property. Several wells listed in Levings (1980, Table 4) show temperatures of between 15-20° C in the general area but these appear to be average temperatures of the water pumped out of the well from the entire depth of the wells (some of which penetrate deeper than 700 feet) and likely represent mixed temperatures. No depth-vs.-temperature data was supplied. Ross and Farrar (1980) reported silica equilibrium temperatures (an indicator of past geothermal activity) from water samples in the area which do not show much evidence of elevated temperatures. Therefore, temperature may not be a productive means of correlating water in the area.

Besides temperature, other means of constraining the flow-direction of groundwater within the Redwall (and also within the Supai Formation) include the use of isotopic and/or chemical tracers. Oxygen and hydrogen isotopic studies have been performed with great success world-wide for many years to help constrain sources and flow paths of water (among other things—see Wirt and Hjalmarson, 2000 for a good example). These analyses can be done inexpensively and quickly and need only very small water samples (20 ml or so). In order to determine the source of water in the Redwall Limestone, for example, water samples from the Redwall from several different wells should be collected, analyzed, and compared. If they all contain similar isotopic ratios then the confidence that they are reflecting a common source is high. If the isotopic signature is no different from that of water in the overlying Supai Formation then both formations probably derive water from the same source. If the signatures are different then they likely derive water from different sources. To determine the source itself, many more measurements need to be made of different possible source waters and then compared to the groundwater samples. As a first approximation flow direction beneath the WWTP can be determined by drawing a line between the analyzed sample location and the source. This assumes that a unique source can be identified. This may not be possible, as sources both north and east could possibly yield similar isotopic ratios, owing to their similar topographic and geologic expressions. Blasch and others (2005) report numerous isotope data for the Verde Valley. The range in values, however, does not allow for an unambiguous identification of source waters for the Sedona area.

Another means of constraining the direction of flow in the Redwall Limestone is to compare the chemical constituents of the water from several wells that penetrate the Redwall Limestone and compare them to both the water in the overlying Supai Formation and to the water issuing from Page Springs and Spring Creek. If the water quality in both the Redwall Limestone and Supai Formation are different, then it is possible that one or the other will be a match for the water issuing from the springs. If they are mixing then a mixed signature may be visible. If they are the same, then it may not be possible to determine which formation is the source.

An examination of the available water chemistry data (Twenter and Metzger, 1963; Levings, 1980; Levings and Mann, 1980) shows, as summarized by Twenter and Metzger (1963, p. 90), that all of the springs and wells in Paleozoic rocks yield water containing less than 500 ppm dissolved solids; silica 15-20 ppm; calcium 40-75 ppm; magnesium 15-40 ppm; sodium and potassium 5-30 ppm; and bicarbonate 200-375 ppm. No water chemistry data with respect to formation was given. Levings (1980, p. 32) did report water chemistry data for water collected in Oak Creek below Page Springs hatchery, but it is not clear if this represents water from Page Springs only or if it represents a mixture of Page Springs water and Oak Creek water. It would be beneficial to collect more water samples from wells which are screened only within the Redwall Limestone, from wells that penetrate only the Supai Formation, and from Page Springs and Spring Creek and their data compared to see if they can be distinguished on the basis of water quality. As mentioned above, if the water quality in the Redwall and Supai Formations are significantly different then in principle it may be possible to determine which is the leading contributor of water to the springs.

5.0 RECHARGE OPTIONS

5.1 Direct Injection into the Supai Formation.

Various lithologic logs exist for Monitor Well 4A (55-526825) located approximately ¾ mile south of the WWTP on the east side of Highway 89A. The drillers' log shows alluvium and basalt down to a depth of 140 feet. The log provided by Hydrometrics (2001) also for "Hole 4-A" (with the same cadastral location) shows conglomerate to a depth of 214 feet. Using 200 feet as a conservative estimate of the total thickness of relatively impermeable rocks above the Supai Formation, and a depth of 450 feet as the depth of the water table, this allows for recharge storage space of 250 feet within the relatively more permeable Supai Formation.

Hydrometrics (2001) conducted two infiltration tests within the Supai Formation. The first was at 300 feet at a rate of 12 gallons per minute, and the second was at rates up to 70 gallons per minute. The transducer was placed at depths of 310 feet and 320 feet, respectively. The water level never rose to the transducer and Hydrometrics concluded that it was the fractures within the Supai Formation (visible in their video log) that were allowing this amount of recharge (70 gpm = 4,200 gallons per hour = 100,800 gallons per day) to occur. Few other details about the injection tests were recorded. Even though these tests put the injection line at specific depths within the well they did not really test the recharge capacity of the well because no water level data were gathered to reflect rise in water level with respect to the injection rates. Based on the hydrologic conductivities of the Supai Formation, the injected water should quickly mound and flow laterally along one of the bedding planes within the formation. Based on the limited data available it is uncertain if the mounded water would flow laterally towards Oak Creek.

5.2 Direct Injection into the Redwall Limestone.

Direct injection into the Redwall Limestone aquifer might be a feasible option, however at present there is almost no information about the hydrology of the Redwall aquifer in this area, so recharging via direct injection has unknown consequences. More work needs to be done to prove this capability, including surface geophysics and the drilling of several deep monitor wells within 2-3 miles of the WWTP.

Burgess and Niple (2008) concluded that groundwater within the Redwall Limestone flows through cavities and caverns towards the southwest and surfaces at Page Springs (*Figure 5*). ***Therefore, the Redwall Limestone might provide an ideal formation for recharge, assuming that acceptable water quality can be maintained.***

5.3 Surface recharge.

As mentioned above the short term hydraulic conductivity of the alluvium at the surface has been measured at 5.92 feet per day (Engineering-Science, 1991; DEI, 1995; Hydrometrics, 2001). ***The underlying basalt, has an average hydraulic conductivity of 0.6514 feet per day, and this much lower rate is the limiting factor in performing surface recharge at the WWTP.***

The water levels in the piezometer wells adjacent to the storage basins in Area 2 of the WWTP frequently exceeded ADEQ's upper limit of 6 feet below the basins. No data was immediately available that might allow any correlation between the amount of water supplied to the basins and the water level in the piezometer wells (personal communication with City personnel). The elevated water levels may have been caused by the inability of the subsurface materials to infiltrate water downward at a rate sufficient to keep pace with the water supplied to the storage basins.

Basalt is typically an impermeable rock even when filled with porous vesicles because those vesicles are typically not connected to one another to create flow paths. Even though DEI (1995) observed that fractures in the basalt were 'infilled' with other material, there must be some amount of fracture porosity in the basalt to allow infiltration. The relatively low hydraulic conductivity of the basalt does not necessarily preclude surface recharge in the area as long as land is plentiful and the lateral migration of the water is controlled.

The Town of Gilbert, in the Phoenix metropolitan area, was among the first municipalities to construct a successful large-scale surface recharge facility. Surface soils there are also clay-rich yielding low infiltration rates. The infiltration rates at the Neely facility on Cooper Road, though variable, range from 3-4 inches per day up to 1 foot per day, with an average infiltration rate of about 6 inches per day (personal communication with the Gilbert Public Works Dept.).

Town of Gilbert personnel (personal communication) have found that, for the average infiltration rate of 6 inches per day, a maximum starting water depth of 18 inches in the recharge basins is optimum for the following reasons: this depth allows infiltration to complete one cycle (going from wet to dry) in about three days, which includes flooding and subsequent drying of the basin. Drying is an important consideration because it significantly reduces the formation and build-up of biologically produced biofilms, which clog the sediment and reduce the effectiveness of recharge. Drying also kills off mosquito larvae which have a 3-day maturation period.

For infiltration rate comparisons from other areas, a study by Brown and Caldwell (2002) for Greenbush Draw near Bisbee reported measured infiltration rates of 0.017 to 2 feet per day. A study by Milczarek, et al. (2004) for a stream channel near Sierra Vista reported infiltration rates of 0.2 to 0.5 feet per day. These rates are comparable to estimated infiltration rates developed for the Draft 2003 Drainage Design Manual for Maricopa County available on the MCFCD website.

An important consideration, as mentioned above, is the fact that all of the infiltration data reported were the results of short-term tests. In HSI's experience with infiltration and falling-head tests, the infiltration rate drastically decreases over periods of days or weeks. In some cases the infiltration rates declined by an order or magnitude or more. ***Therefore, the short-duration tests are unlikely to be representative of the long-term infiltration rate beneath the WWTP site. The infiltration rate is probably much lower. The fact that the water levels in the piezometer wells were so high is probably good evidence of the low infiltration that occurs beneath the site.***

Assuming for the moment that surface recharge was employed, of particular concern is whether or not the recharged water will flow into Oak Creek. It is not possible to answer this question with the existing hydrogeologic data. The basalt will act as a temporary perching layer and some horizontal flow will likely occur, probably down-gradient to the southwest, before water infiltrates completely through the basalt. Another unknown is if there are any layers within the Supai Formation that would preferentially direct flow laterally towards Oak Creek. This is likely the most important issue to address (see recommendations below).

It is unclear if water recharged via surface ponds at the WWTP would remain in perched water system close to the surface and flow to the southwest, eventually makes its way into Dry Creek, before joining Oak Creek.

However, it appears that the surface sediments pinch out on the west side of the WWTP where basalt is exposed at the surface. There is only one small drainage that projects from the facility through the basalt towards Dry Creek. If the water supplied is carefully regulated to the basins and is kept to a rate to allow for infiltration into the basalt beneath the WWTP then perching and drainage through this drainage could be kept to a minimum if not eliminated. Several shallow piezometer wells in this area may be required to monitor these perched conditions.

Since the Supai Formation has a much greater hydraulic conductivity, another option might be to locate surface recharge basins north of the facility within surface outcrops of the Supai Formation. However, this location places the basins in close proximity to Oak Creek and may hence negate its consideration.

5.4 Recharge south of the Sheephead Fault.

The inferred existence of the Sheephead fault about 3 miles southwest of the WWTP (DeWitt et al., 2008)(see *Figure 2.* Also named the Spring Creek Fault in *Figures 5 and 6*) is apparently based on the presence of much thicker Verde Formation (greater than 1,485 feet) only ½ mile south of its onlap onto basalts. If the two well logs drilled in A(16-4)20 are reliable, then the formations south of the Sheephead fault have been down-dropped more than 2,000 feet relative to the formations immediately to the north (*Figures 5 and 6*). According to the well logs, coarse conglomerates at depth were probably shed southward off a formerly exposed fault scarp. As Burgess and Niple (2008) pointed out, these coarse, and deep, deposits might make an ideal location for injection recharge and might avoid any potential lateral migration problems associated with the inferred Page Springs and Sheephead faults (this is their 'State Land option'). A considerable amount of additional hydrogeologic work would need to be performed to prove up this site. This work would include surface geophysics and test well drilling.

6.0 SUMMARY

If it can be shown that recharged water does not flow toward Oak Creek, then recharging into the Supai Formation or injecting into the Redwall Limestone beneath the WWTP may each be viable recharge options. ***Proving the direction of groundwater flow for either option will require surface geophysical work such as CSAMT (Controlled Source Audiomagnetotellurics) coupled with the drilling of several new monitor and test wells, plus longer-term injection tests coupled with water chemistry measurements.***

For the Supai Formation, it is possible that mounded injected water in the well could raise too high and flow laterally along bedding plains towards Oak Creek without proper injection well construction. A potential obstacle to either method may be the inferred presence of the Page Springs fault two miles to the southwest, which may (or may not) divert recharged water towards Oak Creek. To verify the existence of this fault, a relatively low-cost surface geophysical method such as CSAMT could help provide the answer.

If acceptable recharge water quality can be maintained, from the WWTP, then either of these two options may prove feasible. Injection into the Redwall Limestone may be a best alternative, but it will first be necessary to explore the hydrologic characteristics of this deeper aquifer. Fortunately, the Redwall Limestone is shallower here than in other areas and is only about 900 feet below the surface. As Burgess and Niple (2008) concluded, recharge south of the inferred Sheephead fault may be the option with the fewest unknowns, if the costs of the land and water conveyance are not insurmountable.

7.0 RECOMMENDATIONS

1. Surface recharge. ***Surface recharge is not recommended as an option at the WWTP.*** The elevated water levels in the Piezometer wells, and the probability that the short-term infiltration tests are not representative of the long-term infiltration rate decrease the confidence in the viability of this recharge method. However, this does not preclude the idea of creating surface amenities with a portion of the treated water. Construction of a wetlands nature habitat is probably quite feasible. The predicted low long-term infiltration rate may even help to reduce loss of surface water via percolation.

2. Direct injection in the Supai Formation deserves further testing and evaluation. The available specific capacities of the Supai Formation are based on short-term aquifer tests. Well log data also suggest that permeability is strongly dependent on the availability of fractures. A longer-term (72-hours or more) pumping test in the production well located near the WWTP entrance would probably give a more realistic estimate of the specific capacity of this well. The existing monitor wells to the south and southeast can be used to verify groundwater flow direction. If no water level decline is measurable within the existing monitor wells then it may be necessary to drill one or more monitor wells closer to the production well. An injection test should then follow the pumping test to determine the Supai Formation's ability to accept recharge water. If allowable, effluent onsite could be used for the injection test. It should be kept in mind that as a rule of thumb, the amount of water that can realistically be *injected* back into the well is about one half of the amount produced. Depending on the results of the long-term pumping test the injection rate may be too low to make this a feasible option.

3. Direct injection into the Redwall Limestone also appears to be a feasible option. It will be necessary to use a surface geophysical technique such as CSAMT to help locate possible caverns within the Redwall and estimate hydrologic parameters. This work will be instrumental in locating monitor and test wells. This may require the drilling of several wells to depths of 1,000 feet and perform pump tests to determine hydrologic characteristics of the Redwall aquifer in this area.

   A potential benefit of this recharge method is the fact that the Redwall Limestone is wholly at a lower elevation than is Oak Creek, and is separated from the bulk of the overlying Supai Formation by the relatively impermeable lower Supai Formation (or Naco Formation).

4. Use surface geophysics such as the CSAMT technique to help locate fractures and cavities in the underlying Supai Formation and the Redwall Limestone. Water flows preferentially along these paths and CSAMT is well suited to help detect them. CSAMT is a non-intrusive surface geophysical technique that involves measuring radio frequencies at a series of equally spaced electrodes along a line across the area of interest. The wide range of frequencies from 1 Hz to more than 8,000 Hz are measured at each station and integrated into a repeatable model of the resistivity up to several thousand feet beneath the Earth's surface. The resulting data are plotted as color cross-sections that show the distribution of resistivity both horizontally and vertically.

5. Sheephead fault option. As proposed by Burgess and Niple (2008) this option still appears to be feasible. Further evaluation should be performed as to the feasibility of both acquiring State Trust land south of the Sheephead fault and of conveying the water to that site. An injection test should be performed in one or both of the deep wells in cadastral A(16-4)20 (55-614259) which is 1,485 feet deep, and Cottonwood #1 which is 1,190 feet deep) in order to validate that injection will work at this site. It may also be possible to inject directly into the fault zone, in which case the CSAMT method may be helpful in locating the fault and positioning the injection well.

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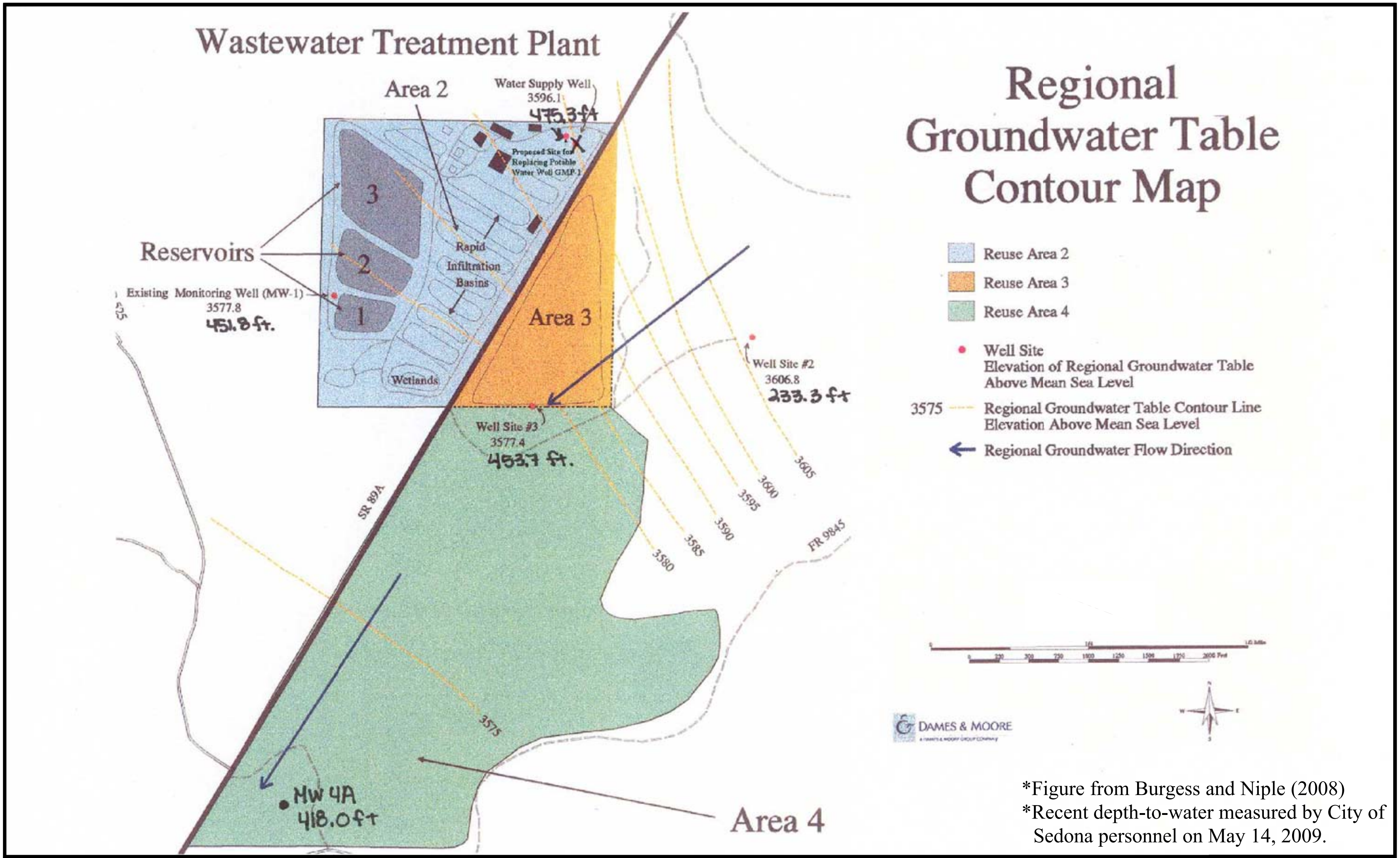
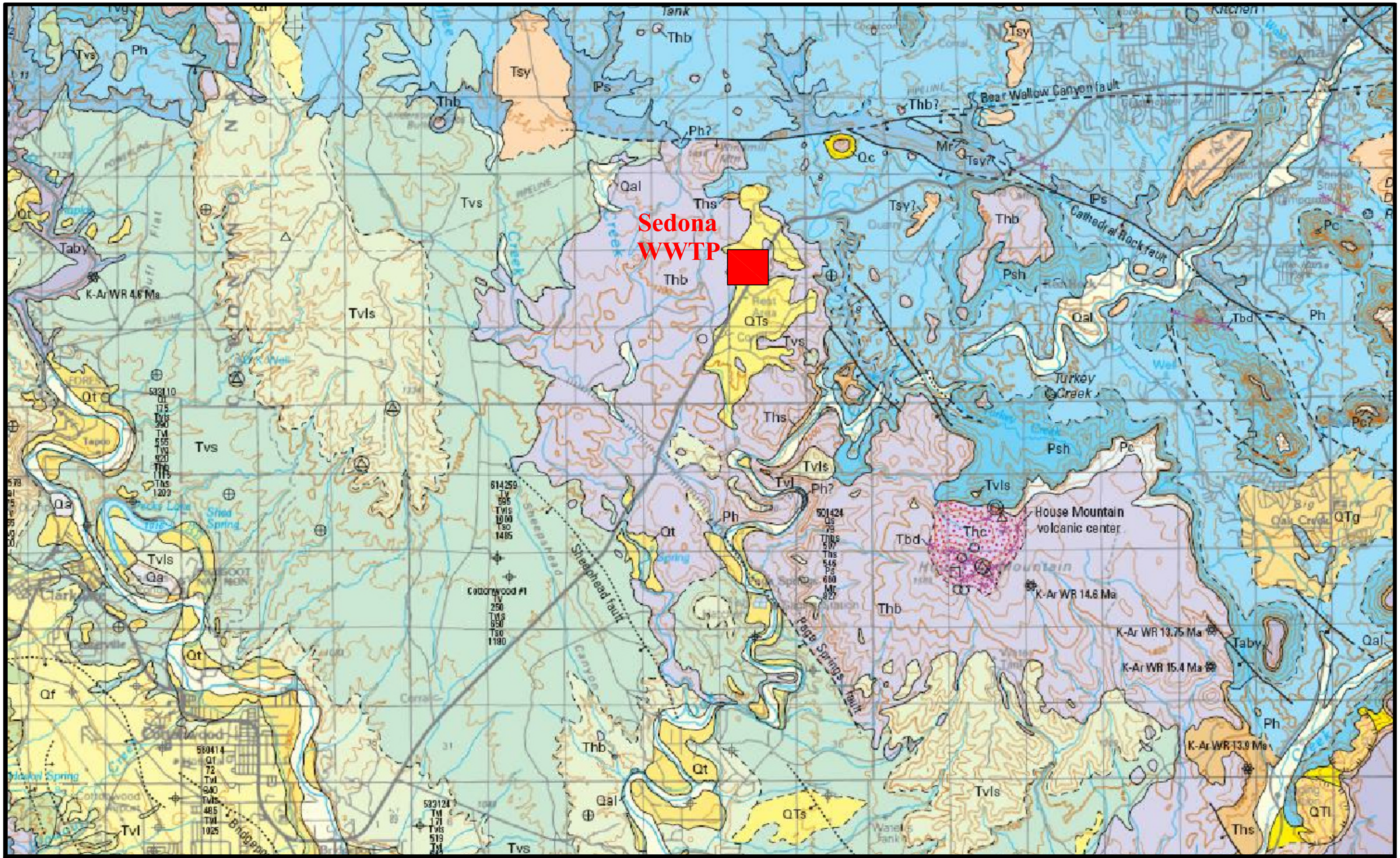


*Figure from Burgess and Niple (2008)
*Recent depth-to-water measured by City of Sedona personnel on May 14, 2009.

HSI HydroSystems Inc.	**Monitor Well Location Map** **Sedona WWTP**	Figure 1



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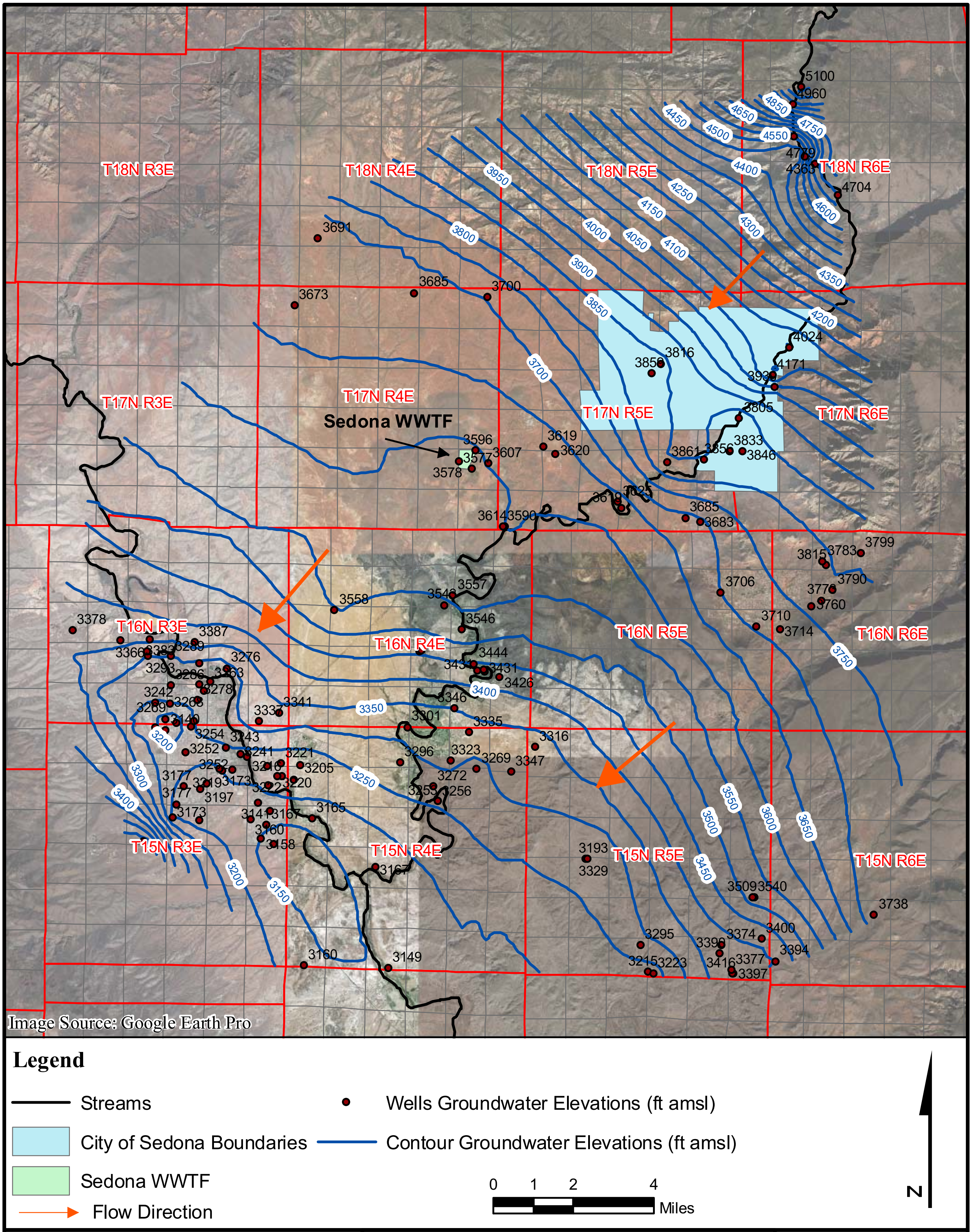
Geologic Map of the Area Surrounding the Sedona WWTP (from DeWitt et al., 2008)

Figure 2



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Sedona Recharge Project
50 ft Contour Groundwater Elevations

Figure 3

S:\08-563 Carollo-Sedona Recharge\Figures\Figure 3 GWE map.mxd 06/08/2009

	Mesh	Inches	TP-6 (1-3')	TP-7 (13')	TP-14 (0-5')	1 (5')	2 (0')	3 (5')	6 (5')	11 (10')	13 (0')	17 (10')	26 (10')	26 (25")	28 (0')
G	1	1						100	100				100	100	100
G	0.75	0.75	100	100	100	100	100	88.5	97.8	100		100	94.8	100	100
G	#4	0.187	55.2	93	96.1	96.6	98.8	80.8	84	97.6	100	88.4	52.5	74.6	98.6
C. Sand	#10	0.072		88		83.6	93.9	70.3	51.7	90.7	97.6	75.6	32.5	43.3	
C. Sand	#16	0.046	36.7	84	94	75.9	92.8	66.2	38.3	73.2	92.8	68.7	26.2	32.6	95.2
M.Sand	#30	0.023		80		66.1	89.4	62.8	31.6	63.2	84.5	59.4	23.6	28.3	92.9
F.Sand	#40	0.015	23.2	78	90.6										
F.Sand	#100	0.0055	15	64	63.6	45.2	56.9	53.4	14.8	33.4	46.4	41.2	15.6	19.2	78.2
Fines	#200	0.0029	12.2	40	32.1	33.7	32.8	47.8	3.18	29.7	24.9	31.9	10.8	13.7	62.2

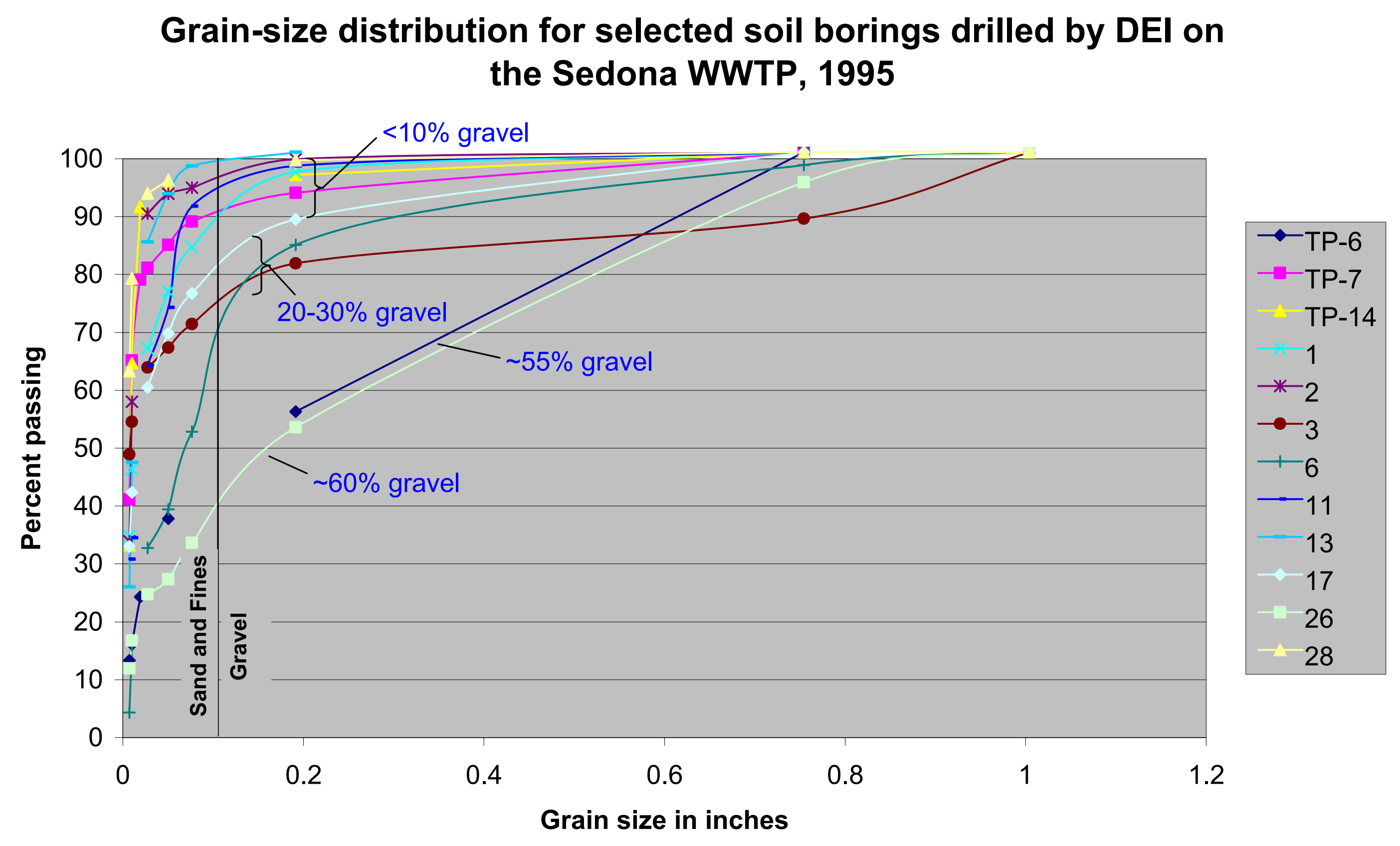

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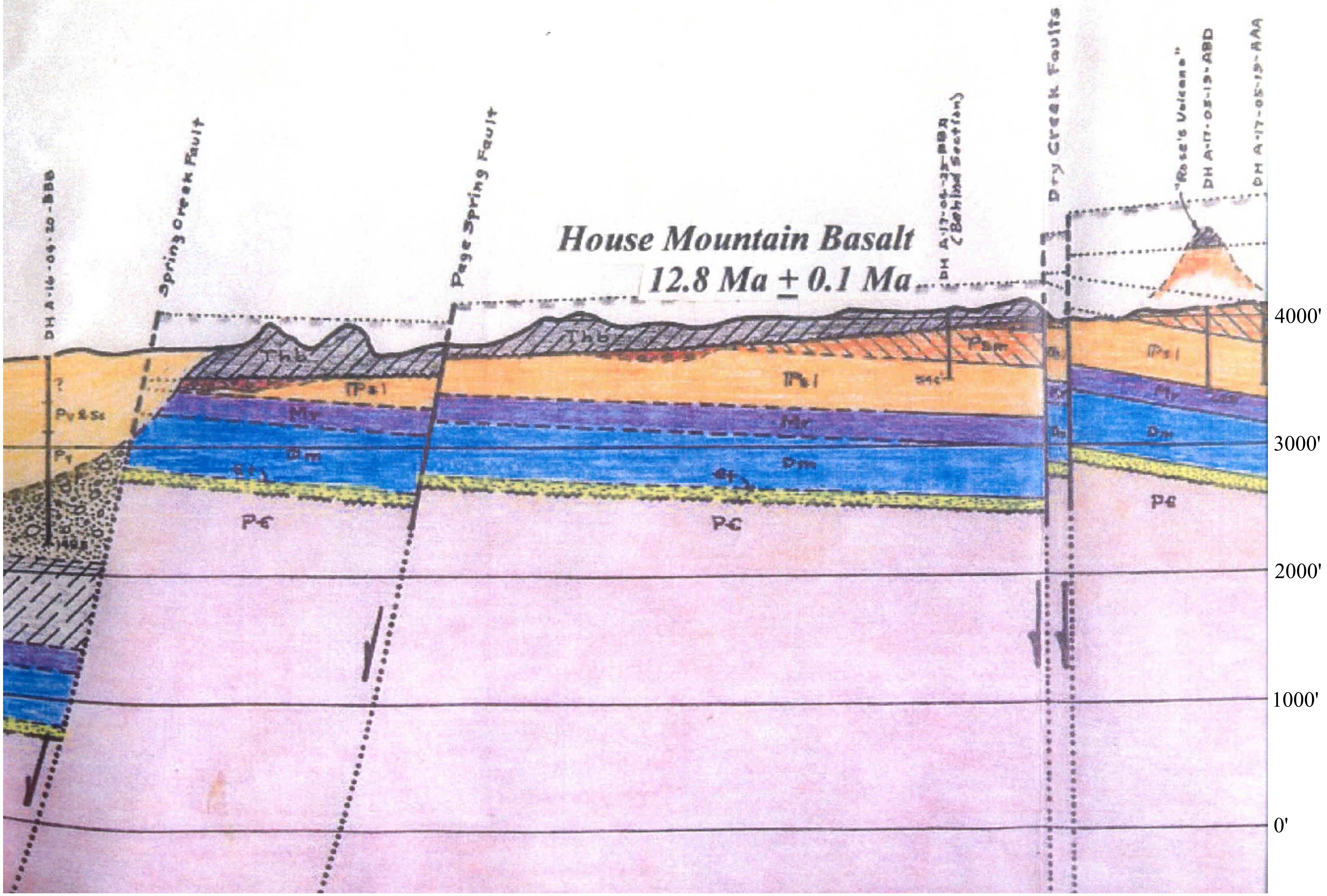
Figure 4. Grain-size distribution of selected surface deposits at the Sedona WWTP



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SW-NE Geologic Cross-Section
(from Paul Lindberg in Burgess and Niple, 2008)

Figure 5

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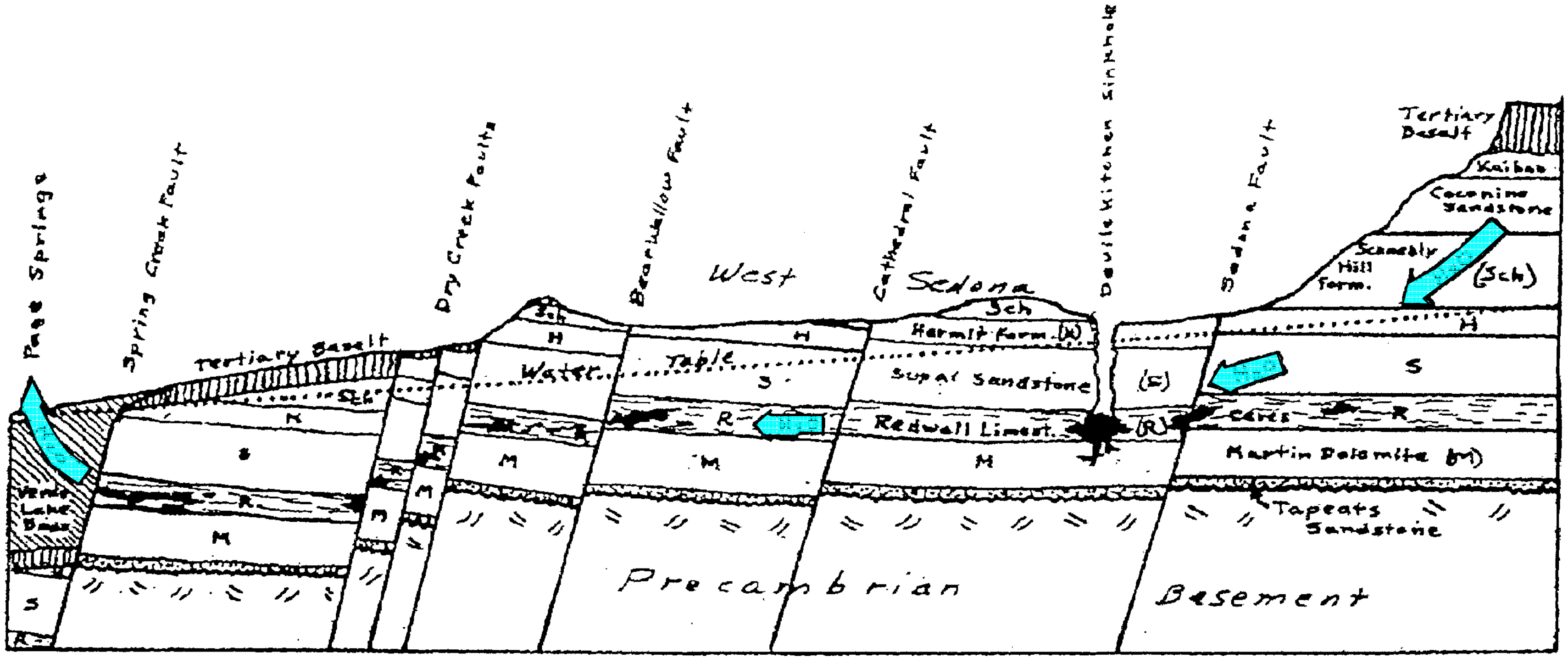

Schematic cross section through West Sedona from the Colorado Plateau to the Page Springs area showing suspected subsurface groundwater flow. This section is looking toward the northwest in the direction of prominent joint fractures that allowed surface-derived water to percolate downward and dissolve solution caves in the underlying Redwall Limestone. Water collects in the subsurface cave system and ultimately discharges to the southwest (left) in the Page Springs area.

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Geologic Cross-Section Showing Postulated Subsurface Water Flow through the Redwall Limestone to Page Springs (from Burgess and Niple, 2008)

Figure 6