Glossary Terms for Hydrological Parameter Analysis for ASR-

Parameter name	Category	Notes
Horizontal hydraulic conductivity	**Recharge**, Recoverability	Primary factor for rate of recharge or production
Storage zone depth	Recharge	Depth to top of aquifer in a confined system. In an unconfined system, storage zone depth is estimated to be 100 feet below the top of the saturated zone.
Available Draw-Up	Recharge	Distance between hydraulic head and ground surface
Dominant lithology	**Recharge**, Recoverability	Aquifer texture/porosity. Parameter scoring also includes secondary porosity features associated with fractured rock and limestone or karst formations.
Aquifer thickness	**Storage**, Recharge	For unconfined aquifers, this is based on saturated thickness
Aquifer storativity	Storage	Relevant in confined aquifers
Specific yield	Storage	Relevant in unconfined aquifers
Sediment age	Storage	A qualitative indication of aquifer induration.
Groundwater quality	Recoverability	Total dissolved solids (TDS)
Confinement	Recoverability	Important for control of recharge water
Available Drawdown	Recoverability	Amount of head available above the top of aquifer
Drift velocity	Recoverability	Natural drift of recharged water

Note: Where multiple categories exist, the category for which the parameter contributes to scoring is bolded.

<u>Horizontal Hydraulic Conductivity</u> – Horizontal hydraulic conductivity is important for both recharge and recovery in ASR. The parameter is positively correlated to suitability and score increases from 0.2, for values less than one foot per day to 1 for values greater than 30 feet per day. For reference, formations with hydraulic conductivity from 0.1 to 1 foot per day are generally considered marginal aquifers. Also, one can generally assume about one half the average productivity in recharge versus discharge in an ASR well.

<u>Storage Zone Depth</u> – Storage zone depth is a consideration for cost, temperature, and pumping technology factors affecting project viability. Wells deeper than 2,500 feet would likely require staging of the pump system, lower diameter well screens and as a result would be less productive generally. As a result, the scoring rationale reduces the suitability of wells deeper than 2500 feet and gives them a parameter score of 0.1. Because shallow ASR wells also offer challenges in hydraulic control, confinement and environmental protection, the normalized score was reduced for wells less than 200 feet depth.

<u>Available Draw-Up</u> – Drawup available is a parameter that is analogous to the more commonly used “drawdown available” (discussed below), but is relevant to recharge rather than recovery. Figure 4 illustrates how drawup available and drawdown available are calculated. The rate of recharge is dependent on both the transmissivity and the amount of positive head above static water level that is applied. The amount of positive static water level at the wellhead that can be applied is the sum of the distance from the head in the aquifer to ground surface, plus whatever additional overpressure can be applied (i.e. the height of head above ground surface that can be

applied at the wellhead). Because the amount of overpressure is a well construction factor, we are considering only the distance from the head in the aquifer to ground surface for this parameter. The normalized score varies from a low of 0.1 for 50 feet to 1.0 for 400 feet or more. At 50 feet, overpressuring the wellhead is a likely requirement. At 400 feet, a specific recharge capacity of 1-2 gallons per minute per foot provides a recharge range of 400 to 800 gallons per minute, a desirable range for an ASR well.

<u>Dominant Lithology</u> – The type of aquifer and associated soils has a clear correlation to the suitability of ASR. Sediments that are clastic, have high porosity (low induration), high storativity, and high hydraulic conductivity are considered more favorable. The parameter score divides lithology classes between clay/silt, rock (assumed to be indurated), limestone, sand and gravel with gravel and sand getting the highest scores. For two lithology classes, an additional parameter was included to modify the dominant lithology parameter based upon secondary processes that have the potential to increase aquifer porosity and hydraulic conductivity. These two controls are fractures in indurated rocks and karst development in limestone. An example of the latter is the Edwards Aquifer. This parameter is not applied to the other lithology classes. The method proposed is to add the lithology score to the macro-porosity parameter to get a modified lithology suitability parameter based upon secondary processes altering the hydrologic properties associated with the lithology. The **Table** shows the 31 aquifers and their assigned dominant lithology types.

<u>Aquifer Thickness</u> – In siting an ASR well, one generally wants to find a high productivity interval with good confinement both above and below. These intervals are typically on the range of 100 to 150 feet thick or less. At this thickness, the recharge water can generally be controlled, and the volume of mixing zone water is minimized and recharge water between wells can comingle. At the scale of this analysis, every 90 square-mile part of Texas aquifers could not effectively be characterized with a representative lithologic column. Therefore, we have used aquifer thickness as a proxy for finding an acceptable recharge interval. As a result, the suitability score increases with aquifer thickness which would imply that the probability of an acceptable recharge interval increases as the thickness increases. The normalized score of 0.1 at 100 feet of thickness reflects that low probability of any given 100 foot interval being an ideal storage zone. At 300 feet, chances of finding 100 feet of productive sand is much higher in a typical aquifer, so the score is set to 1.0.

<u>Aquifer Storativity</u> - Specific Storage is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head in a confined aquifer. Aquifer storativity is equal to the product of specific storage and aquifer thickness for a confined aquifer. The higher the aquifer storage, the more water can be recharged in the aquifer for a given increase in head over a set amount of time. The score for this suitability parameter increases with increasing storativity. The normalized scoring approach reflects a linear change versus logarithmic variation in storativity over the typical range in aquifer storativities, since storativity is typically a log-distributed parameter.

Specific Yield – Specific yield is used as an indicator of storage potential in unconfined aquifers. It is directly correlated to the storage potential of an unconfined aquifer and therefore the score is directly correlated (score increases as specific yield increases). Similar to storativity, the normalized score was varied over the typical range of specific yield values found in Texas aquifers. The lower specific yield values are typically found in aquifers dominated by secondary porosity (such as karst aquifers).

Sediment Age - Sediment age was used as a qualitative indication of aquifer induration. As sediments become older and subject to both deep burial processes and near surface processes, the rocks generally lose porosity and become more indurated. This has a tendency to increase heterogeneity and reduce storativity, both which are important to suitability for ASR. The normalized score was varied from 0.1 to 1 based on sediment age from the start of the Eocene (56 mya) to the start of the Cambrian (541 mya). The **Table** below shows the 31 aquifers and their assigned ages.

Groundwater Quality – Groundwater quality has several implications for AR, including recovery efficiency and treatment costs from constituents in the vadose zone being mobilized into the saturated zone and ultimately the recovered water. At the scale of this analysis, detailed chemical data which may identify areas suitable because of vadose zone constituent mobilization or cause issues with treatment is generally lacking. However, total dissolved solids (TDS) is available for all aquifers at the scale required for this analysis. Generally, the higher the TDS in the receiving aquifer, the lower the recovery efficiency and recoverability, due to the increased size of the mixing zone between the recharge water and native groundwater. The normalized score was just varied linearly within the typical range of TDS for the major and minor aquifers in Texas.

Confinement – Overall confinement, combined with thickness, provides the best opportunity to find good target storage zones. In an unconfined aquifer, recoverability can be a challenge because you lack the ability to control vertical hydraulics. In addition, unconfined aquifers can be more vulnerable to influence from surface activities. The normalized score is has only low and high values (binary field), reflecting the challenge of achieving confinement in unconfined aquifers versus confined aquifers.

Available Drawdown – Drawdown available is the distance from the static water level to the top of the aquifer for a confined aquifer, or the distance from static water level to some minimum saturated thickness in an unconfined aquifer. The **Figure** illustrates drawdown available for a confined aquifer. Because productivity is dependent on both transmissivity (hydraulic conductivity multiplied by the completion interval length) and the amount of drawdown created at the well, drawdown available is an important factor in recoverability. The normalized scoring approach is identical to drawup available.

Drift Velocity – Drift velocity is the tendency of the centroid of the stored water to drift away from the recharge well location. The greater the drift velocity, the more consideration must be taken on wellfield design in order to ensure good recoverability. Drift velocity is estimated by multiplying the hydraulic gradient by the hydraulic conductivity, then dividing by estimated porosity. A "rule-of-thumb" for the most suitable drift velocity is less than 20 feet per year (David Pyne, personal communication), while as much as 100 feet per year is still acceptable without additional considerations for hydraulic control. Over 100 feet per year may require additional extraction wells or other forms of hydraulic control.

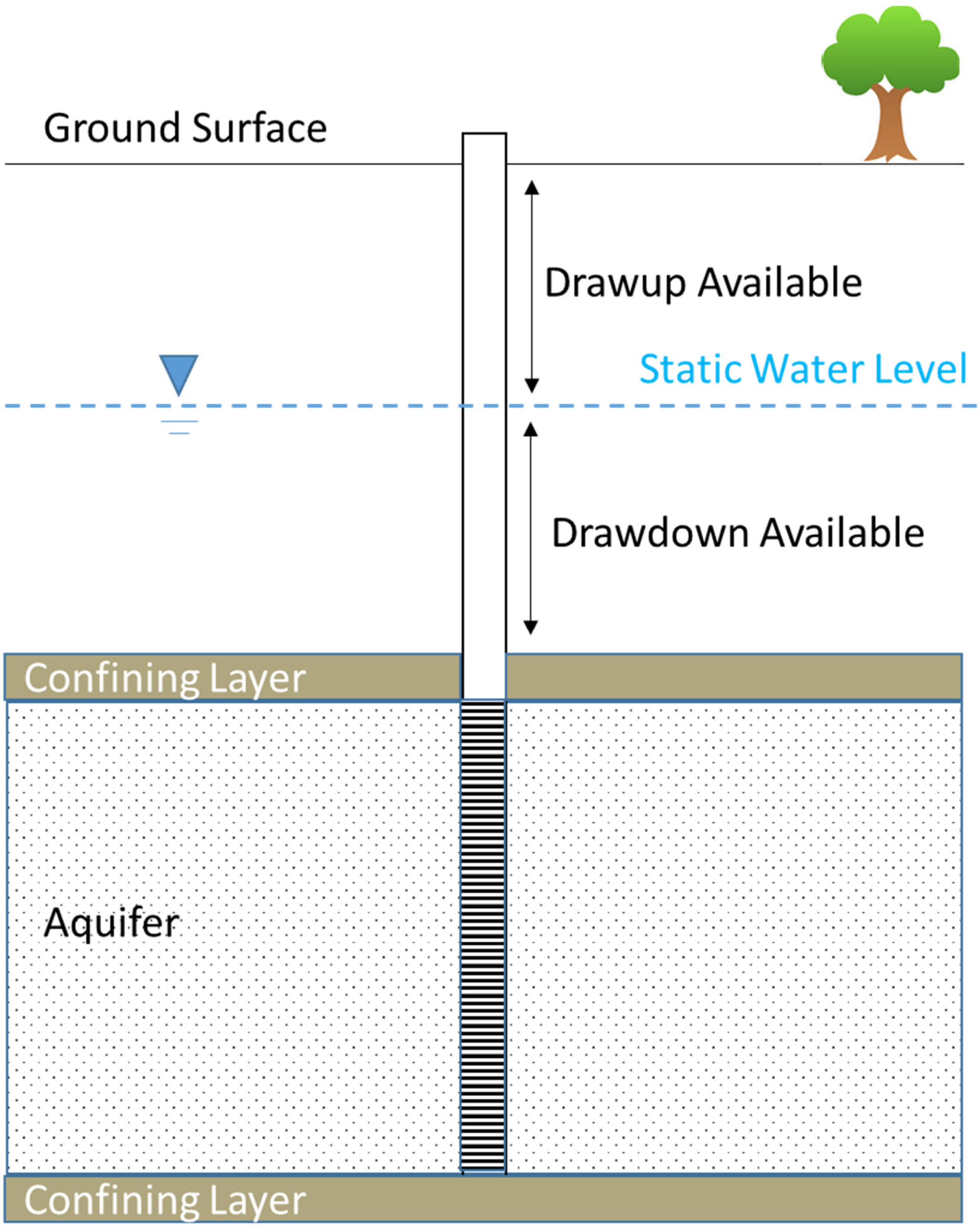

Figure. Illustration of drawup available and drawdown available

Table – Assigned lithologies and ages

Aquifer	Lithology	Age (mya)
CZWX	sands	62-52
EBFZ	limestone	108
ETPT	limestone	125-100.5
GLFC	sands	24-0
HMBL	sands	18-0
OGLL	sands	12-4
PECS	sands	38-0
SYMR	sands	2-0
TRNT	sands	125-108
BLIN	shale	272-260
BLSM	sands	90-80
BSVP	limestone	280-271
BSRV	sands	0.012-0
CRCX	limestone	272-260
CSTB	sandstone	308-280
DCKM	sandstone	223-200
ETHP	limestone	125-100.5
EBSS	limestone	500-472
HCKR	sandstone	541-509
IGBL	rock	48-27
LIPN	gravels	2.6-0.012
MRTN	limestone	488-299
MBLF	limestone	318-311
NCTC	sands	71-66
QNCT	sands	48-38
RTBC	sands	161-94
RSLR	limestone	260-251
SPRT	sands	48-38
WXBL	sands	23-0
WDBN	sandstone	100-94
YGJK	sands	48-34