

An Assessment of Wind-Powered Desalination Opportunities in the Arizona

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Introduction

Historically, energy and water management issues have been addressed separately, but modern energy and water shortages and increasing costs have highlighted the inextricable link between them. The demand for both resources will increase over time requiring that we seek alternatives that support economic growth while minimizing environmental impacts. This study looks at wind-powered desalination as one such possible alternative. This study assessed the availability of brackish groundwater in Arizona using a geographic information system (GIS). These assessments were correlated in GIS to wind resources that can potentially be used to pump and desalinate co-located saline groundwater resources.

Changes in U.S. population, increased urbanization, and periodic and prolonged drought have brought much attention to the reliability of U.S. water supplies particularly in the southwestern U.S. (Hutson *et al*, 2004; USDOE, 2006a; Carter and Morehouse, 2001; Barnett *et al*, 2008; GAO, 2003; NRC, 2008). Nationally, some portion of 36 states including Arizona was deemed likely to experience water shortages during the ten year period starting in 2003 (Figure 1).

Southwestern water supplies including Arizona's are already stressed with a projected 50% increase in the region's population expected between 1995 and 2025 (GAO, 2003). Northern Arizona is expected to see a 90% to 111% increase in non-tribal population between 2002 and 2050 with tribal population increasing at an estimated 2.5% growth rate (U. S. Bureau of Reclamation (USBR), 2006).

The costs of desalination have deterred a more widespread integration of brackish water into the portfolios of water resource managers, but desalination is becoming more attractive in regions where alternatives also carry a high cost or are nonexistent. The energy requirements of desalination usually require construction of new power plant facilities adding to the difficulty in gaining support for the use of brackish water as a resource alternative. However, the use of renewable energy systems for the energy requirements of desalination equipment may make this an even more attractive alternative due to decreased environmental concerns and the benefits of point of use energy generation. Unfortunately, to date, there are no regional assessments or national assessments in the U.S. of how any renewable energy resource can be used for this purpose.

The most recent assessments of water use in the U.S. indicated 1.5 billion m³/d were withdrawn from all sources mainly (48% of total withdrawals) for thermoelectric power generation (Hutson *et al*, 2004). In 2000, only 1.5% of total U.S. groundwater withdrawals (23 million m³/d), were from saline sources for use almost entirely by the mining industry. A small percentage was used by other industry with none for domestic use. Saline surface-water contributed 23% of all surface-water use, largely for thermoelectric power. Brackish groundwater provided 2% of all brackish water used, or only 0.3% of all water used in the U.S. in 2000.

Arizona had withdrawn an average of 25.5 million m³/d, 13 million m³/d from groundwater of which 0.3 million m³/d were from brackish sources Hutson *et al* (2004). Hutson *et al* (2004) also noted 95% of the Arizona public was served by public water supplies.

Due to widespread decreases in potable-water availability coupled with population growth and an increasing global demand for clean, inexpensive energy, there emerges an opportunity to consider renewable energy-powered desalination in meeting global potable-water needs (Garcia-Rodriguez, 2003; Tzen and Morris, 2003; Romero-Ternero, 2005; Alcocer and Hiriart, 2008). The types of renewable energy capable of desalination vary by region but may

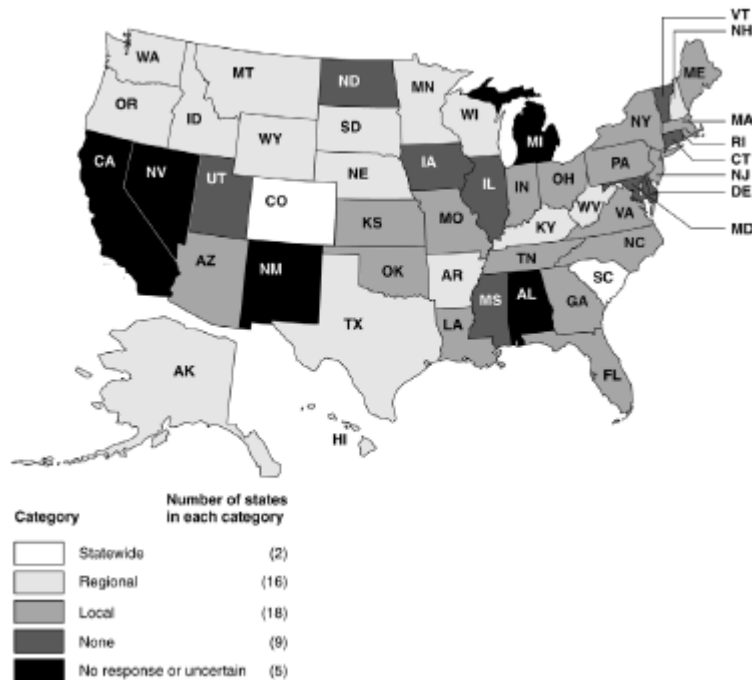


Figure 1: States likely to have water shortages under average water conditions over 10 year period beginning in 2003 (GAO, 2003).

include solar, wind, biomass, tidal, or geothermal energy. However, solar and wind technologies are capturing an increasingly larger proportion of the renewable electricity industry. Wind energy is cost competitive with wholesale energy prices with a capacity-weighted average cost of new wind generation near \$45/MWh in 2007 and is expected to continue to dominate the renewable energy market in future new electrical generation capacity (Wiser and Bolinger, 2008; Swezey *et al.*, 2007).

Objectives

The most basic purpose of this project is to apply the mapping technique in Arizona, specifically in areas of the state with a potential need to develop saline water resources, and to take it one important step further: to “microsite” specific conceptual designs for two actual sites to determine economic feasibility by example. Where wind-desalination looks feasible, one question to be addressed will be to determine if, for economic viability, the wind and desalination facilities need to be co-located, or if one could develop them in separate places and connect them through the utility grid.

Specific task objectives of the study included:

1. Creating GIS maps that display the potential for wind-powered desalination in Arizona,
2. Quantifying the costs of desalination in Arizona through the formulation of an economic model, and
3. Implementing the economic model in GIS to create maps that display the costs of desalination.

This study was conducted using Arc-GIS to map the location of brackish groundwater and wind resources potentially capable of supplying the electrical demand of desalination equipment. This assessment of resources in Arizona applies the mapping technique developed previously for an U.S. assessment, but was refined using well and spring data from the USGS National Water Information System (NWIS) (USGS, 2009), the Arizona Department of Water Resources (ADWR) Ground Water Information System (GWIS), and from the works of various authors describing the hydrogeology of basins in Arizona containing brackish groundwater. This assessment includes an estimation of the volume of water using porosity or storativity parameters to determine the availability of brackish groundwater resources, and applies an economic model to estimate the costs of pumping and desalinating brackish groundwater by location and at various total dissolved solid levels. This assessment identifies communities in Arizona that have a brackish groundwater resource, the volume of that resource, the availability of wind resources potentially capable of generating the electrical demand of desalination equipment, and estimates the costs associated with wind-powered desalination.

Lastly, once appropriate mapping resources were available, many sites were taken into account for a “micrositing” feasibility analysis. This analysis took into account the area’s resources, the local community’s need, and the desire to further broaden the project’s findings by comparing locations with the conceptual facility both collocated, and not, with wind resources. These individual locations will necessarily have differing requirements, economic and otherwise, that might not have been reflected in the more general statewide assessment.

Background Information

Water Resources and Demand

The USGS provided a historical account of groundwater assessment in the U.S. with the first occurring in 1923 (Reilly *et al*, 2008). National-scale assessments have been generalized with limited application for planning purposes. The USGS Groundwater Atlas of the United States (Groundwater Atlas) is a culmination of the information gathered during these assessments providing groundwater information for sixty one principle aquifers throughout the country. A regional-scale approach to groundwater assessment is underway with the USGS Ground-Water Resources Program taking into consideration groundwater flow systems, thus increasing the applicability to water-use planning (Reilly *et al*, 2008). Assessment of groundwater quality is also underway. Of the sixty one principal aquifers, one third was included in an initial study of the quality of national water resources, the National Water-Quality Assessment (NAWQA) Program. The NAWQA Program was conducted with three objectives: to assess water quality conditions in the U.S., to determine change in these conditions over time, and to determine the effect of natural and human influence on these conditions (USGS, 2001). The NAWQA Program was initiated in 1991 and led to collection and analysis of water quality data from both streams and aquifers.

Nationally, the USGS maintains verified groundwater data in the National Water Information System (NWIS) accessible online (USGS, 2009). The USGS NWIS provides field measurements of water levels for 826,674 sites. Some of which also contain water-quality information or data provided as real-time data from automated recorders. In Arizona, groundwater data are maintained by the Arizona Department of Water Resources (ADWR) in the Groundwater Site Inventory database (GWSI) accessible online (ADWR, 2009). The ADWR

GWSI provides records of groundwater levels for 210,000 sites some of which also contain water-quality information. Both databases provide spatial and geographical data for use in GIS. Groundwater is found throughout Arizona in alluvial aquifers of the Basin and Range Province and in sedimentary and volcanic aquifers on the Colorado Plateau. These aquifers are discussed in more detail in the following section, Hydrogeology.

Hydrogeology

The following subsections provide information regarding brackish groundwater resources in the Colorado Plateau and Basin and Range basin-fill aquifers of Arizona including what is known about the location and quality of these resources, geologic structure affecting the modeling of the aquifers, and the aquifers' hydraulic properties.

Colorado Plateau Aquifers

The Colorado Plateau is a laterally extensive region of uplift covering a large portion of the Four Corner States. In Arizona, the Colorado Plateau is a structurally deformed but nearly flat-lying (2° northward dipping) sequence of sedimentary and volcanic Paleozoic through Cenozoic rocks ranging in total thickness from 5,000 ft (1524 m) in Northern Arizona to 8,000 ft (2,438 m) in Central Arizona (Anning *et al*, 2006; Bills *et al*, 2007). These sedimentary and volcanic rocks uncomfortably overlie granitoid and metamorphic Precambrian basement rocks. Excellent descriptions of the geology of the Colorado Plateau are provided by Blakey (1990), Geldon (2003), Bills and Flynn (2002), and Bills *et al* (2007).

The aquifers of the Colorado Plateau in Arizona consist of local perched aquifers primarily in Cenozoic volcanic rocks of the San Francisco and Mount Floyd Volcanic Fields and in regional sedimentary aquifers of Mississippian through Permian ages (**Figure 2**). The perched aquifers are typically good quality groundwater and very localized, and as such they are not considered in this assessment. The Groundwater Atlas (Robson and Banta, 1995) describes the Uinta-Animas, the Mesaverde, the Dakota-Glen Canyon, and Coconino-De Chelly Aquifers of the Colorado Plateau. The Uinta-Animas Aquifer is not present in Arizona and is not discussed here. The Dakota-Glen Canyon Aquifer System consists of four related aquifers. Two of which are principle aquifers in Arizona, the upper-most, the Dakota Aquifer, and the lower-most, the Glen Canyon Aquifer locally known as the Navajo Aquifer. The Navajo Aquifer generally contains fresh groundwater and is not considered in this assessment; however, the Glen Canyon Aquifer does yield brackish groundwater in other states and is included in the national assessment. (ADWR, 2006). The Coconino-De Chelly Aquifer contains both fresh and brackish groundwater. Underlying the Coconino Aquifer is an additional aquifer known to contain brackish groundwater that is not discussed in the USGS Groundwater Atlas, the Redwall-Muav Aquifer. To summarize, the aquifers of the Colorado Plateau in Arizona addressed in this assessment consist of the Coconino (C) Aquifer, the Redwall-Muav (R) Aquifer and in the Black Mesa Basin, the Dakota (D) Aquifer. These aquifers are known for the primary units that contain them.

In general, the Colorado Plateau aquifers are recharged by precipitation infiltration, infiltration of snow melt in the San Francisco Volcanic Field and along the Mogollon Rim, leakage from overlying aquifers, and to some degree regional groundwater flow from the east.

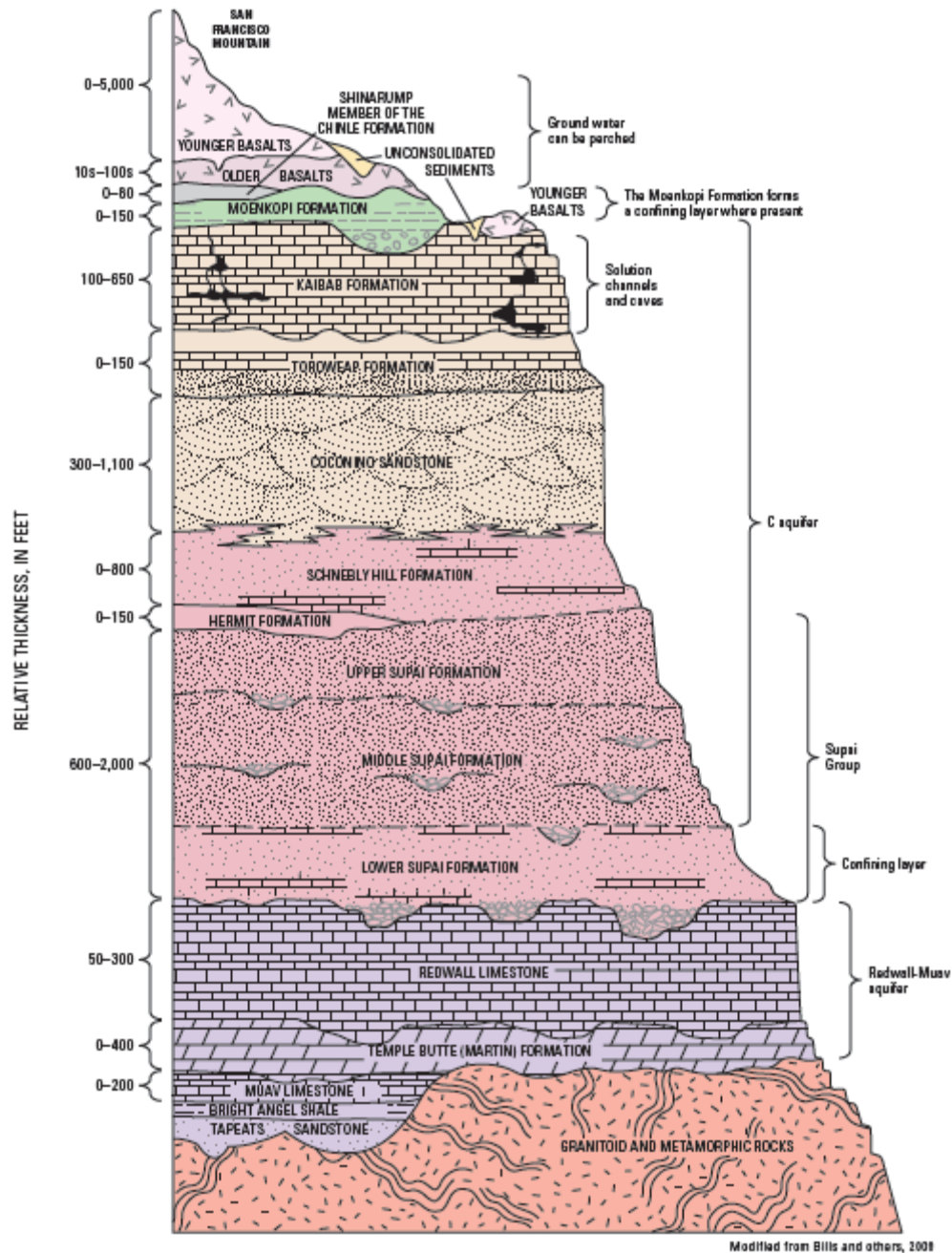


Figure 2: Generalized stratigraphic section of the Colorado Plateau, Arizona showing the geologic units that make up the C and R Aquifers (Bills *et al*, 2007).

Overall, the area represents a region of topographic high with a regional groundwater divide occurring below the San Francisco Volcanic Field (Figure 3).

The hydraulic properties of the vertical sequence change with each package of geologic units forming a stacked system of aquifers and leaky confining units. There is little hydraulic connectivity between the aquifers, and the transmissivity and hydraulic conductivity within the aquifers are highly variable largely due to the degree of faulting and fracturing at a particular

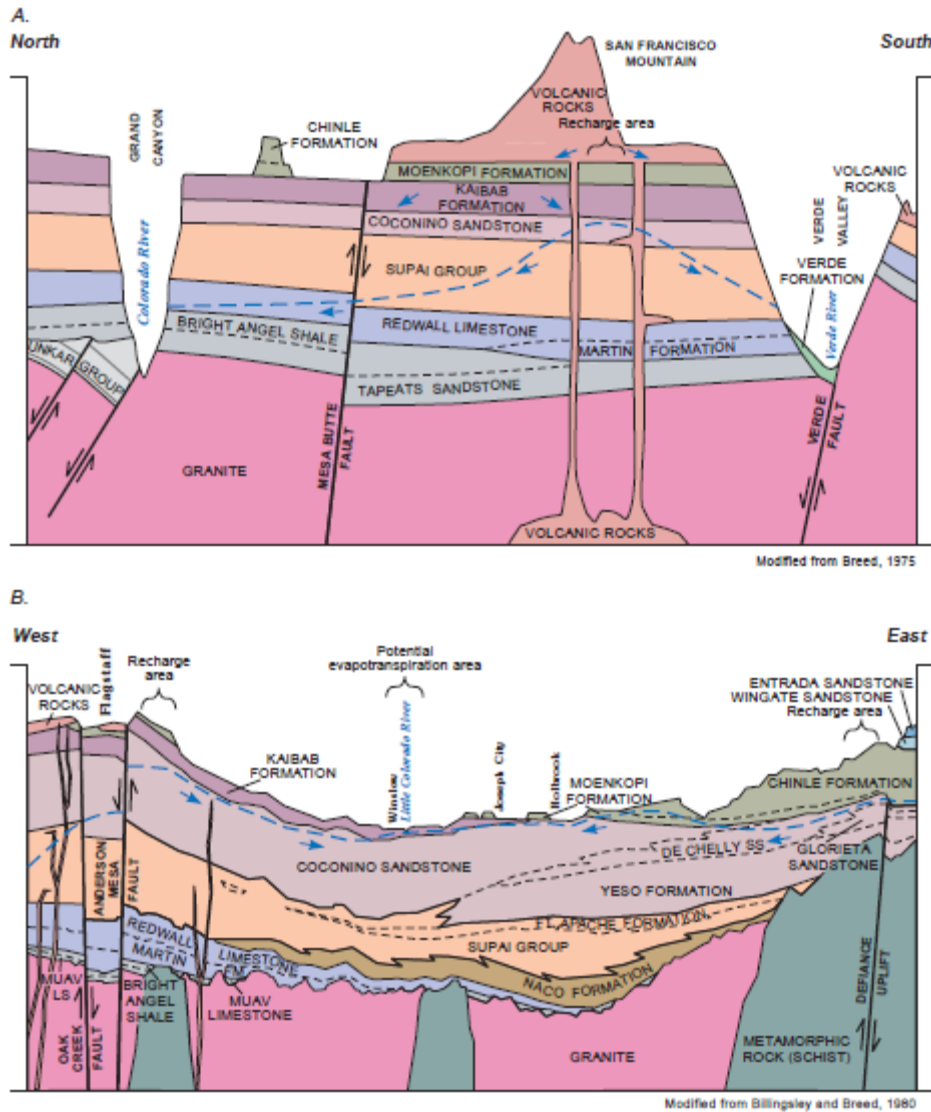


Figure 3: Generalized hydrogeologic cross-section of the Colorado Plateau of Northern Arizona A) from the Colorado River to the Verde River and B) from Flagstaff to the Arizona-New Mexico border (Hart *et al*, 2002).

location (Leake *et al*, 2005; ADWR, 2006a). The groundwater chemistry is generally of a calcium magnesium bicarbonate type (Bills *et al*, 2007); however, chloride and sodium have been noted as dominant ions in the C Aquifer (Hoffman *et al*, 2005). The hydrogeologic character of each aquifer will be discussed separately in descending stratigraphic order.

Dakota Aquifer

The D Aquifer is 3,125 mi² (8,094 km²) in extent and is contained within the Dakota Sandstone, the Westwater Canyon Sandstone Member and Junction Creek of the Morrison Formation, and the Cow Springs Sandstone of the Entrada Sandstones on the Hopi and Navajo Reservations with an estimated 15 million acft (18.5 billion m³) of groundwater in storage

(Cooley *et al*, 1969; ADWR, 2006a). In Arizona, the D Aquifer is limited to Black Mesa Basin and exhibits artesian conditions in the central basin. The D Aquifer is separated from the underlying N Aquifer by the Carmel-Twin Creek Formation (Robson and Banta, 1995). This aquifer is generally unsuitable for domestic use with dissolved solid concentrations ranging from 190 to 4,410 ppm TDS.

The Dakota Sandstone has an average thickness of 100 ft (30 m) (Cooley *et al*, 1969). The Cow Springs and Entrada Sandstones range in thickness from 100 to 300 ft (30-91 m) and 50 to 350 ft (15-107 m), respectively, thinning to the south. The Cow Springs Sandstone intertongues with the Morrison Formation to the north thickening the aquifer northward. Cooley *et al* (1969) noted the following porosity values for the D Aquifer: Dakota Sandstone, 23 to 28%; Cow Springs, 19 to 25%; the Morrison Formation, 19 to 25%; and the Entrada Sandstone, 25 to 31%.

Coconino Aquifer

The C Aquifer has an aerial extent of 21,655 mi² (56,086 km²) with groundwater storage estimates ranging from 166 to 293 million acft (205-360 billion m³) (ADWR, 2006a). The C Aquifer has been defined to include the Kaibab Formation, the Toroweap Formation, the Coconino Sandstone, the Schnebly Hill Formation, and the Upper and Middle Supai Formations (Bills *et al*, 2007). The Kaibab Formation is limestone up to 650 ft (200 m) thick (Leake *et al*, 2005). Both the Kaibab Formation and the Toroweap Formation are absent in the northern and eastern parts of the Little Colorado River Basin. The Coconino Sandstone ranges in thickness from 300 to 1,100 ft (90-330 m) and is regional in extent. The Schnebly Hill Formation thins to extinction to the north and is up to 1970 ft (600 m) thick in the Holbrook Basin (Blakey, 1990). The Upper and Middle Supai Formations are part of the Supai Group of which the Lower Supai Formation makes up the lower confining unit of the C Aquifer. The Supai Group ranges in thickness from 600 to 2,400 ft (180-730 m) with the lower confining unit averaging 300 ft thick (91 m) (Blakey, 1990; Leake *et al*, 2005).

Groundwater discharges as springs to the south along the Mogollon Rim into the Verde Valley and as springs to the north into the Little Colorado River Basin and the Grand Canyon. Groundwater in the C Aquifer is also lost to evapotranspiration, seepage to the R Aquifer, and withdrawal by private and municipal wells.

Bills *et al* (2007) noted the following regarding the location of saturated and unsaturated geologic units. The Kaibab Formation, Coconino Sandstone, and Schnebly Hill Formation are unsaturated north and west of Flagstaff, but the Upper and Middle Supai are saturated. Towards the Mogollon Rim to the south, the down-gradient movement of water leaves the Kaibab Formation and Coconino Sandstone unsaturated, and the aquifer is unsaturated west of Parks to Cameron, between Williams and the Big Chino Valley, and in the upper Verde Valley. The saturated thickness of the aquifer ranges from 600 to 2,200 ft (180-670 m) northeast to southeast with an average saturated thickness of 1,200 ft (370 m). Cooley *et al* (1969) noted porosity values for the De Chelly Sandstone, 13.6 to 27.2%, and the Coconino Sandstone, 27.6%.

The C Aquifer generally contains good quality groundwater, but due to evaporite deposits of the Middle Supai Formation and great depths in the Black Mesa Basin, the lower portions of the C Aquifer are known to contain brackish groundwater (USBR, 2006).

Redwall-Muav Aquifer

The R Aquifer has been defined to include the carbonate units of the Redwall Limestone, the Temple Butte/Martin Formation, the Muav Limestone, the Bright Angle Shale, and where present, the Tapeats Sandstone (USBR, 2006; Bills *et al*, 2007). The R Aquifer varies in thickness from 50 to 900 ft (15-270 m), and depths to the aquifer base range from a few hundred feet to 2,900 ft (880 m). Transmissivity has been estimated as ranging from 0.1 to 742 ft/d (0.03-226 m/d). However, few wells are completed in the R Aquifer. The R Aquifer is a confined aquifer and is fully saturated throughout much of its extent.

Bills *et al* (2007) noted the following regarding the location of saturated and unsaturated geologic units. The Redwall Limestone is partially to unsaturated in areas near the south rim of the Grand Canyon and variably saturated in other areas of the Coconino Plateau. The Temple Butte Formation thins to extinction south of the Grand Canyon. The Muav Limestone is fully saturated where penetrated by wells and also thins to extinction to the south lapping onto the Martin Formation. The Martin Formation thickens southward and is fully saturated where penetrated by wells except where it discharges to the south. The Bright Angle Shale and Tapeats Sandstone are fully saturated where present. However, the Tapeats Sandstone thins to extinction south of the Grand Canyon and the Bright Angle Shale does not exist in the central Coconino Plateau. The saturated thickness of the R Aquifer equates to the combined thicknesses of the Redwall Limestone, the Muav Limestone, and the Tapeats Sandstone, 640 to 2,000 ft (200-610 m), averaging about 1,000 ft (300 m) thick.

The R Aquifer discharges as springs in the Grand Canyon, the Verde Valley, and the Little Colorado River and its tributaries, as regional flow into the Verde Valley, and as evapotranspiration where water table is near the surface (Bills *et al*, 2007). Recharge occurs from downward leakage from the overlying C Aquifer.

Water quality ranges from good to poor based primarily on springs data (USBR, 2006). The poor water quality is thought to result from dissolution of the carbonate units of the aquifer, dissolution of- and leakage from overlying geologic units, and upwelling of deeper, ancient groundwater.

Basin and Range Basin-Fill Aquifers

The Basin and Range basin-fill aquifers of the Southwest are typically unconsolidated alluvial fan, flood plain, and lacustrine deposits between north-south trending block faulted mountain ranges and are typically unconfined except in basin centers where fine grain evaporites can form an overlying confining layer (Robson and Banta, 1995). Basement rock is dominantly plutonic and metamorphic rock of Precambrian and Cambrian age forming the lower confining units for the aquifers. The high solubility of the evaporites including gypsum, halite, and anhydrite causes high concentrations of dissolved solids in the groundwater (Anning *et al*, 2006). Dissolved solid concentrations of the groundwater are related to the surface water of streams within the basin and vary by season, by location relative to large reservoirs, and by the rock type of the stream's drainage basin. During periods of high runoff occurring during winter and summer storms, dissolved solid concentrations are decreased, and dissolved solid concentrations are also decreased down stream of dammed reservoirs and where streams are draining igneous or metamorphic rock as opposed to sedimentary rock (Anning *et al*, 2006). Most assessments of groundwater quality provide water quality in terms of specific conductance where the ratio of dissolved solid concentrations to specific conductance ranges from 0.55 to 0.63 in the Central Arizona Basins (CAZBs) (Anning *et al*, 2006).

Previous works noted by Huff (2004) indicate the existence of brackish groundwater near Wilcox, Case Grande, Tucson, Coolidge, and Phoenix and in alluvial deposits of the Gila, Salt, and Colorado Rivers. Anning *et al* (2006) provided a detailed study of brackish groundwater near the confluence of the Gila and Salt Rivers including the East Salt River Valley, the West Salt River Valley, the Eloy Basin, and the Maricopa-Stanfield Basin. Dickinson *et al* (2006) note dissolved solid concentrations ranging from 801 to 3,020 ppm TDS in the South Gila Valley and near Yuma Mesa in a 3-D groundwater model of the Yuma area.

Groundwater is discharged from the aquifers by evapotranspiration of shallow groundwater, withdrawal from wells, seepage to streams in gaining reaches, discharge to springs, and regional groundwater flow (Anning *et al*, 2006). Recharge to CAZBs occurs as infiltration of precipitation during periods of higher than normal rainfall, infiltration of excessive urban and agricultural runoff, and canal seepage.

Desalination

Utility-scale desalination is accomplished typically by thermal evaporation or by forcing water through a semi-permeable membrane designed to selectively prohibit passage of certain ions such as salts. Reverse osmosis (RO) and other membrane processes such as nanofiltration, electrodialysis, and electrodialysis reversal are fairly mature technologies and are the most common methods of desalination in the U.S. (NRC, 2008). RO is the type of desalination discussed in this work. The characteristics of RO are discussed briefly here for groundwater desalination.

The characteristics of RO are discussed briefly here for groundwater desalination, but are discussed in greater detail and for different types of systems by the National Research Council (2008) and in the Desalting Handbook for Planners (USBR, 2003). The desalination processes involve saline water intake, pretreatment, the desalination process, post-treatment, and concentrate management. Brackish groundwater generally produces a higher-quality feedwater than in seawater desalination minimizing the need for pretreatment. Pretreatment processes the feedwater to remove suspended solid and control biological growth which is not a common issue with groundwater desalination. However, pretreatment to remove dissolved iron, manganese, and sulfides may be necessary to prevent fouling of RO membranes. Sedimentation, coagulation, flocculation, and filtration are common methods of pretreatment. A slow sand filtration augmented with activated carbon or iron has been suggested as potentially appropriate for Arizona (Arizona Water Institute (AWI), 2008). Because the product water has significantly reduced dissolved ions concentrations, it has low hardness and alkalinity requiring post-treatment to prevent the corrosion of pipeline materials and the introduction of metals into the water. This may include the addition of calcium hydroxide or sodium hydroxide to adjust hardness, alkalinity, and pH depending on product water chemistry. The concentrate removed during desalination may also require some post-treatment. Concentrate management techniques vary by site and local regulations but include surface-water discharge, sewer discharge, subsurface injection, land application, and evaporate ponds.

Over 8,600 desalination plants were installed across the globe by 1999 with about 20% of these in the U.S. (USBR, 2003). In 1999, 59% of desalinated water produced globally came from seawater, 26% brackish groundwater, 6.0% from river water, 4.4% from waste water, and 0.23% from brine (Gleick, 2000). The world currently desalts 42 million m³/d water with the U.S. contributing approximately 5.7 million m³/d, primarily in Florida, California, and Texas

(NRC, 2008). The following are examples of the volume of water produced at existing desalination plants in the U.S. The Eastern Municipal Water District (EMWD) of the West San Jacinto Groundwater Basin, Southern California desalted 20.2 MGD (76,500 m³/d) brackish (<14,600 ppm TDS) groundwater at its two desalination plants, the Menifee and Perris Desalters in 2007 and is planning a new desalter, the Perris II, to produce another 12.5 MGD (47,300 m³/d) (EMWD, 2008). The Kay Bailey Hutchinson Desalination Plant in El Paso, Texas is the world's largest inland desalination plant producing 27.5 MGD (105,000 m³/d) or roughly 15% of their fresh water supply at approximately an 83% recovery rate (El Paso Water Utilities Public Service Board website available at www.epwu.org/water/desal_info.html#). The Tampa Bay Seawater Desalination Plant is the nation's largest seawater desalination plant producing 25 MGD (94,600 m³/d) or roughly 10% of their fresh water supply (Tampa Bay Seawater Desalination website available at www.tampabaywater.org/watersupply/tbdesal.aspx). In Arizona, the Yuma Desalter was built to desalinate Colorado River water, but was never operational except for short test periods.

Energy requirements and the financial costs are also of great concern with inland desalination (NRC, 2008). These plants can be located close to the point of use minimizing distribution and thus the cost and environmental impact of long pipelines. RO desalination is a pressure-driven process capable of recovering 50-90% of the feedwater as fresh water (200 to 500 ppm TDS) depending on the initial salinity and the presence of relatively insoluble salts and silica. The pressure requirements range from 1,000 to 8,300 kilopascals, and the energy requirements range from 0.5 to 3 kWh/m³ (Figure 4)(NRC, 2008).

Both factors depend on the degree of salinity of the feed water. Site design, environmental site conditions, and financing packages vary greatly for the existing desalination plants resulting in differing costs of production. The NRC (2008) noted the costs from two inland desalination plants in the U.S., \$0.63/m³ (Inland Empire) and \$0.43/m³ (El Paso/Ft. Bliss); however, they also noted some difficulty in their comparison due to some variety in the reported data. Wittholz *et al.* (2008) created a cost database of 331 desalination plants worldwide to estimate the costs associated with desalination for several types of desalination plants and various source waters (Figure 5 and Figure 6). From the database, they created a power law model to determine the relationship between capital costs and plant capacity. Ninety of the desalination plants were brackish water RO with water production costs in the range \$0.14-\$0.38/m³ and capital costs in the range \$8.1-\$145.4 million for plant capacities 10,000-500,000 m³/d. Costs were given in 2006 U.S. dollars.

Wind Energy and Technology

In the U.S., electricity generated from renewable energy sources were projected to increase from 0.4 trillion kWh in 2005 to 0.7 trillion kWh in 2030 (EIA, 2008). This increase was projected to occur due to increasing development of wind, solar, geothermal, and biomass resources and the implementation of State renewable portfolio standards (RPS) which are state policies requiring sellers of electricity to incorporate a specified portion of their electricity from renewable sources. Currently, twenty four states have implemented RPSs including Arizona.

To consider wind power as an energy source for desalination, several characteristics of wind must be considered such as the spatial distribution of wind resources relative to brackish groundwater, the temporal variability of wind, and several economic and environmental issues such as capacity, output stability and reliability, cost, in terms of both capital and operational

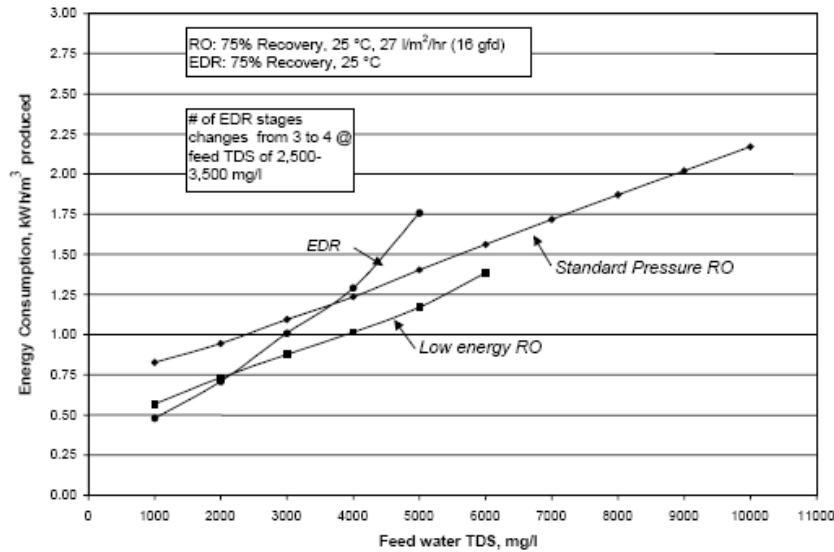


Figure 4: The increasing energy requirements for desalination equipment to produce a unit of water as a function of increasing salinity of the feed water (USBR, 2003).

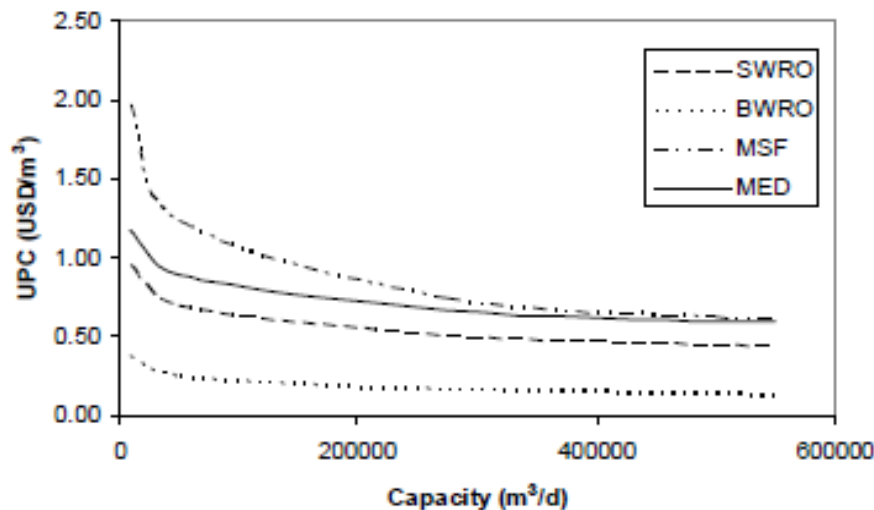


Figure 5: Desalination production costs as a function of plant capacity for several types of desalination plants worldwide (SWRO-seawater reverse osmosis; BWRO-brackish water reverse osmosis; MSF- multi-stage flash distillation; MED- multi-effect distillation) (Wittholz et al, 2008).

costs, and the impact wind turbines have on the environment and visa versa, as well as a comparison of these factors to those of other energy sources.

The spatial distribution of wind resources of the U.S. has been compiled and verified for 35 states including Arizona from various sources by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy (Figure 7). These data are available as maps and as GIS data available online (USDOE, 2008a). The wind resources presented by NREL are annual wind resources at 50 m height above ground with a 200 to 1,000 m resolution which excludes

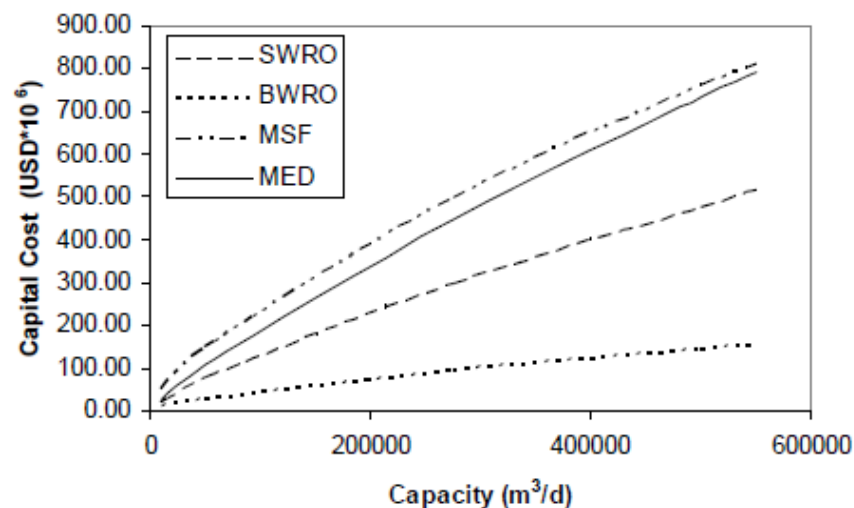


Figure 6: Capital costs of desalination as a function of plant capacity for several types of desalination plants worldwide (SWRO-seawater reverse osmosis; BWRO-brackish water reverse osmosis; MSF- multi-stage flash distillation; MED- multi-effect distillation) (Wittholz *et al*, 2008).

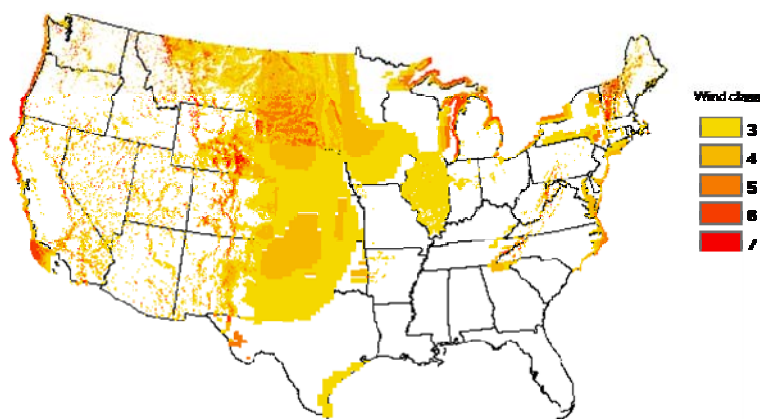


Figure 7: U.S. wind map showing wind class 3-7. This map was created in ArcGIS from NREL wind data (USDOE, 2008a).

areas with slopes greater than 20%. In general, a wind class 3 or greater is required for utility-scale electrical generation (Table 1. Relationship between wind class and wind power density/wind speed at 10 m and 50 m above ground level (modified from USDOE, 2008a).

10 m (33 ft)			50 m (164 ft)	
Wind Power	Wind Power Density (W/m^2)	Speed m/s (mph)	Wind Power Density (W/m^2)	Speed m/s (mph)
1	0	0	0	

2	100	4.4 (9.8)	200	5.6 (12.5)
3	150	5.1 (11.5)	300	6.4 (14.3)
4	200	5.6 (12.5)	400	7.0 (15.7)
5	250	6.0 (13.4)	500	7.5 (16.8)
6	300	6.4 (14.3)	600	8.0 (17.9)
7	400	7.0 (15.7)	800	8.8 (19.7)

).

Wind power is a rapidly expanding utility-scale energy resource in the U.S. and throughout the world. The installed capacity of wind energy in the U.S. has increased from around 2,500 MW in 2000 to 25,408 MW at the end of 2008 (Wiser and Bolinger, 2008; U.S. Department of Energy (USDOE), 2008a). The total worldwide capacity is in excess of 74,000 MW, and is expected to grow nearly 20% per year for the next few years. As wind energy becomes common in the utility system and for stand-alone applications, and as system planners

Table 1. Relationship between wind class and wind power density/wind speed at 10 m and 50 m above ground level (modified from USDOE, 2008a).

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	Wind Power Density (W/m ²)	Speed m/s (mph)	Wind Power Density (W/m ²)	Speed m/s (mph)
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and operators become comfortable with how to accommodate variability and uncertainty of wind energy, more applications for wind turbine systems will arise.

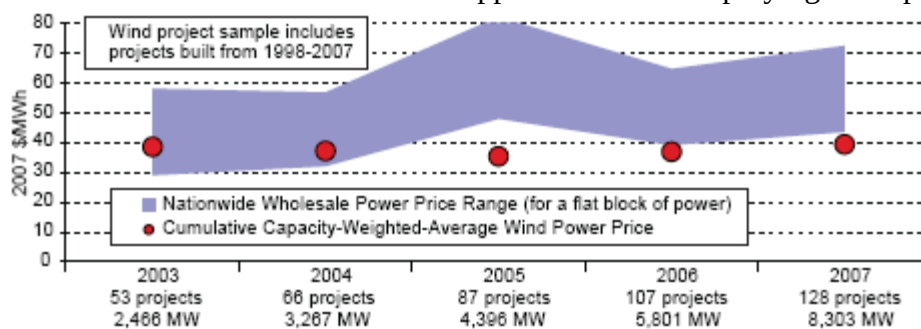
New U.S. installations accounted for approximately 25% of new installation globally. Texas is currently the largest U.S. market for wind energy with a total of 4,446 MW of installed capacity. Arizona has no electricity generated by wind at the utility scale although the wind

potential exists in many areas. Wind energy with the potential to generate electricity is located on 6% of land in the western U.S. (Nielson *et al*, 2006). This energy resource is capable of supplying five times the energy demand of the region as recorded in 1999. On the Navajo reservation in Arizona, the wind energy potential capacity has been estimated at 14,046 MW at a 70 m hub height (Brummels *et al*, 2006).

The weighted average cost of wind power from 128 wind projects in 2007, was just under \$40/MWh and has been found to be competitive with whole sale power prices nationally for several years (Wiser and Bolinger, 2008) (**Figure 8**). The U.S. Department of Energy (2008b) also noted that the cost of electricity produced by wind power is more stable overall due to a lack of dependence on fossil fuel price variability. Capital costs of wind projects have risen about 27% from the 2001-2003 average due to rising turbine costs and have ranged between \$1,240/kW and \$2,600/kW with an average of \$1,710/kW in 2007 (Wiser and Bolinger, 2008). The dollar amounts presented here reflect federal and state tax and other financial incentives. The cost generally decreases with increasing wind farm generation capacity due to cost savings in civil works costs.

Methods

This section describes the methods employed in this assessment of brackish groundwater occurrence and distribution and the opportunities for employing wind-power to supply the



Source: FERC 2006 and 2004 "State of the Market" reports, Berkeley Lab database, Ventyx.

Figure 8: Comparison of the cumulative capacity-weighted average cost of electricity generated from various wind power projects to the national wholesale price of electricity from 2003 to 2007 (Wiser and Bolinger, 2008).

electrical requirement of desalination. This assessment was conducted at the state-scale for Arizona using ArcGIS (ESRI ArcMap-ArcInfo 9.3). This assessment includes the location and volumetric estimates for brackish groundwater and the implementation of an economic model to estimate the costs associated with desalination and wind-powered electrical generation. Cost estimates were determined for desalination using both grid electricity and electricity generated by wind-power.

Generally, the aquifers were modeled by interpolating a top and a bottom aquifer surface from point data representing the surfaces as either depth to the surface from land surface or elevation above sea level and calculating the volume in between these surfaces. This volume represents the aquifer's saturated thickness. Using a generalized porosity value for the aquifers, a volume of water was estimated from the aquifer's saturated thickness. The interpolation of

these surfaces and calculations based on the interpolated surfaces produce a raster grid of cells of a given length and width and have values representing depth, elevation, or thickness. Using these values, various calculations were conducted to estimate the aquifer's saturated thickness and volume. These data were then extracted by additional raster data sets containing regions of high TDS concentrations and average annual wind class potential to locate and estimate areas with brackish groundwater resources where sufficient wind resources exist for desalination.

An economic model was also employed in ArcGIS. This model includes capital-cost estimates for desalination facilities, wind turbines, and well-field development, and a unit production cost estimate for the operation and maintenance of these facilities. The details of this model and its implementation are explained in the Economic Model subsection.

Wind Data

The USDOE, National Renewable Energy Laboratory (NREL) has produced wind-power density maps for 35 states of the U.S., 24 of which are high resolution (200-1000 m spatial resolution) with four more planned (USDOE, 2008a). Nine other states are available at lower resolution. The high-resolution wind-power maps have enough detail to show wind potential on ridge-tops and other geographic features. The accuracy of the wind-power maps are typically within 20% for 80% of the areas covered (USDOE, 2006b). We display the annual average wind-power density as wind-power class at a height of 50 m above land surface for our GIS, but other wind-power maps are available for different heights and for different seasons. Wind-power classes range from 1 to 7, where each is a representation of a range of wind-power densities or equivalent mean wind speeds 50 m above ground. These classes serve as an indicator of a region's wind-power development potential. In general, a class 3 wind resource or better is required to develop utility-scale wind power. NREL extrapolated wind speeds vertically based on the 1/7 power law to 50 m height, but utility-scale wind-power turbines typically exceed 50 m with hub heights between 70-100 m. Therefore, these wind maps may represent a minimum wind-power potential.

Aquifer modeling

The general methods involved to model the aquifers were outlined in the introduction of this section. However, different types of data were available to model the Basin and Range basin-fill aquifers and the Colorado Plateau Aquifers requiring slightly different methods. The data available to model the Basin and Range basin-fill aquifers included a digital contour map showing the depth to low-permeability or basement geologic units forming the lower confining units of the basins (Arizona Geological Survey (AGS), 2007) and well site information providing the depth-to-groundwater and water-quality data as specific conductance or "conductivity". Conductivity was changed to total dissolved solid (TDS) concentration for ease in comparing information from various sources. The relationship between conductivity and TDS is site specific and must be determined through experimentation on samples from the site. However, for the purposes of this assessment, TDS was estimated as 60% of conductivity. The data available to model the Colorado Plateau Aquifers included well and spring site information, geologic cross-sections showing the depth to geologic units, and descriptions of the geology of the region from various sources. The sources of these data and their implementation in this assessment are described in the following Groundwater Data, Basin-fill Aquifers of the Basin and Range Province, and Colorado Plateau Aquifers subsections. Available upon request in digital format is a detailed account of the GIS methods used in for this assessment.

Maps were created using North American Datum 1983 and were projected in Albers Equal Area Conic to preserve spatial dimensions for area calculations. Albers Equal Area Conic projection is suited for the conterminous U.S. and has a 1.25% maximum scale distortion between 29°30' and 45°30' north latitude.

Groundwater Data

Groundwater data for this assessment were divided into two general categories, general data for the national assessment and well log data for the Arizona assessment. General information regarding the nation's aquifers was obtained from the USGS Groundwater Atlas online (<http://pubs.usgs.gov/ha/ha730/gwa.html>). This information was used to model the brackish groundwater of the nation's principle aquifers. The assessment of brackish groundwater in Arizona was based on well and spring site information containing groundwater level and water-quality data and on depth to lower confining unit information from various publications.

Groundwater level and water-quality data were provided by the USGS National Water Information System (NWIS), the Arizona Department of Water Resources (ADWR) Groundwater Site Information (GWSI) database (USGS, 2009; ADWR, 2009), Leake *et al* (2005), and Bills *et al* (2007). Additional information from various sources was also used in the interpolation of aquifer surfaces as described in the following sub-section in which they apply. The USGS NWIS database houses most of the nation's groundwater level and water-quality data collected and verified by the USGS Science Centers across the country. These data are available for download by the general public (<http://nwis.waterdata.usgs.gov/usa/nwis/gwlevels>). The ADWR GWIS database contains additional well and spring sites not contained in the USGS NWIS and is available for download at their website (<http://arcims.azwater.gov/gwsi/waterresourcedata.aspx>). Leake *et al* (2005) produced a hydrogeologic model of the C-Aquifer in northeastern Arizona and presented some well log data not found in the USGS NWIS or the ADWR GWSI. Data from Bills *et al* (2007) were limited to spring data from their assessment of the hydrogeology of the Coconino Plateau as all other data that they presented were included in the USGS NWIS. Other sources of groundwater data may be available, but are generally of lesser quality and yield little additional information. Bills and Flynn (2002) note additional well data from the U.S. National Park Service and U.S. Forest Service databases, private well owners, tribal well data, and NAU and UNLV thesis studies. However, 80% of the well data used (1,767 total sites) in their assessment of hydrogeologic data for the Coconino Plateau were retrieved from the USGS NWIS and all of the data they retrieved from sources other than the USGS NWIS were verified and entered into the USGS NWIS.

Data were retrieved from the USGS NWIS database January 5, 2009 as a "ground-water levels for the nation" search based on Arizona State as a site location. The output format of this search was as follows:

Site description information displayed in table format with the following fields selected: site id number, site name, site type, decimal lat/long/datum, hydrologic code, local aquifer code, well depth, water-quality begin date, water-quality data count, groundwater data count. Data were retrieved from 1999/01/01 to 2009/01/05.

This search retrieved all available well site information between the dates specified in the output format. This initial search yielded nearly 4,000 wells sites, but only 890 contain depth-to-water data and an additional 30 well sites with water-quality data given as specific conductance. However, not all of the well sites contain water-quality data, and such data were not provided as part of the readily available and downloadable well site information. The water-quality data had to be looked up separately within the individual well site descriptions. Many of the well sites were provided as time-series data or contained many water-level readings over time. Many of which were older than the date range specified in the output format. In such cases, the water-level data were averaged for sites within the date range. The same method was applied to water-quality data. However, because the water-quality data were not part of the readily available and downloadable data, the date range specified in the output format did not apply resulting in water-quality data that may only exist as older readings. In such cases, the most recent reading was used, providing the most current data on record even if it was older than the date range specified.

The groundwater information obtained from the ADWR GWSI database was accessed from a compact disk purchased from ADWR in January, 2009. The database contains 17 data tables for over 44,000 well and spring sites in Arizona. The data tables containing well site locations, water-level data, and water-quality data (GWSI_SITES, GWSI_WW_LEVELS, and GWSI_WQ_REPORTS) were used in this assessment.

Well and spring site locations that were related to geologic units not under consideration in this assessment were removed from the database. In the Basin and Range Province, many well sites do not list the geologic unit in which the well was completed. In such cases, the well sites were removed or kept based on an interpretation of the well's location relative to the basin's confining mountain range and the well's depth. On the Colorado Plateau, well and spring sites that did not list a related geologic unit were removed. The most recent depth-to-water measurement since January 1, 1999 was used from water-level data disregarding negative depths to water.

Groundwater data sets from Leake *et al* (2005), Bills *et al* (2007), USGS, and ADWR were combined into one data set containing 11,598 well and spring site locations. These data were separated by location into data sets for the Basin and Range basin-fill aquifers, Redwall-Muav (R) Aquifer, Coconino (C) Aquifer, and Dakota (D) Aquifer.

Basin and Range Basin-fill Aquifers

The Basin and Range Province contains many individual groundwater basins which may be defined by the surface-water divides between them (Figure 9). This assumes some hydrologic disconnect between the hydrologic basins, although some hydrologic connection is known to exist in terms of both surface water and groundwater (Anning and Konieczki, 2005). The basin-fill aquifers were divided into hydrogeologic areas (HGAs) on this basis. These boundaries were used as the maximum geographic extent of a modeled aquifer in the interpolations and to select data for an aquifer. Only basins with at least three data points containing water-quality data within the HGA were modeled. Some basin-fill aquifers contain well sites with water-quality data, but not depth-to-groundwater data. In these cases the depth-to-groundwater was estimated for the purpose of creating an upper aquifer surface and a saturated aquifer thickness

Colorado Plateau Aquifers

The aquifer's geographic extents were derived from a digital geologic database produced by the USGS (Ludington *et al*, 2007) except as noted in the following discussion. The geologic

units selected to represent the aquifer's geographic extents were selected based on the following UNIT_LINK attributes:

- D Aquifer- AzJs;0 representing the Carmel Formation and Entrada Sandstone,
- C Aquifer- AzPPA;0 representing the Hermit Formation, Supai Group, Schnebly Hill Formation, and Naco Group,
- R Aquifer- AzMCA;0 representing the Tapeats Sandstone, Bright Angel Shale, Muav Limestone, Temple Butte Formation, Redwall Limestone, Bolsa Quartzite, Abrigo Formation, Martin Formation, and Escabrosa Limestone.

The southern extent along the Mogollon Rim was drawn where the geologic units containing the aquifers outcrop except in the southeastern most extent of the region where the boundary of the C Aquifer is not well defined. The extent in this area was modeled from the description of the Coconino-De Chelly Aquifer in the USGS Groundwater Atlas of the United States (Robson and Banta, 1995). Bills *et al* (2007) note that the C aquifer is dry in the western portion of the Coconino Plateau to the west of Flagstaff roughly correlative to the north-northeast trending Mesa Butte Fault with the exception of some perched aquifers that are disconnected from the regional aquifer. The geographic extent of the C aquifer was modeled to match this dry-line and extended to the north to match the boundary described by Robson and Banta (1995). It was assumed that the units of the C aquifer were also dry in much of the region to the north of the Grand Canyon. The R aquifer was assumed to underlie all of the Colorado Plateau. In the Verde

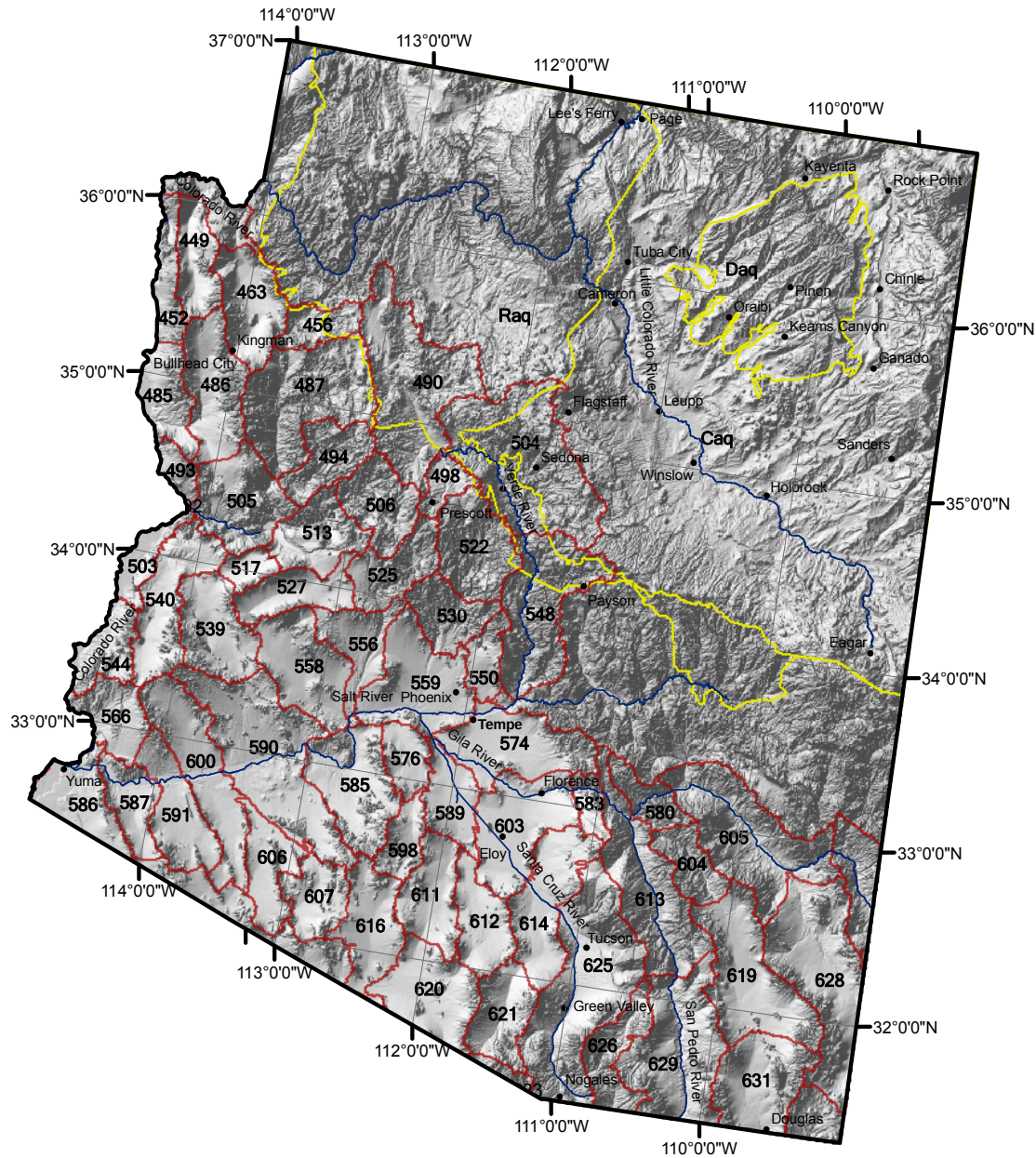


Figure 9: Relief map of Arizona showing the geographic extent of the Colorado Plateau and Basin (yellow) and Range basin-fill aquifers (red)

Valley, the southern extent of the R aquifer was modified as described by Blasch and others (2006) in a hydrogeologic assessment of the upper and middle Verde watersheds.

Additional groundwater data for modeling the Colorado Plateau Aquifers were obtained from various published sources, mainly as geologic cross-sections in USGS publications (Cooley *et al*, 1969; Repenning *et al*, 1969; Irwin *et al*, 1971; Blakey, 1990; Billingsley and Workman, 2000; Bills *et al*, 2000; Billingsley and Wellmeyer, 2002; Bills *et al*, 2002; Truini and Macy, 2005; Billingsley *et al*, 2006a, Billingsley *et al*, 2006b; Blasch *et al*, 2006; Billingsley *et al*, 2008) for determining depth to confining units in the interpolations of aquifer surfaces.

The aquifers' upper surfaces were modeled from well and spring site information contained in the USGS NWIS, ADWR GWSI, and other publications providing depth to the bottom of upper confining units. The well and spring site sources provide water-level data at a specific location as either depth to water below land surface (bls) or elevation of water level above sea level (asl) and in some cases both were given. Strictly, the depth to the bottom of upper confining units may not represent the water level in a well drilled at a location due to potentiometric pressure or the aquifer may not be fully saturated. However, where well and spring site data were not available, depth to the bottom of the upper confining units were used to approximate water level. Measurements for the lower confining units, the aquifers' bottom surfaces, were derived from USGS geologic cross-sections which were given as elevational data. To estimate the depth to groundwater in the Colorado Plateau Aquifers, the top surface interpolation was subtracted from an Arizona 90-m DEM containing land surface elevation within the extent of the aquifer modeled.

Polylines are used in some interpolations to constrain the modeled estimation where geologic structure or geomorphology causes a hiatus in hydrogeologic characteristics. The polylines allow for variable modeling within an aquifer's geographic extent by providing a breakline or barrier that limits the selection of points used in the interpolation to either side of the barrier. Polylines were used as described in the following discussions for the D and R Aquifers.

Dakota Aquifer

Well site data for wells completed in the Toreva Formation, Entrada Sandstone, and Morrison Formation were selected for the D Aquifer. The D Aquifer is separated from the underlying Navajo Aquifer by the Carmel-Twin Creek Formation (Robson and Banta, 1995). However, this aquiclude provides some leakage between the aquifers in the southeastern portion of Black Mesa and may be water bearing in the Winsor and Paria Creek Members of the Carmel Formation (Truini and Macy, 2005). For the purposes of this assessment, the Carmel Formation is considered a single, non-water bearing geologic unit forming the lower confining unit of the D Aquifer. The upper surface of the Carmel Formation was modeled as the bottom surface of the D Aquifer from geologic cross-sections created by Truini and Macy (2005) as part of an assessment of the linkage between the D and N Aquifers. The Carmel Formation is assumed to be in the subsurface throughout the modeled extent. The D aquifer is confined below the Mancos Shale through much of its extent, but is exposed at the surface in the northeast. Points (0 m depth to water) were added to the top point data set to represent this exposure, and a polylines was used in the interpolation to constrain the estimation. North and east of the constraining polyline, wells are completed in the C and R Aquifers at depths ranging from 20 to 498 m. Therefore, the D Aquifer was assumed to be dry where it exists to the northeast of the polyline. Additionally, points were added for the elevation at the top of the D Aquifer where confined (NGVD 1929) at well sites presented by Truini and Macy (2005) to represent groundwater elevation.

Coconino Aquifer

Well site data from wells completed in the Kaibab Limestone, Coconino Sandstone, De Chelly Sandstone, and Upper and Middle Supai were selected for the C Aquifer. The C aquifer is unconfined over much of its extent, and is the principle and upper-most aquifer in these areas. The C Aquifer is confined below Black Mesa separated from the overlying Navajo Aquifer by the Chinle and Moenkopi Formations. Many wells exist around the periphery of Black Mesa,

but few wells are completed in the confined region below Black Mesa. Depths to the C and R Aquifer below and east of Black Mesa were derived from estimated thicknesses of Triassic, Permian, and Pennsylvanian geologic units (Repenning *et al*, 1969; Irwin *et al*, 1971; Truini and Macy, 2005).

Redwall-Muav Aquifer

Well site data from wells completed in the Redwall, Martin, and Muav Limestones, and the Tapeats Sandstone were selected for the R Aquifer. Many well sites within the R Aquifer extent do not list the geologic unit the well was completed in, but do provide the well's depth. In such cases, the well depth was compared to nearby wells that do list the geologic unit the well was completed in and included or excluded accordingly. For well sites not providing a related geologic unit in the Upper Verde Valley region, well site locations and well depths were compared to hydrogeologic assessment of the Upper and Middle Verde River watershed provided by Blasch *et al* (2006). Blakey (1990) noted the R Aquifer is not present in the region of the Defiance Uplift. Elevation data of the Precambrian basement geologic units were used to model the bottom surface of the R Aquifer (Butler, 1991). Polylines were used along the Colorado River in the Grand Canyon to divide the interpolation of points north and south of the river and to designate major faults systems and monoclines where they result in abrupt changes in the geologic units' elevation of at least 300 m including Big Springs Fault, Uncle Jim Fault, Hurricane Fault, Main Street Fault, Big Chino Fault, Oak Creek Fault, Verde Fault, Railroad Fault, Bridgeport Fault, East Kaibab Monocline, and Supai Monocline.

Surface Interpolations

ArcGIS Spatial Analyst offers three methods for interpolating surfaces from point data, kriging, inverse distance weighted (IDW), and spline. The interpolated surface is a prediction of the surface modeled between geographically located points using an algorithm. The kriging method assumes there is a statistical relationship, either distance or direction, between the entered points. The data used in this assessment have no such relationship; therefore this method is not used. The IDW method assumes the influence of a sampled point decreases with distance which results in lines of equal elevation that radiate around the sampled points. Spline minimizes the curvature of the surface producing a surface that passes through the points rather than around them as in the IDW interpolation. The IDW method was used exclusively in the national assessment for simplicity of modeling a large number of aquifers from varying data. See the supporting materials for the manuscript for details on the use of this method in the national assessment. Both IDW and spline methods are used in the assessment for Arizona and are described here.

The method of interpolation used to model an aquifer surface varied by aquifer and was dependent on the orientation of the available points to be interpolated. For surfaces with ample data points spread fairly evenly throughout the modeled extent, the spline method of interpolation provided the best fit to the sampled points. However, the spline method tends to produce unrealistic predictions in areas beyond the sampled points. The IDW method of interpolation provides a more conservative estimate where the sampled points are narrowly grouped leaving large areas within the modeled extent without data to constrain the interpolation. A more conservative estimate with regard to the values interpolated in this assessment means, for example, that TDS interpolations result in lower estimated TDS values and surface interpolations result in shallower estimates for the top and bottom surfaces in areas without constraining sample

points. The spline interpolation provides a more conservative estimate than the IDW interpolation limiting the extent of groundwater with the highest estimated TDS concentrations where the TDS values of the sampled points are relatively similar in an area. However, the spline interpolation tends to under represent values that are extreme compared to points in the same area. The method selected for a particular interpolation was determined by how well the interpolation represented the data input from recorded data at known locations and how the data were estimated in areas where no data exist.

The interpolation process produces a grid of cells within the geographic extent of the modeled aquifer known as a raster. Each grid cell in the raster is associated with a length and width value determined during the interpolation, as well as a depth or elevational value depending on the type of data input. In this assessment the length and width values were calculated in Spatial Analyst with the Options parameters for cell size set to Minimum of Inputs. This causes Spatial Analyst to calculate the grid cell size based on the smallest north-south or east-west dimension of the modeled geographic extent. Generally, the geographic extent for modeling an aquifer was taken as the data set used in the interpolation process with the largest geographic footprint, typically the hgaxxx_extent shape file.

Confidence levels were given to each interpolation to generally describe the degree of confidence in the data used in the assessment and the resultant interpolation. Generally, three aspects of the data were considered in assigning a confidence level: the number of well sites available, the distribution of data throughout the basin, and whether the geologic unit the well was completed in was provided in the primary database. A high confidence was given to interpolations made from a high amount of data that was at least fairly well distributed or a moderate amount of data that was evenly distributed. A moderate confidence was given to interpolations made from a moderate amount of data that are not well distributed in some areas of the basin or a low amount of data that are well distributed. A moderate-low confidence was given to interpolations made from a low amount of data that are at least fairly well distributed. A low confidence was given to interpolations made from data that are concentrated in a small area of the basin regardless of the amount of data available, to interpolations made from very little available data regardless of its distribution. The inclusion of the geologic unit in which the well was completed was weighted secondarily in the assignment of the confidence levels. Some of the available data used in the basin-fill aquifer interpolations do not include this information, so that some of the data used may represent wells completed in basement or volcanic rock units not basin-fill material. However, attempts to avoid this were made by comparing the well site locations and depths to geologic and topographic maps.

Raster calculations

A number of different raster calculations were conducted in this assessment using Raster Calculator in ArcGIS Spatial Analyst, herein simply called Raster Calculator. First, as mentioned in the introduction of this chapter, the saturated aquifer thickness was calculated as the vertical difference between the interpolated upper and lower aquifer surfaces. This was conducted to estimate the volume of groundwater potentially available in an aquifer. Second, the volume of brackish groundwater within the aquifers was determined by extracting raster grid cells representing an aquifer's groundwater volume using the interpolated surface representing TDS concentration values. Third, the location and volume of brackish groundwater co-located with wind resources potentially capable of supplying the electrical demand of desalination were determined by extracting the raster grid cells representing the volume of available brackish

groundwater using a raster representing annual average wind class potential (USDOE, 2008a). These methods are explained in detail in the following sub-sections.

Saturated aquifer thickness

For the Basin and Range basin-fill aquifers, an aquifer's saturated thickness was estimated by subtracting the upper aquifer surface from bottom aquifer surface (**Figure 10**). For the Colorado Plateau aquifers, the bottom surface was subtracted from the upper surface. The methods for these calculations were different due to the varying types of data available to model the aquifers. The data for the basin-fill aquifers represent depths from land surface. Subtracting top from bottom yields primarily positive values for aquifer thickness. While positive values were required to represent an aquifer's thickness, negative values may result in some regions of an aquifer. Negative values in the resulting raster may be interpreted as areas where the lower confining unit defining the aquifer bottom is above the water level indicating dry regions of the aquifer.

Such regions were disregarded in the maps produced and in the volume calculations. The data for the Colorado Plateau aquifers represent elevation above sea level. Producing positive values for aquifer thickness required subtracting the bottom surface from the top. These calculations produced raster grids with cells representing an aquifer's saturated thickness. The saturated thickness was multiplied by a generalized aquifer porosity of 10% to estimate the thickness of the aquifer associated with groundwater in an aquifer's pore space.

Brackish groundwater volume

Estimating the volume of brackish groundwater available in an aquifer required "extracting by mask" the grid cells with values associated with the thickness of an aquifer that can be attributed to groundwater using the interpolated TDS concentration as a mask in the extraction. Using the cells' associated length, width, and thickness values, a volume for each grid cell was calculated. All such volumes were totaled to estimate the overall volume of brackish groundwater for an aquifer. These methods assume that the entire volume of the aquifer represented by each grid cell contains brackish groundwater which may not accurately reflect conditions throughout the entire aquifer.

Volume of brackish groundwater with co-located wind

The volume of brackish groundwater available where wind resources can potentially be used to supply the energy demand of desalination were estimated by extracting values associated with the thickness of an aquifer containing brackish groundwater in the salinity range of 1,000-10,000 ppm TDS within 20 km of the average annual wind class potential data provided the USDOE (2008a). The total volume of brackish groundwater co-located with wind was calculated in the same manner as described for calculating the brackish groundwater volume in the previous sub-section.

Economic Model

Two methods of determining costs are generally of concern with desalination, capital costs and production costs. An estimate of these two cost factors were presented as a GIS model based on this assessment of brackish groundwater (Figure 11).

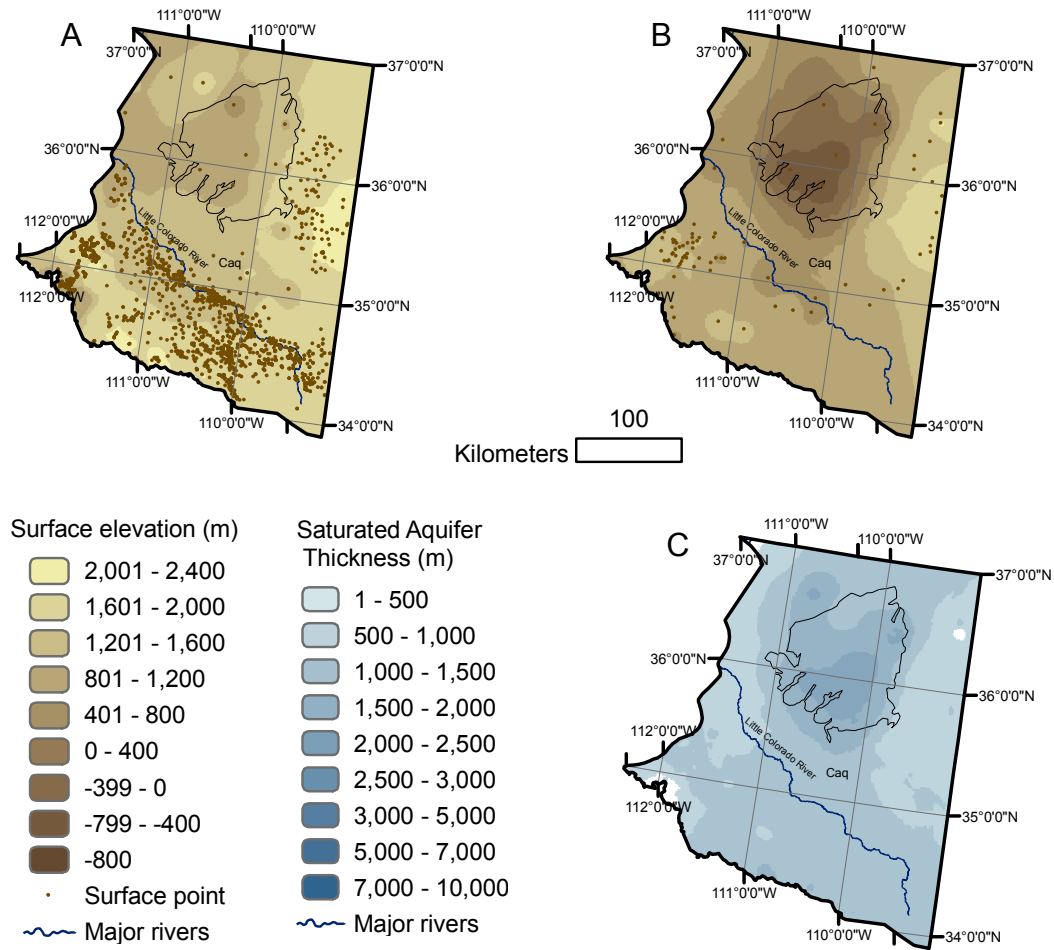


Figure 10: Example of surface interpolations from point data and saturated aquifer thickness calculation using data for the Coconino Aquifer of the Colorado Plateau, Arizona. The difference between the A) upper and B) lower surface interpolations was used to estimate C) the saturated aquifer thickness. The points shown on A and B were used to interpolate the surfaces.

The desired recovery rate, the amount of water produced from the amount of water processed, is an important cost determining factor affecting both capital and production costs. For example, lowering one cost raises the other. Increasing the recovery rate can lower the capital costs by reducing the membranes needed, but increase the production cost due to increasing pressure requirements (USBR, 2003). However, for simplicity in this assessment, the financial effect of varying recovery rates was not considered, but should be in any feasibility study of a particular project. This economic model was meant to provide a first approximation of the costs associated with wind-powered desalination of Arizona's brackish aquifers. This

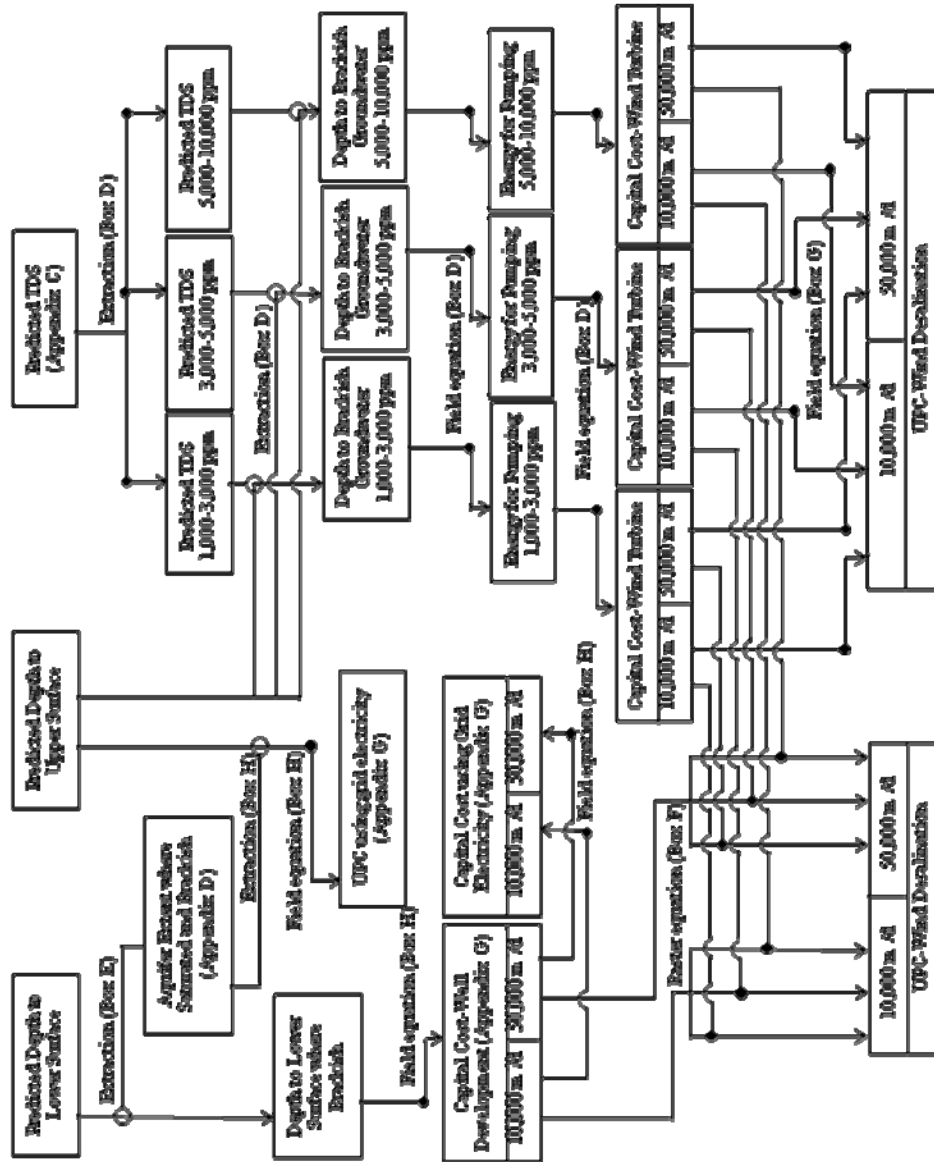


Figure 11: Flow diagram showing creation of rasters for economic calculations.

assessment also presents an estimate of the costs associated with desalination using grid electricity for comparison. The estimated costs may be used by water managers in decisions regarding the pursuit of a more detailed feasibility study.

The economic model is dependent on several factors such as depth to brackish groundwater, depth to an aquifer's lower confining unit, desalination plant capacity, feedwater salinity, and equipment costs. The depth to saline groundwater and lower confining units were determined from the surface interpolations created in this assessment. The plant capacities used in this model include moderate and large utility-scale desalination plant capacities, 10,000 m³/d (2.6 MGD) and 50,000 m³/d (13.2 MGD). These plant capacities were chosen for ease in comparison to published desalination plant data (Wittholz *et al*, 2008). Feedwater salinity was divided into three ranges, 1,000-3,000 ppm TDS, 3,000-5,000 ppm TDS, and 5,000-10,000 ppm

TDS with salinity determined from the TDS interpolation created in this assessment. Equipment costs are discussed in the following sections.

Capital costs

To estimate the capital costs of desalinating brackish groundwater, the costs of the desalination plant, wind turbine, and well development were considered. These factors were added together to estimate the overall capital costs as a function of desalination plant size and feedwater salinity:

$$\begin{aligned} \text{Capital costs (\$)} = & \text{Desalination plant capital} + \text{Wind turbine capital} \\ & + \text{Well development costs} \end{aligned} \quad (1)$$

The wind turbine capital costs were not used in modeling the costs associated with using grid electricity to supply the energy requirements of desalination. Using grid electricity for a utility-scale desalination plant may require the installation of new power generation facilities, but the costs associated with such facilities were not considered in this model.

Desalination plant capital costs

The capital costs of the desalination plants were taken from the cost assessment conducted by Wittholz *et al* (2008) which included plant and land costs, civil works, and amortization (**Figure 12**). The capital cost of a 10,000 m³/d and a 50,000 m³/d desalination plant are \$8.1 million and \$26.5 million, respectively (Table 1).

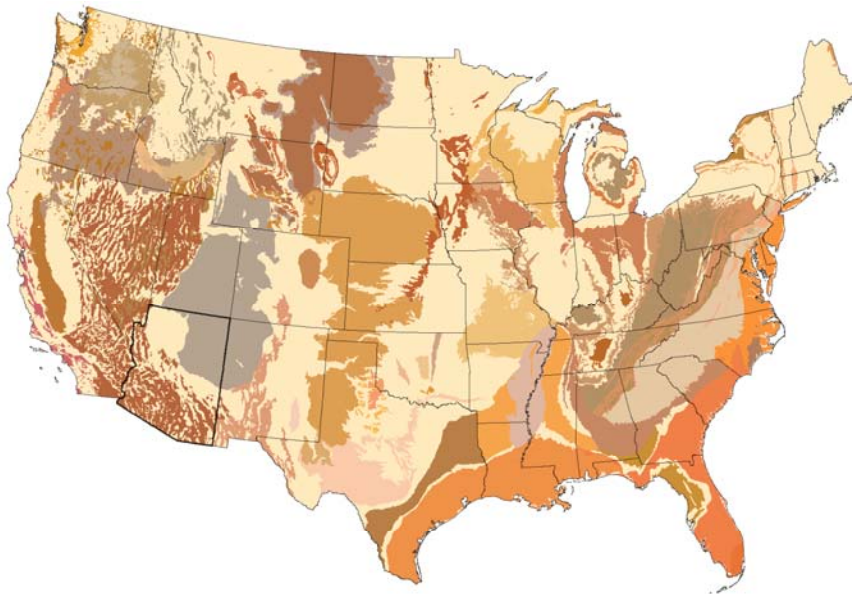


Figure 12: Map showing the principle aquifers of the continental U.S. as described by the USGS Ground Water Atlas of the United States with the Basin and Range (dark brown) and Colorado Plateau Aquifers (grey) highlighted by a bold Arizona border (modified from USGS, 2008).

Table 1: Estimated costs of brackish water RO desalination calculated from a database of desalination plants worldwide (Wittholz *et al*, 2008). The capital costs and unit production costs (UPCs) were from Wittholz *et al*. The other estimates were calculated to determine the annual operating costs and estimated costs of energy used in determining the UPCs.

Capacity (m ³ /d)	Capital costs (\$ × 10 ⁶)	Unit production cost (\$/m ³)	Annual operating cost (\$ × 10 ⁶)	Annual energy cost (\$)	Average energy required (kW)	Cost of energy (\$/kWh)
10,000	8.1	0.38	1.4	650,000	1865	0.07
50,000	26.5	0.25	4.6	2,100,000	9325	0.05

Wind turbine capital costs

The wind turbine capital costs were determined by the wind turbine output requirements for desalination and pumping groundwater to the surface and the cost of the wind turbine according to the following equation:

$$\text{Capital cost}_{\text{wind turbine}} (\$) = \text{Energy output} \times \text{Cost per output} \quad (2)$$

where the output was given in kW and the cost was estimated as the 2007 average cost for wind projects, \$1,710/kW (Wiser and Bolinger, 2008).

The wind turbine energy output should be sufficient to pump and desalinate groundwater. The energy output required for pumping and desalination depends on the desalination plant capacity, salinity and depth of the feedwater, and the turbine's operating capacity according to the following general equation:

$$\text{Energy output (kW)} = \left(E_{\text{salinity}} + E_{\text{pumping}} \right) \times \text{Desalination plant capacity} \times \text{Wind turbine operating capacity} \quad (3)$$

where E_{salinity} and E_{pumping} are the energy requirements for various salinity concentrations and pumping depths in kWh/m³. The wind turbine's operating capacity was assumed to be 35% (Wiser and Bolinger, 2008).

The energy requirements for the desalination plant increase with increasing feedwater salinity and depth. For the salinity ranges designated in this assessment, the energy required was taken for the largest salinity concentration in each of the ranges. The following rates were used: 1,000-3,000 ppm TDS requires 1.10 kWh/m³, 3,000-5,000 ppm TDS requires 1.4 kWh/m³, and 5,000-10,000 ppm TDS requires 2.20 kWh/m³ (USBR, 2003).

Energy output requirements are also dependent on the depth to groundwater. Increasing depth requires more energy to pump water to the surface. The energy output requirement in groundwater pumping calculations are generally given as total dynamic head which is a function of the static groundwater level, groundwater drawdown, additional lift after the pump, frictional losses in the pipes, and discharge pressures. The amount of groundwater drawdown is dependent on well design and aquifer characteristics, and additional lift after the pump, frictional losses in the pipes, and discharge pressures are dependent on the desalination plant design. While important for a site-specific design, for simplicity in estimating the energy required for

groundwater pumping as a generalized regional assessment, only the static groundwater level was considered here and was taken from the depth to the aquifer's upper surface as modeled in this assessment. Also important for a more detailed feasibility study is the effect potentiometric pressure might have on groundwater level in confined areas of an aquifer.

The energy required for pumping was modeled after techniques used by the Irrigation Training and Research Center (ITRC) in an analysis of the energy requirements for irrigating over 9 million acres in 87 districts in California by California's agricultural industry (ITRC, 2003). Their estimate of the energy requirements for groundwater pumping was conducted according to the following equation:

$$E_{\text{pumping}} \text{ (kWh/acft)} = (\text{TDH}/\text{OPPE}) \times 1.023 \quad (4)$$

where TDH was given in feet and OPPE was the overall pumping plant efficiency. OPPE was estimated as the mid-range value, 65%, as calculated by the ITRC (2003) for pumping efficiencies of wells in California. Equation 4 was modified for conversion to metric measurements and simplified to the following:

$$E_{\text{pumping}} \text{ (kWh/m}^3\text{)} = \text{TDH} \times 0.00039 \quad (5)$$

Given these energy output requirements for various salinity concentration ranges and pumping depths, the two desalination plant capacities, the estimated wind turbine operating capacity, and the 2007 average cost for wind projects, Equation 2 for wind turbine capital costs was rewritten for the various salinity concentrations and plant capacities:

10,000 m³/d:

1,000-3,000 ppm TDS:

$$[(\text{TDH} \times 0.00039) + 1.1](\text{kWh/m}^3) \times 10000(\text{m}^3/\text{d}) \div 24(\text{hr/d}) \div 0.35 \times 1710(\$/\text{kW}) \quad (6)$$

3,000-5,000 ppm TDS:

$$((\text{TDH} \times 0.00039) + 1.4) \times 10000 \div 24 \div 0.35 \times 1710 \quad (7)$$

5,000-10,000 ppm TDS:

$$((\text{TDH} \times 0.00039) + 2.2) \times 10000 \div 24 \div 0.35 \times 1710 \quad (8)$$

50,000 m³/d:

1,000-3,000 ppm TDS:

$$((\text{TDH} \times 0.00039) + 1.1) \times 50000 \div 24 \div 0.35 \times 1710 \quad (9)$$

3,000-5,000 ppm TDS:

$$((TDH \times 0.00039) + 1.4) \times 50000 \div 24 \div 0.35 \times 1710 \quad (10)$$

5,000-10,000 ppm TDS:

$$((TDH \times 0.00039) + 2.2) \times 50000 \div 24 \div 0.35 \times 1710 \quad (11)$$

where 24 is a time conversion and Equation 6 shows the units typical of all equations.

Well development costs

The cost of developing the well to obtain groundwater for desalination was estimated from relationships between production rate and well depth determined by LBG-Guyton Associates (2003) for the Texas Water Development Board (Table 2):

$$\text{Well costs (\$/ft)} = 22,000 + (60 \times \text{Plant capacity}) + (320 \times \text{Well depth}) \quad (12)$$

This cost estimate includes drilling, well development, well testing, pump, controls, and column piping. For the purposes of this assessment, a 10,000 m³/d (1,835 gallons per minute) desalination plant was assumed to require a 16-inch diameter well and a 50,000 m³/d plant was assumed to require five such wells. However, a smaller number of larger diameter wells may reduce the estimated costs for the larger capacity plant. Their equation (Eq. 12) was modified with a conversion from feet to meters and simplified to result in the following equation to estimate well development costs:

$$\text{Well costs (\$/m)} = 22,000 + (60 \times \text{Plant capacity}) + (97.5 \times \text{Well depth}) \quad (13)$$

The well depth was determined by the depth to the aquifers' lower confining units as interpolated in this assessment. The depth to the bottom of an aquifer represents the maximum drilling depth required and may over estimate the actual drilling depth required for a location, because a well's screened interval may not have to extend to an aquifer's lower confining unit.

Unit production costs

To estimate the unit production costs (UPC) of water produced from desalinating brackish groundwater with co-located wind and grid electricity, the annualized capital costs and costs of operation and maintenance for the desalination plant and wind turbines and the costs of pumping groundwater to the surface were considered. The cost of concentrate management can also significantly increase the costs associated with desalination. Such costs are not considered in this cost estimate, because they are design specific and are dependent on the type of management practice employed. The UPC model was based on the equations:

$$UPC_{\text{co-located wind}} (\$/\text{m}^3) = UPC_{\text{desalination}} + UPC_{\text{wind turbine}} \quad (14)$$

$$UPC_{\text{grid electricity}} (\$/\text{m}^3) = UPC_{\text{desalination}} + UPC_{\text{pumping}} \quad (15)$$

Table 2: A well development cost model used to estimate desalination costs for a regional water plan assessment by the Texas Water Development Board relating the cost of well development to production rate and well depth (LGB Guyton Associates, 2003).

Well Diameter (inches)	Typical Production Range (gpm)	Estimated Cost (2002 \$) a=production rate (gpm), b=well depth (feet)
6	25-150	7000 + 68a + 60b
8	150-300	10000 + 65a + 140b
10	300-500	15000 + 63a + 180b
12	500-800	20000 + 60a + 225b
16	800-2000	220000 + 60a + 320b

UPC of desalination

The unit production costs of desalination were estimated from Wittholz *et al* (2008) calculations for 10,000 and 50,000 m³/d brackish water RO desalination plants. Wittholz *et al* calculated the UPC from the following equation:

$$\frac{(\text{Capital costs} \div \text{Plant life}) + \text{Annual operating costs}}{\text{Plant capacity} \times \text{Plant availability}} \quad (16)$$

where costs for the plant, land, civil works, and amortization were considered in capital costs and costs for energy, maintenance, labor, and chemicals in pre- and post-treatment were considered in operating costs. The numerator of Equation 16 represents the total annual cost. Plant life and availability were estimated at 20 years and 90%, respectively (Wittholz *et al*, 2008). In this assessment, the cost of electricity was varied for comparison and was based on electricity produced by co-located wind and grid electricity at the 2006 average Arizona retail cost, \$0.0824/kWh (EIA, 2007).

Unfortunately, the UPCs determined by Wittholz *et al* (2008) were calculated from many desalination plants with variable energy costs making direct use of their data in this assessment impossible without first determining what the average energy rates were that went into their calculations and comparing these rates to the rates used in this assessment. Considering the average energy requirements of desalination over the range of salinity concentrations (1,000-10,000 ppm TDS) and estimates that energy costs contribute approximately 30% to total annual costs (Wittholz *et al*, 2008), the UPCs presented by Wittholz *et al* (2008) represent estimated energy costs of \$0.05/kWh-\$0.07/kWh. The difference in energy prices, those estimated from Wittholz *et al* (2008) versus \$0.0824/kWh, are minimal suggesting that the annual operating costs calculated from UPCs presented by Wittholz *et al* (2008) may represent a reasonable approximation of costs in Arizona (**Figure 13**) (NRC, 2008). At this level of increase, the annual operating costs at \$0.0824/kWh were an estimated \$1.44 million and \$4.75 million for 10,000 and 50,000 m³/d desalination plants, respectively. The UPC of desalination using grid electricity at \$0.0824/kWh for 10,000 and 50,000 m³/d desalination plants were estimated as \$0.38/m³ and \$0.25/m³ (\$479/acft and \$315/acft), respectively (Table 3).

For desalination using co-located wind power, the energy required is not purchased, but is produced on site negating the cost of electricity in determining the UPC for desalination.

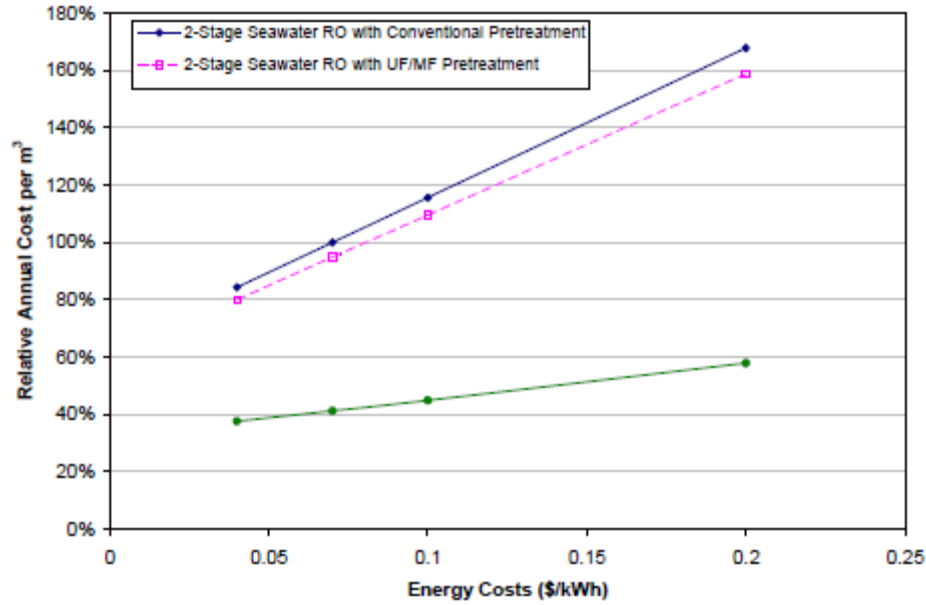


Figure 13: Cost relationship between the cost of energy on annual cost for 189,000 m³/d desalination plants of various type. The green bar represents brackish water RO desalination with conventional pretreatment (NRC, 2008).

However, there still remain operating and maintenance costs for desalination and as well as for wind turbines which are addressed in the following subsection. Considering the average UPCs for desalination plants worldwide producing 10,000 and 50,000 m³/d were an estimated \$0.38/m³ and \$0.25/m³ (\$479/acft and \$315/acft), respectively, and energy costs contribute approximately 46% to operating costs (Wittholz *et al*, 2008), the estimated UPC for desalination using co-located wind was \$0.19/m³ and \$0.13/m³ (\$238/acft and \$163/acft) for desalination plants producing 10,000 and 50,000 m³/d, respectively (Table 3).

UPC for pumping

The UPCs for lifting groundwater to the desalination plant are dependent on the depth to groundwater and cost of electricity. The 2006 average Arizona retail cost of electricity, \$0.0824/kWh (EIA, 2007) was used to estimate the cost of electricity. The UPC for pumping groundwater was estimated from Equation 5 multiplied by the 2006 average Arizona retail cost of electricity and simplified to the following equation:

$$UPC_{\text{pumping}} (\$/\text{m}^3) = TDH \times 0.000032 \quad (17)$$

This cost factor was not used in the model with co-located wind, because the wind power generates the electricity needed. However, even with co-located wind supplying the electrical demand for pumping, there are costs associated with maintenance which are not considered here.

UPC for wind turbines

The UPC for the wind turbines producing the energy for pumping and desalination were estimated from the capacity-weighted average operation and maintenance (O&M) costs of wind

Table 3: Unit production costs (UPCs) for desalination using co-located wind-powered electrical generation and grid electricity at the 2006 average Arizona retail cost for two desalination plant capacities.

Desalination plant capacity (m ³ /d (MGD))	UPC for desalination using co-located wind power (\$/m ³ (\$/acft))	UPC for desalination using grid electricity (\$/m ³ (\$/acft))
10000 (2.6)	0.19 (238)	0.38 (479)
50000 (13.2)	0.13 (163)	0.25 (315)

projects installed in the 2000s, \$0.009/kWh (Wiser and Bolinger, 2008) and the capital costs annualized over 20 years according to the general equation:

$$UPC_{windturbine} (\$/m^3) = O \& M \text{ costs} + \text{Annualized capital costs} \quad (18)$$

The UPCs are dependent on the total wind turbine output capacity required for the various salinity ranges and different desalination plant capacities. The energy cost presented by Wiser and Bolinger (2008), \$0.009/kWh, was multiplied by the energy requirements for various salinity concentrations presented in the Wind Turbine Capital Costs sub-section of this assessment. The annualized capital costs (\$/yr over 20 years) were calculated from the capital costs determined in this assessment. The capital costs were adjusted to reflect the daily cost of capital investment and divided by the various desalination plant capacities (m³/d) considered in this assessment. The UPCs for wind turbines (\$/m³) were estimated by the following equations:

10,000 m³/d:

1,000-3,000 ppm TDS:

$$\left(0.0009 (\$/kWh) \times 1.1 (kWh/m^3)\right) + \frac{(\text{Capital cost}_{wind turbine} (\$))}{(20 (yr) \times 365 (d/yr) \times 10,000 (m^3/d))} \quad (19)$$

3,000-5,000 ppm TDS:

$$(0.0009 \times 1.4) + (\text{Capital cost}_{wind turbine} \div 20 \div 365 \div 10000) \quad (20)$$

5,000-10,000 ppm TDS:

$$(0.0009 \times 2.2) + (\text{Capital cost}_{wind turbine} \div 20 \div 365 \div 10000) \quad (21)$$

50,000 m³/d:

1,000-3,000 ppm TDS:

$$(0.0009 \times 1.1) + (\text{Capital cost}_{wind turbine} \div 20 \div 365 \div 50000) \quad (22)$$

3,000-5,000 ppm TDS:

$$(0.0009 \times 1.4) + (\text{Capital cost}_{\text{wind turbine}} \div 20 \div 365 \div 50000) \quad (23)$$

5,000-10,000 ppm TDS:

$$(0.0009 \times 2.2) + (\text{Capital cost}_{\text{wind turbine}} \div 20 \div 365 \div 50000) \quad (24)$$

UPC with co-located wind

Given the UPC for desalination (\$/m³) and the UPCs for wind turbines (\$/m³) (Eqs. 19-24), Equation 14 becomes:

10,000 m³/d:

1,000-3,000 ppm TDS:

$$0.21 + [(0.0009 \times 1.1) + (\text{Capital cost}_{\text{wind turbine}} \div 73000000)] \quad (25)$$

3,000-5,000 ppm TDS:

$$0.21 + [(0.0009 \times 1.4) + (\text{Capital cost}_{\text{wind turbine}} \div 73000000)] \quad (26)$$

5,000-10,000 ppm TDS:

$$0.21 + [(0.0009 \times 2.2) + (\text{Capital cost}_{\text{wind turbine}} \div 73000000)] \quad (27)$$

50,000 m³/d:

1,000-3,000 ppm TDS:

$$0.14 + [(0.0009 \times 1.1) + (\text{Capital cost}_{\text{wind turbine}} \div 365000000)] \quad (28)$$

3,000-5,000 ppm TDS:

$$0.14 + [(0.0009 \times 1.4) + (\text{Capital cost}_{\text{wind turbine}} \div 365000000)] \quad (29)$$

5,000-10,000 ppm TDS:

$$0.14 + [(0.0009 \times 2.2) + (\text{Capital cost}_{\text{wind turbine}} \div 365000000)] \quad (30)$$

UPC with grid electricity

Given the UPCs for desalination (\$/m³) and the UPC for pumping (\$/m³) (Eq. 17), Equation 15 becomes:

10,000 m³/d:

$$0.39 + (\text{TDH} \times 0.000032) \quad (31)$$

50,000 m³/d:

$$0.26 + (\text{TDH} \times 0.000032) \quad (32)$$

Modeling Results

This section presents the modeling results of the assessment of brackish groundwater and wind-powered desalination in Arizona and includes the cost estimates associated with desalination using both wind power and grid electricity. Several maps were produced for this assessment showing the predicted location, depth, and salinity of brackish groundwater resources (**Figure 14** and **Figure 15**), and the predicted saturated aquifer thickness where brackish groundwater was predicted to exist (**Figure 16** and **Figure 17**).

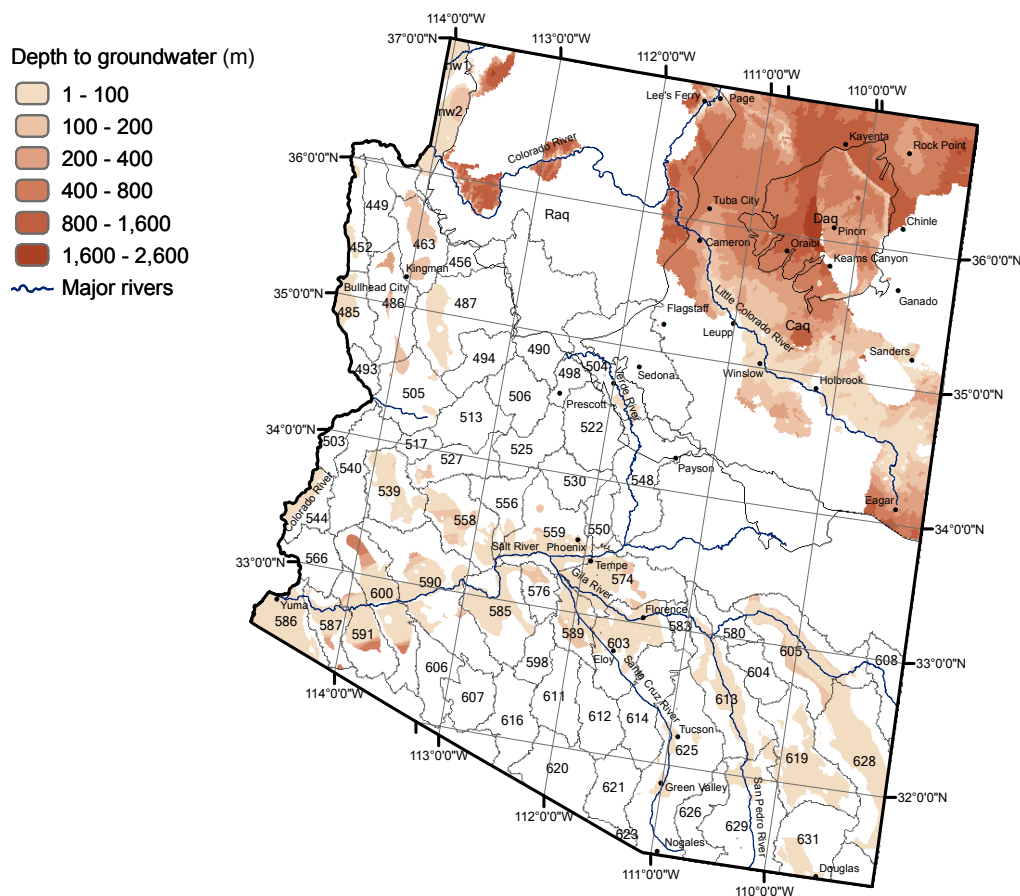


Figure 14: Predicted depth to select aquifers in Arizona containing known resources of brackish groundwater.

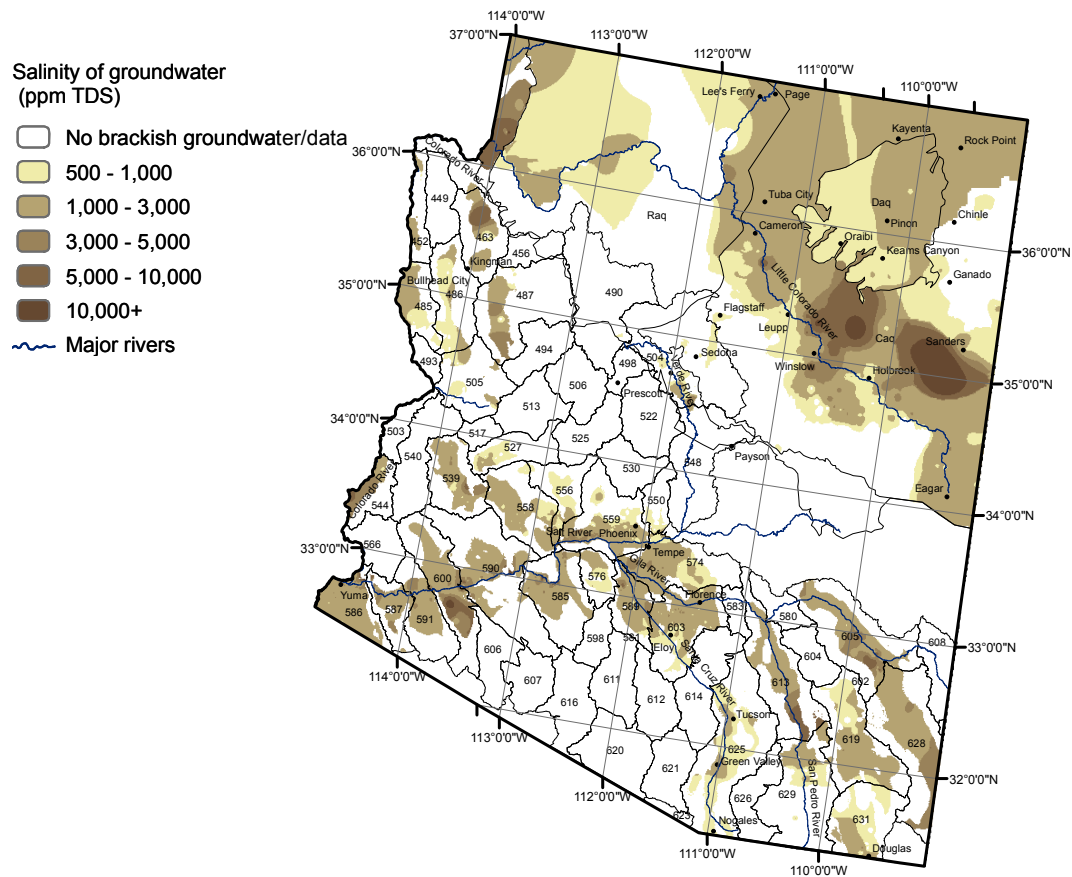


Figure 15: Predicted salinity of groundwater for select aquifers in Arizona containing known resources of brackish groundwater.

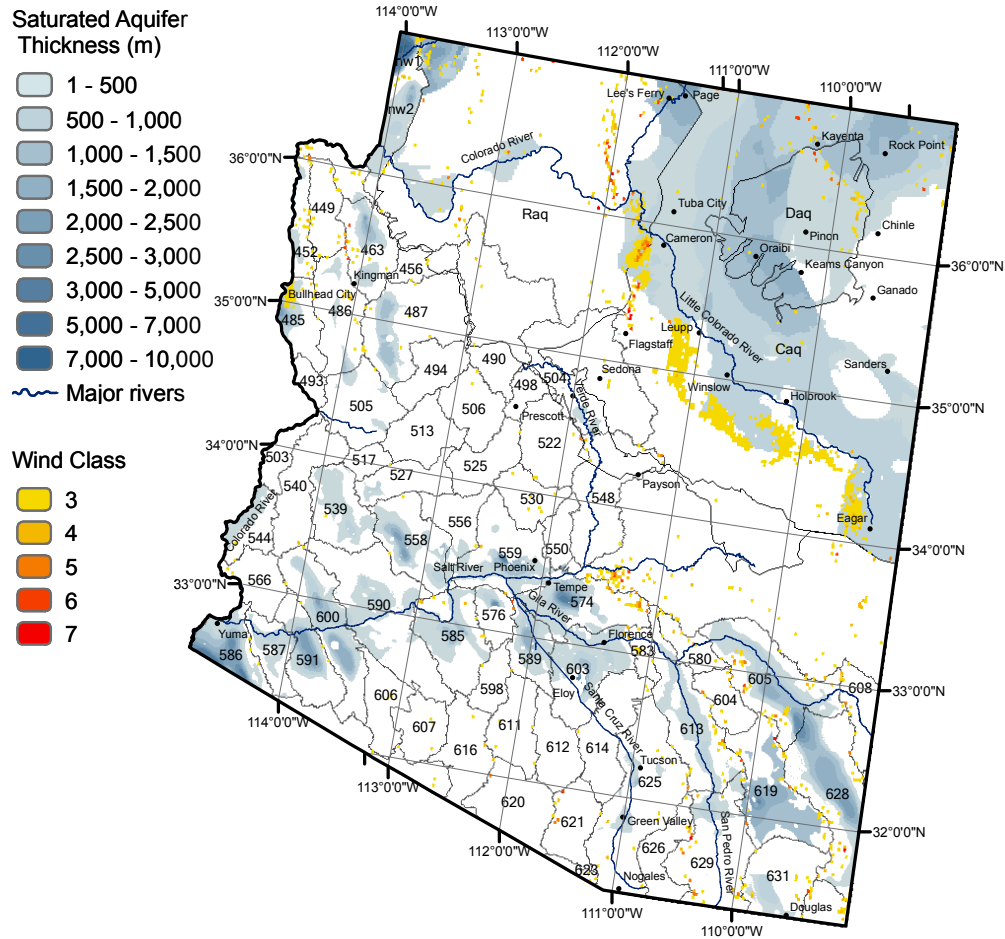
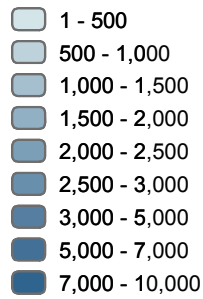


Figure 16: Predicted saturated aquifer thickness for select aquifers in Arizona containing known resources of brackish groundwater where such resources were predicted to exist. Wind resources were overlain to show the spatial relationship to groundwater.

**Saturated Aquifer
Thickness (m)**



Major rivers

Wind Class

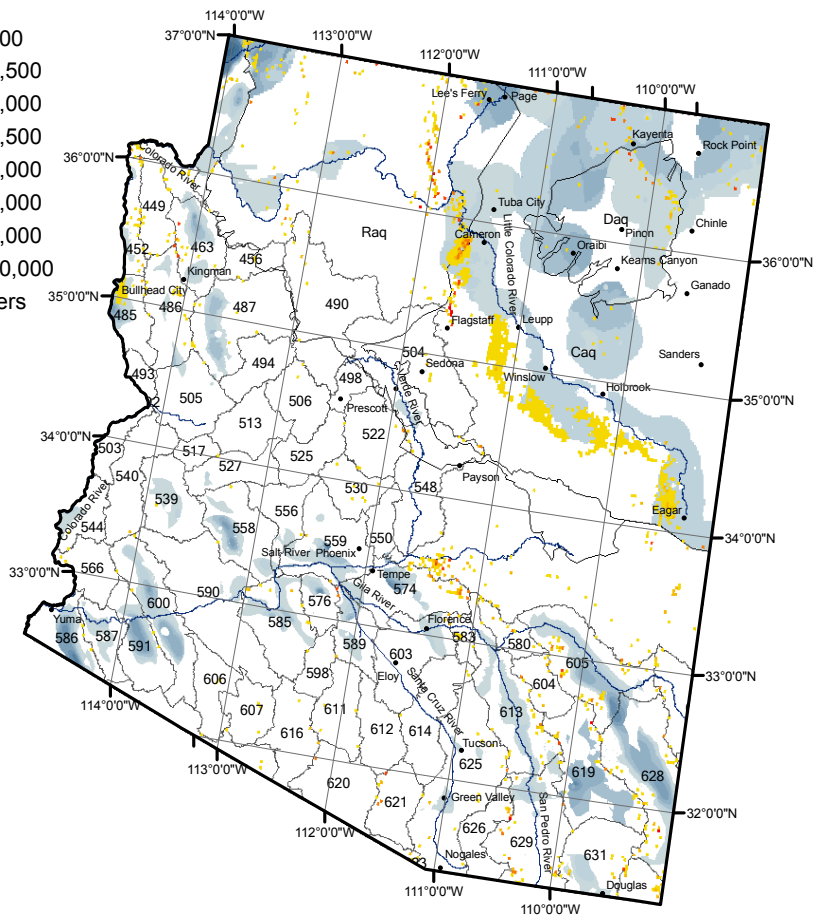


Figure 17: Predicted saturated aquifer thickness for select aquifers in Arizona containing known resources of brackish groundwater where such resources were predicted to exist within 20 km of average annual wind class 3 or greater.

The interpolated saturated thicknesses were used to estimate the total volumes of brackish groundwater available and the volume of brackish groundwater co-located with wind resources. Several maps were also produced to show the estimated costs of desalination as total capital costs and unit production costs (\$/m³) for wind-powered desalination (**Figure 18** and **Figure 19**) and desalination using grid electricity (**Figure 20** and **Figure 21**).

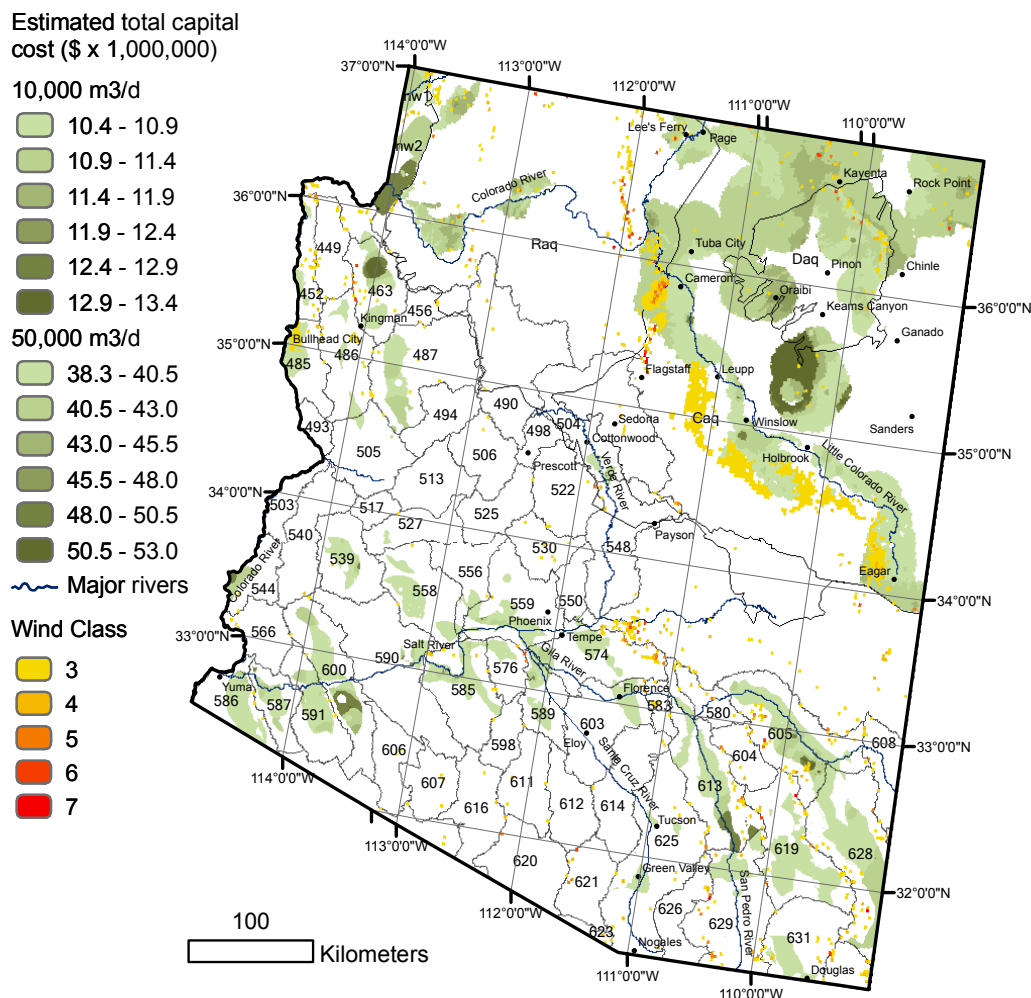


Figure 18: Estimated capital costs for wind-powered desalination at two desalination plant capacities where brackish groundwater resources were predicted to exist within 20 km of average annual wind class 3 or greater in Arizona.

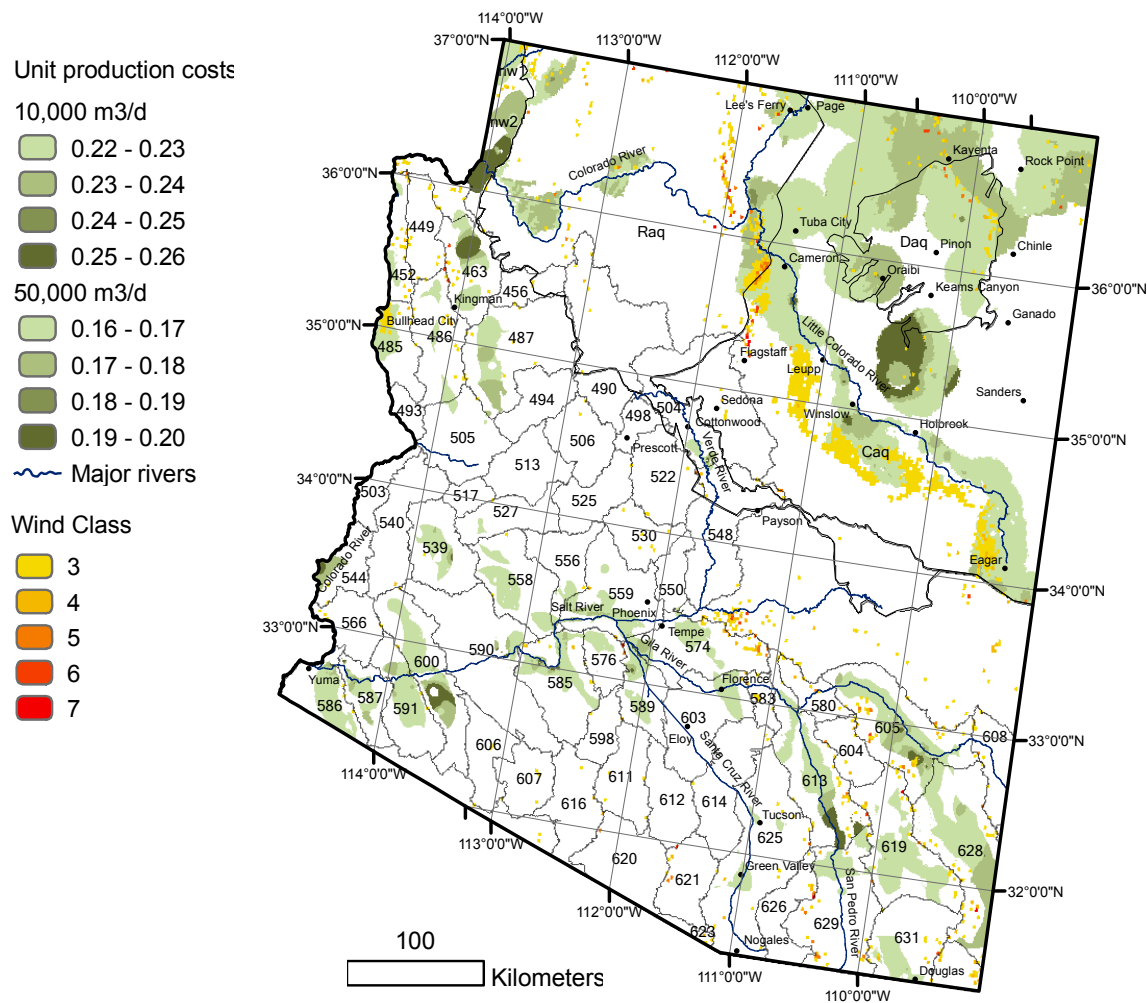


Figure 19: Estimated unit production costs for wind-powered desalination at two desalination plant capacities where brackish groundwater resources were predicted to exist within 20 km of average annual wind class 3 or greater in Arizona.

Estimated total capital
cost (\$ x 1,000,000)

10,000 m3/d

- 8.2 - 8.3
- 8.3 - 8.4
- 8.4 - 8.5
- 8.5 - 8.6

50,000 m3/d

- 27 - 27.5
- 27.5 - 28
- 28 - 28.5
- 28.5 - 29

Major rivers

Transmission lines

KV

- 115
- 138
- 161
- 230
- 345
- 500



Figure 20: Estimated capital costs for desalination at two desalination plant capacities using grid electricity where brackish groundwater resources were predicted to exist in Arizona.

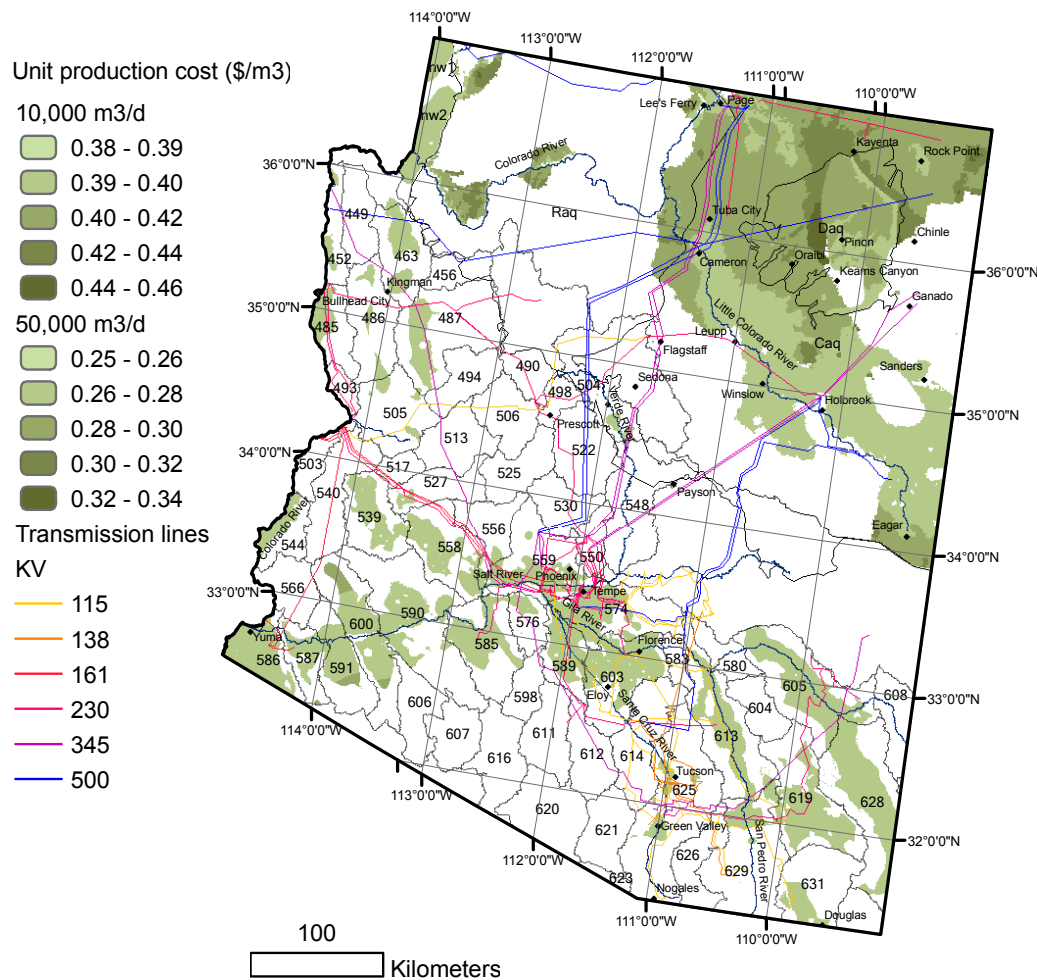


Figure 21: Estimated unit production costs for desalination at two desalination plant capacities using grid electricity where brackish groundwater resources were predicted to exist in Arizona.

Surface Interpolations and Volume Calculations

Depth to water and salinity interpolations

Sixty-three basins were identified in the Basin and Range Province of Arizona. The USGS and ADWR databases provided water quality data and depth to groundwater for thirty-three of the Basin and Range basin-fill aquifers and the three aquifers of the Colorado Plateau (Figure 22).

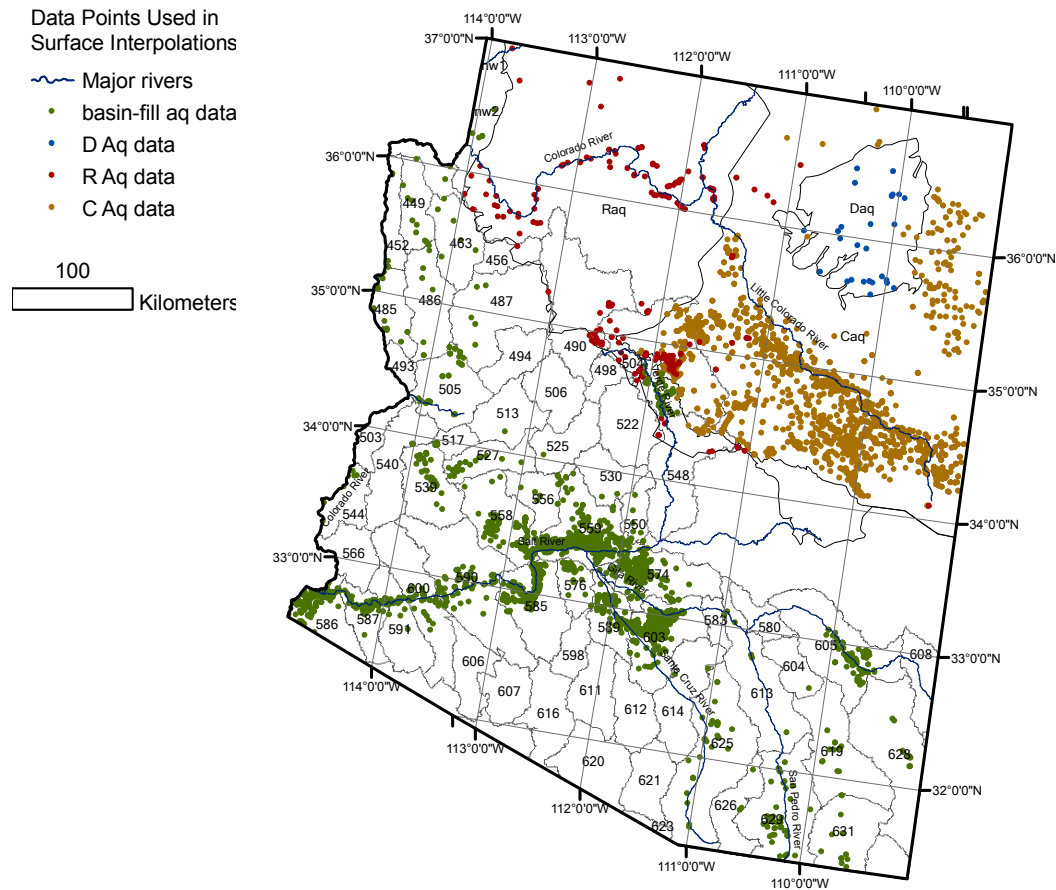


Figure 22: Data points used for surface interpolations.

These data were interpolated in ArcGIS to show the location of brackish groundwater by its degree of salinity and depth to groundwater, and the resulting interpolations were used in cost estimate calculations and as masks for data extraction from other data sets. Brackish groundwater was found to exist largely in the Gila, San Pedro, Santa Cruz, and Salt River drainage basins of Southern and Central Arizona. On the Colorado Plateau, brackish groundwater was found to exist in the deepest portion of the D Aquifer and in the C Aquifer along the Little Colorado River Basin. In the R Aquifer, brackish groundwater was found to exist in Northeastern Arizona where the R Aquifer is present north of the Defiance Uplift, as well as sporadically in its northwestern most extent. The maximum predicted salinity of the basin-fill aquifers was found to be 27,000 ppm TDS (Table 5). The highest salinities were predicted below the Muddy Creek Formation in northwestern Arizona, and sporadically along the Salt, Verde, Gila, and San Pedro Rivers. The D, C, and R Aquifers have a maximum predicted salinity of 2,600, 38,000, and 4,700 ppm TDS, respectively. The highest values were predicted for the C Aquifer in the Holbrook Basin northeast of Winslow and Holbrook (Table 5).

The maximum predicted depth to brackish groundwater was 500 m bls in the Basin and Range basin-fill aquifers, and 2,800 m bls in the R Aquifer below Black Mesa on the Colorado Plateau (Table 5). In basins of the Basin and Range Province containing ephemeral rivers, the depth to brackish groundwater generally increases with distance from the river. On the Colorado Plateau, brackish groundwater of the D Aquifers is deepest below the northeastern portion of the

Black Mesa shallowing to the southwest. In the C Aquifer, the deepest regions are predicted south of Eagar and below and west of Black Mesa. The shallowest region is in the Little Colorado River Valley. In the R Aquifer, the deepest regions are predicted below Black Mesa and are shallowest in the Little Colorado River Valley.

Table 5. Estimated values for depth, saturated aquifer thickness, salinity, and volume for the aquifers of Arizona.

Aquifer	Minimum Depth to Water (m)	Maximum Depth to Water (m)	Maximum Saturated Thickness where Brackish (m)	Average Saturated Thickness where Brackish (m)	Maximum TDS (ppm)	Brackish groundwater volume (m ³)	Brackish groundwater volume with co- located wind (m ³)
hganw1	1	280	7,300	3,600	2,200	1.7×10^{11}	1.7×10^{11}
hganw2	17	18	2,300	970	13,000	4.5×10^{10}	4.0×10^{10}
hga631	22	68	930	460	4,300	2.9×10^{10}	2.8×10^{10}
hga629	2	180	960	470	2,600	2.2×10^{10}	2.2×10^{10}
hga628	100	100	2,800	1,400	5,300	3.1×10^{11}	2.7×10^{11}
hga625	2	140	1,400	540	2,200	1.7×10^{10}	1.2×10^{10}
hga619	10	48	3,600	1,700	3,600	9.2×10^{10}	8.4×10^{10}
hga613	10	99	960	470	7,000	3.2×10^{10}	3.2×10^{10}
hga605	4	22	2,800	1,200	10,400	1.6×10^{11}	1.6×10^{11}
hga603	10	150	2,900	1,000	5,528	7.0×10^{10}	1.1×10^{10}
hga600	1	500	2,400	1,100	13,500	1.4×10^{11}	1.2×10^{11}
hga591	10	500	2,400	1,200	4,500	1.1×10^{11}	9.2×10^{10}
hga590	9	500	950	440	27,000	3.7×10^{10}	2.8×10^9
hga589	10	140	1,900	960	10,500	5.8×10^{10}	2.3×10^{10}
hga587	9	480	1,500	600	6,600	1.6×10^{10}	9.2×10^9
hga586	1	99	3,400	1,700	18,600	2.4×10^{10}	1.2×10^{11}
hga585	7	98	1,400	700	12,000	4.9×10^{10}	3.0×10^{10}
hga576	82	170	2,800	1,200	3,000	1.3×10^{10}	1.3×10^{10}
hga574	10	240	3,400	1,600	4,300	1.2×10^{11}	5.6×10^{10}
hga559	3	190	3,400	1,100	7,300	7.0×10^{10}	4.4×10^{10}

Table 5 continued.

Aquifer	Minimum Depth to Water (m)	Maximum Depth to Water (m)	Maximum Saturated Thickness where Brackish (m)	Average Saturated Thickness where Brackish (m)	Maximum TDS (ppm)	Brackish groundwater volume (m ³)	Brackish groundwater volume with co- located wind (m ³)
hga558	6	140	2,400	1,100	4,100	7.7×10^{10}	6.2×10^{10}
hga556	7	140	920	380	4,600	5.2×10^9	3.0×10^9
hga550	39	260	1,400	760	1,400	1.2×10^9	8.1×10^8
hga544	3	99	960	480	6,400	9.5×10^{10}	1.5×10^{10}
hga539	19	130	870	400	9,600	2.2×10^{10}	1.0×10^{10}
hga527	10	170	870	380	3,4002	4.1×10^9	1.7×10^9
hga505	2	200	1,300	390	2,100	2.7×10^9	1.2×10^9
hga504	12	160	440	130	15,000	5.1×10^9	5.0×10^9
hga487	15	110	1,400	700	4,400	6.3×10^{10}	6.3×10^{10}
hga486	19	330	1,400	670	3,100	9.6×10^9	9.6×10^9
hga485	1	153	2,400	1,200	2,500	7.8×10^{10}	7.2×10^{10}
hga463	110	200	2,300	970	9,600	4.9×10^{10}	4.9×10^{10}
hga452	10	100	110	56	1,400	7.8×10^8	7.8×10^8
Dakota	1,500	1,900	330	200	2,700	1.1×10^{11}	8.3×10^{10}
Coconino	600	2,300	1,600	830	38,000	2.2×10^{12}	1.5×10^{12}
Redwall-Muav	1	2,800	2,400	1,000	4,700	3.6×10^{12}	2.8×10^{12}
Volume Totals:						8.1×10^{12}	6.0×10^{12}

Saturated Thicknesses and Volume Calculations

The saturated aquifer thicknesses (

Figure 23) were created as the difference between the upper and lower aquifer surfaces interpolated from well and spring data indicating the depth to groundwater (upper surfaces) and geologic cross-sections and geophysical data indicating the depth to lower confining units (lower surfaces).

Saturated Aquifer
Thickness (m)

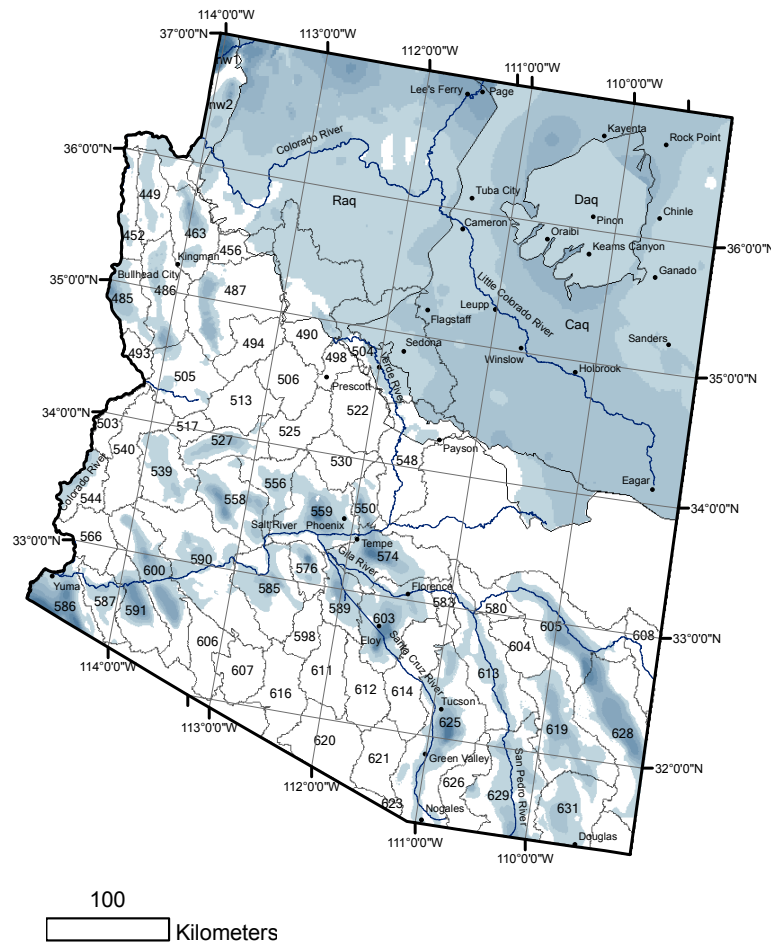
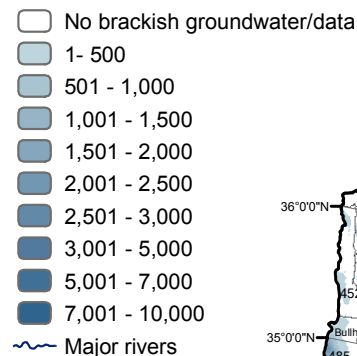


Figure 23: Predicted saturated aquifer thickness for select aquifers in Arizona containing known resources of brackish groundwater.

These maps were only meant to show the location of the saturated portion of the water-bearing geologic units in an aquifer's basin and to provide an estimated thickness of these units where saturated. They do not indicate the location of brackish groundwater. The saturated thicknesses of the aquifers where brackish groundwater was predicted to exist were determined by extracting the aquifer saturated thickness data using the interpolated salinity shape files.

These extracted data are presented here. The average predicted saturated thicknesses for the basin-fill aquifers range from 56 m to 3,625 m (Table 5). The D, C, and R Aquifers have average predicted saturated thicknesses of 200 m, 830 m, and 1,000 m, respectively. These thickness values apply only to the regions saturated with brackish groundwater and do not include regions of fresh groundwater. The thickest saturated regions of the basin-fill aquifers were found in the basin centers, thinning to the basin margins. On the Colorado Plateau, the D Aquifer's saturated region is thickest below the northeastern portion of Black Mesa and thins to the southwest. The C Aquifer's thickest saturated region is below Black Mesa and in northeastern Arizona near the Four Corners area. The R Aquifer's thickest saturated regions were predicted in the western portion of Black Mesa and in Northeastern Arizona near the Four Corners area.

By extracting the saturated thickness estimates where brackish groundwater was predicted, the total volume of brackish groundwater in Arizona was estimated to be $8.1 \times 10^{12} \text{ m}^3$ using a generalized aquifer porosity of 10% (Table 5). All of the thirty-three basin-fill aquifers were found to contain some brackish groundwater within 20 km of annual average wind resource class 3 or greater. The total volume of brackish groundwater found to exist near wind resources potentially sufficient to supply the electrical demand of desalination was estimated to be $6 \times 10^{12} \text{ m}^3$ (Table 5). Wind resources were found to exist primarily on the ridge tops surrounding the basins containing groundwater. The largest windy areas are along the southern rim of the Little Colorado River Valley from Eagar, Arizona to Cameron, Arizona. However, many of the ridge tops from Phoenix, Arizona to the southeastern-most corner of Arizona also contain potentially sufficient wind resources. Such resources also exist sporadically throughout the Basin and Range Province as well as along the northeastern ridge of the Black Mesa Plateau.

Economic Model

The economic model was created to show two categories of costs associated with desalination, total capital costs and unit production costs, for both wind powered- desalination and desalination using grid electricity. These models were created to estimate costs for two desalination plant capacities 10,000 m^3/d and 50,000 m^3/d .

Total Capital Costs

The total capital cost model for wind-powered desalination was based on well development costs and the capital costs of the desalination and wind turbine equipment. The total capital cost model for desalination using grid electricity was also based on well development costs and the cost of desalination equipment, but does not include the capital costs associated with wind turbine equipment. The estimates for the total capital costs are presented here with further explanation of the cost estimates used to obtain these values in the following paragraphs. The estimated capital cost for wind-powered desalination ranges from \$10,500,000 to \$13,400,000 and from \$38,300,000 to \$53,000,000 for 10,000 and 50,000 m^3/d desalination plant capacities, respectively (Figure 18). The estimated capital cost for desalination using grid electricity ranges from \$8,230,000 to \$8,950,000 and from \$27,200,000 to \$30,700,000 for 10,000 and 50,000 m^3/d desalination plant capacities, respectively (Figure 20).

To obtain these estimates for total capital costs, the costs associated with well development and desalination and wind turbine equipment also had to be estimated. The capital costs estimated for a 10,000 m^3/d and a 50,000 m^3/d desalination plant were \$8.1 million and

\$26.5 million, respectively, based on a database of desalination plants worldwide (Wittholz *et al*, 2008).

Wind turbine capital costs were determined by estimating the energy output required for desalination of brackish groundwater at various salinity concentrations and pumping depths assuming a 35% wind turbine operating capacity multiplied by the average cost of wind projects in the U.S. in 2007 (Wiser and Bolinger, 2008). The following salinity concentrations and their respective energy requirements were considered: 1,000-3,000 ppm TDS requires 1.10 kWh/m³, 3,000-5,000 ppm TDS requires 1.4 kWh/m³, and 5,000-10,000 ppm TDS requires 2.20 kWh/m³ (USBR, 2003). The estimate for the energy output required for pumping groundwater was based on the depth to brackish groundwater and an analysis of the energy requirements for groundwater pumping by California's agricultural industry (ITRC, 2003). The energy output required for groundwater pumping was estimated to range from 0.00039-0.97 kW/m³ with the most energy intensive regions located where groundwater is deeply buried in the C and R Aquifers (**Figure 24**). Wind turbine equipment capital costs were estimated to range from \$2,240,000 to \$4,970,000 and from \$11,200,000 to \$24,900,000 for 10,000 and 50,000 m³/d desalination plant capacities, respectively (**Figure 25**). The highest values for each desalination plant capacity were predicted where groundwater was predicted to be highly saline.

Estimated Energy Requirements for
Groundwater Pumping (kWh/m³)

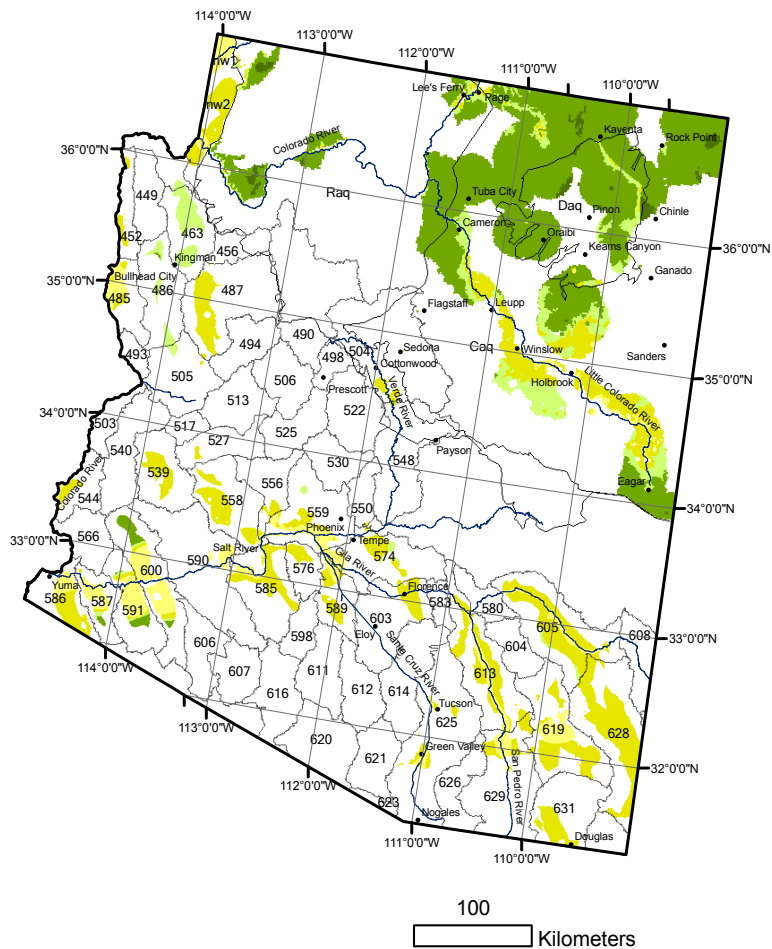
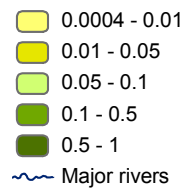


Figure 24: Estimated energy output requirements for pumping groundwater where brackish groundwater was predicted to exist within 20 km of annual average wind class 3 or greater in Arizona.

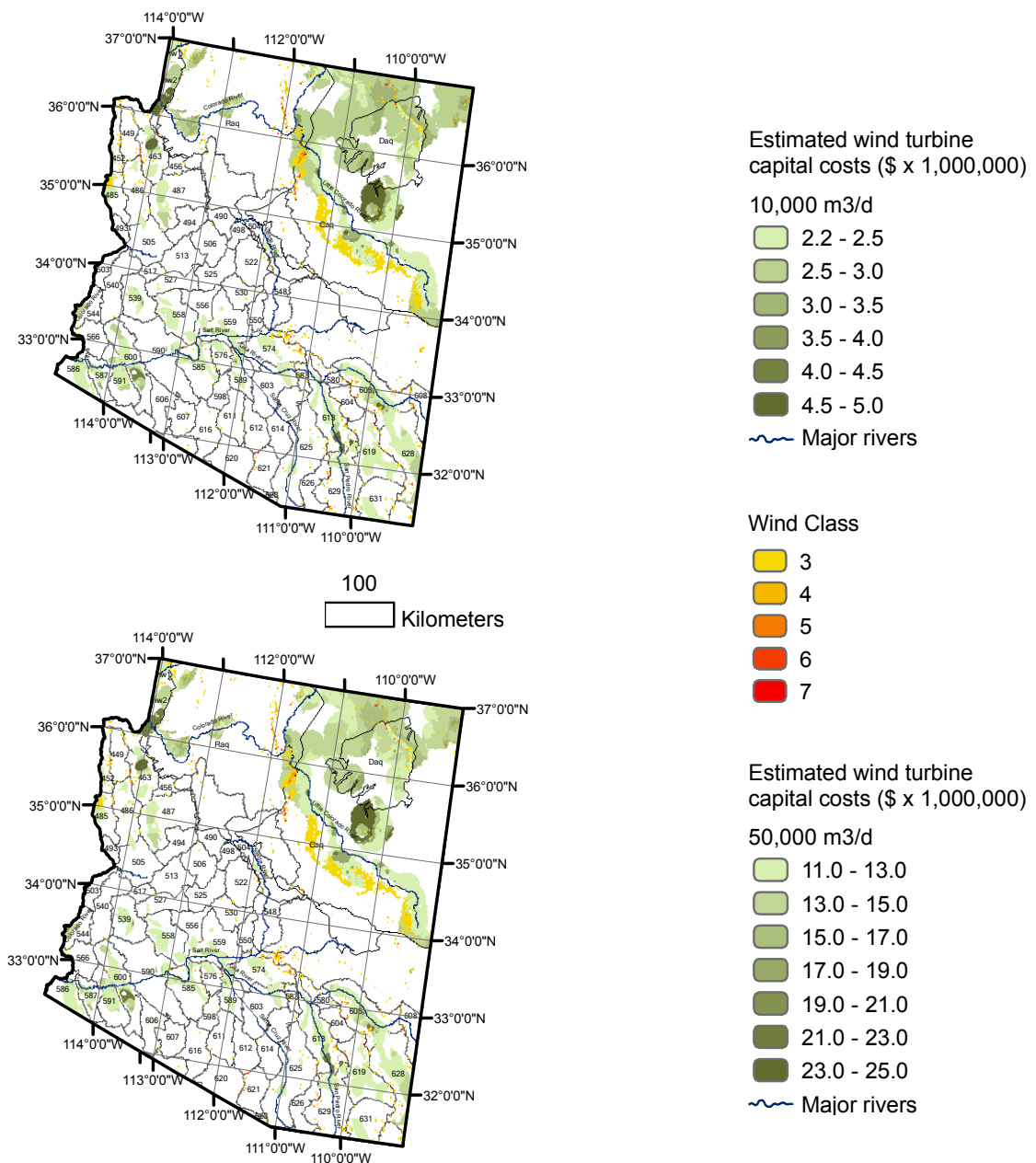


Figure 25: Estimated wind turbine capital costs for wind-powered desalination at A) 10,000 m³/d and B) 50,000 m³/d where brackish groundwater was estimated to exist within 20 km of annual average wind class 3 or greater in Arizona.

The costs associated with well development were estimated based on a cost estimate equation produce for the Texas Water Development Board that considers production rate and well depth (LGB Guyton Associates, 2003). Well development costs were estimated to range from \$132,000 to \$850,000 and from \$660,000 to \$4,200,000 for 10,000 and 50,000 m³/d desalination plant capacities, respectively (**Figure 26**).

Estimated Capital Costs
of Well Field Development
(\$ x 1,000,000)

10,000 m³/d

- 0.13 - 0.2
- 0.2 - 0.25
- 0.25 - 0.3
- 0.3 - 0.35
- 0.35 - 0.4

50,000 m³/d

- 0.67 - 1.0
- 1.0 - 1.5
- 1.5 - 2.0
- 2.0 - 3.0
- 3.0 - 4.2

Major rivers



Figure 26: Estimated well development capital costs for desalination at 10,000 m³/d and 50,000 m³/d where brackish groundwater was predicted to exist within 20 km of annual average wind class 3 or greater in Arizona.

Unit Production Costs

UPCs were estimated for both wind-powered desalination and desalination using grid electricity. The UPC for wind-powered desalination considered the UPCs for desalination and wind turbine equipment. The UPC for desalination using grid electricity considered the UPC for desalination equipment and the energy costs associated with groundwater pumping. The UPC for desalination equipment was estimated based a worldwide desalination database which accounted for the costs associated with the plant, land, civil works, energy, maintenance, labor,

chemicals in pre- and post-treatment, plant capacity, annual plant availability, and annualized capital (Wittholz *et al*, 2008). The costs were adjusted from the Wittholz *et al* (2008) estimate to account for the energy cost produced by wind power and the average retail cost of electricity in Arizona in 2006 (EIA, 2007). The UPC for wind turbine equipment was estimated based on the capacity-weighted average O & M costs of wind projects in the U.S. in the 2000s (Wiser and Bolinger, 2008) and the capital costs annualized over 20 years as calculated in this assessment. The energy costs associated with groundwater pumping were estimated based on the ITRC's assessment of groundwater pumping costs in California (ITRC, 2003), the average retail cost of electricity in Arizona in 2006 (EIA, 2007), and depth to groundwater as determined in this assessment.

Accordingly, the UPCs for wind-powered desalination were estimated to range from \$0.22/m³ to \$0.26/m³ and from \$0.16/m³ to \$0.20/m³ for 10,000 and 50,000 m³/d desalination plant capacities, respectively (Figure 19). The UPCs for desalination using grid electricity were estimated to range from \$0.38/m³ to \$0.46/m³ and from \$0.25/m³ to \$0.33/m³ for 10,000 and 50,000 m³/d desalination plant capacities, respectively (Figure 21).

Assessment of GIS model

The modeling technique used in this assessment of wind-powered desalination opportunities involved interpolating the degree of salinity and the depth to groundwater and lower confining units from measured data at known locations and from interpreted data at estimated locations. The accuracy of the outputs can only be as good as the inputs. Given the large scale of many of the aquifers, particularly those of the Colorado Plateau, a large amount of data would be necessary to provide a reasonable interpretation of the aquifers. Unfortunately, the data acquired from recorded sources was limited. Over 70% of the data reported in the ADWR GWSI database does not list the geologic unit related to a well or spring location seriously limiting the number of usable data points. Without the geologic unit information, the site data provided in the database could not be attributed to a particular aquifer and was, therefore, disregarded in most cases. Also, many of the analyses in this assessment were dependent on the predicted location of brackish groundwater which was determined by an interpolation of well and spring data containing salinity concentration values. Only 37% of the usable data contained this information. Error in this interpolation could result in a prediction of brackish groundwater where none exists or the exclusion of such resources in favor of fresh groundwater.

The GIS model presented in this work is adaptable to new data. As new data for either the aquifers or the economics of wind power or desalination become available, the model can be updated. This could be applied to an individual aquifer, a region, or the state as a whole. The model could also be adapted to information for other states. However, there are no immediate plans to do this.

Volume calculations

To determine how well the model represents the aquifers, the groundwater volumes estimated by the model were compared to estimates provided from other sources. Previous investigations have estimated 600,000,000 acft (7×10^{11} m³) of brackish groundwater in Arizona aquifers (McGavock and Cullom, 2008). This is an order of magnitude lower than the estimate presented in this assessment. The McGavock and Cullom (2008) estimate was based on a

Table 6. Comparison of estimated volumes of groundwater for select Basin and Range basin-fill aquifers of Arizona. Groundwater volumes were compared for the upper 1,200 ft (366 m) of the aquifers as modeled in this assessment (numbered hydrogeographic areas) and as presented in the Arizona Water Atlas (basin names) (ADWR, 2006a; ADWR, 2006b).

Basin	Estimated Volume (AZ Water Atlas)	Estimated Volume (this study) (m ³)
Douglas Basin (hga631)	32 million acft (40 billion m ³)	43 billion
Upper San Pedro Basin (hga629)	19.8-59 million acft (24-73 billion m ³)	64 billion
Willcox Basin (hga619)	42-59 million acft (52-73 billion m ³)	65 billion
Lower San Pedro (hga613)	12-27 million acft (15-33 billion m ³)	26 billion
Big sandy basin (hga487)	9.5-21 million acft (12-26 billion m ³)	26 billion
Sacramento Valley Basin (hga486)	7-8.3 million acft (9-10 billion m ³)	15 billion
Lake Havasu Basin (hga485)	1-2 million acft (1-4.5 billion m ³)	32 billion
Hualapai Valley Basin (hga463)	3-5.3 million acft (4-6.5 billion m ³)	17 billion

generalized accounting of a limited number of Basin and Range basin-fill aquifers and the Coconino Aquifer only, and therefore a lower estimate would be expected.

Multiple volumes of the Arizona Water Atlas provide estimates of groundwater in storage for most of the aquifers in Arizona. The volume estimates provided in the Arizona Water Atlas for the basin-fill aquifers of the Basin and Range Province are given predominantly for the upper 1,200 ft (366 m) of the basins and in some cases the upper 1,600 ft (488 m). The average maximum depth of these aquifers as modeled in this assessment is 2,097 m bls with the deepest basin descending to a depth of 7,312 m bls. The estimated volumes of groundwater for the upper 366 m of a few select basin-fill aquifers as modeled in this assessment are of similar magnitude as those presented in the Arizona Water Atlas (ADWR, 2006a; ADWR, 2006b) (Table 6). The Arizona Water Atlas (ADWR, 2006a) also provided rough estimates of groundwater in storage for the D and C Aquifers, but provided no explanation of how these estimates were made. The ADWR (2006a) estimated 15 million acft (18.5 billion m³) and 413 million acft (509 billion m³) of groundwater in storage in the D and C Aquifers, respectively. These aquifers contain an estimated 200 billion m³ and 5,300 billion m³ of groundwater in storage as modeled in this assessment.

The method used in this assessment interpolated data between known points, but also extrapolated that data over the aquifer's geographic extent where data was absent. The extrapolation of groundwater data for the Colorado Plateau aquifers was extensive due to the lack of data in large regions of the aquifers. For the purposes of this assessment, where the aquifers exhibited a predicted saturated thickness, it was assumed that the predicted aquifer thickness was saturated. Error in this assumption could occur where the interpolated surfaces for either the depth to groundwater or the lower confining units were not accurate resulting in the prediction of a saturated aquifer thickness where none exist.

Salinity concentration assessment

The interpolation of salinity data produced variable results depending on the amount and distribution of data available for the interpolation. On the Colorado Plateau, data was obtained for the southern and eastern portions of the D Aquifer, resulting in an interpolation showing

brackish groundwater, 1,000 to 2,700 ppm TDS in the deepest portion of the D Aquifer. However, little data was available for the northern and western portions and the extrapolation of data in these regions is questionable.

The C Aquifer has a significant amount of well distributed groundwater data along the Little Colorado River Basin and east of Black Mesa in the Chinle Valley producing a reasonable interpretation of location and salinity of groundwater resources in these regions. Brackish groundwater was predicted to exist in the Little Colorado River Valley with high salinity concentrations from 3,000 to 38,000 ppm TDS in the Holbrook Basin north of Winslow and Holbrook and background levels from fresh to 3,000 ppm TDS throughout the valley. However, the model extrapolated the data predicting brackish groundwater to the northwestern-most portion of the C Aquifer's geographic extent between Cameron and Page where little groundwater data exists. The interpolation in this region is most likely not very accurate.

The R Aquifer is a large regional aquifer on the Colorado Plateau covering most of Northern Arizona. The data retrieved for this aquifer was grouped in smaller regions around the Colorado River and in the Verde Valley where salinity concentrations show mainly fresh groundwater. This grouping of data left large portions of the R Aquifer open to data extrapolation with few control points, but data bordering these open regions provided enough brackish groundwater data to cause the extrapolation to predict a large region of brackish groundwater across Northeastern Arizona. The predicted extent and salinity in this region is questionable and would require more data limit the interpolation.

In the Basin and Range basin-fill aquifers, the aquifers generally had sufficient data to make a reasonable interpretation of brackish groundwater resources. The interpolation was generally better where data point locations were spread fairly evenly around a basin rather than grouped. Anning *et al* (2007) noted salinity concentrations in the CAZB ranging from 400 ppm TDS at the basin margins to 2,740 ppm TDS in the western-most portion of the CAZB along the Gila River. These ranges correspond to values predicted in this assessment, and the location of the highest salinity concentrations were generally the same. However, the estimates presented here were generally higher than those presented by Anning *et al* (2007) and the higher values covered a larger area. The highest salinity concentration found in this assessment was 17,820 ppm TDS with a significant number of well sites producing values above 3,000 ppm TDS.

Economic Model

Several factors went into the economic model to estimate the costs of desalination using either wind-power or grid electricity. The cost estimates for either electricity source incorporated the capital costs of well field development and desalination equipment capable of producing potable water at 10,000 and 50,000 m³/d. The cost estimates for well field development were based on the maximum drilling depth, depth to an aquifer's lower confining units, to yield a maximum estimated cost. The wind-powered desalination cost estimates were also based on the costs of wind turbine equipment which were dependent on the energy requirements of the desalination equipment as a function of feed water salinity and groundwater pumping as a function of depth to water. These factors, depth to groundwater, depth to lower confining units, and salinity, were based on their assessment in this work, and therefore, their reliability affects the reliability of the costs estimates. These interpretations are the main focus of this sub-section. Certainly, other factors went into these estimates that were taken from various references as cost-unit relationships and operating capacities each of which were based on various factors and assumptions.

Depth to aquifer lower confining units

The estimated capital costs of well field development were based on a production rate-cost relationship developed for the Texas Water Development Board that incorporated costs associated with drilling, well development, well testing, pump equipment, controls, and column piping (LGB Guyton Associates, 2003). Variables in this production rate-cost relationship included desalination plant capacity and well depth. The well depth was taken as the depth to an aquifer's lower confining unit, the bottom aquifer surface as modeled in this assessment. These predicted depths should represent a maximum estimated cost for well development. The actual well depth for an aquifer may not have to extend to the lower confining unit, but may have its screened interval in a productive region above the lower confining unit.

For the Colorado Plateau D and C Aquifers, the data used for the bottom surface interpolations came mainly from generalized geologic cross-sections produced by the USGS showing depth to geologic units. Points were selected along the cross-sectional lines and digitized for interpolation. It was assumed that the geologic cross-sections were representative of the stratigraphy of the Colorado Plateau and the resulting interpolations should also be representative where the lines of cross-section were located. However, such data were only available where the USGS has conducted geologic analyses. The regions included the Chinle Valley, the Little Colorado River Valley, and south to the Mogollon Rim. The interpolation of the depth to the lower confining units outside of the areas may not be representative. Such areas include the Black Mesa Basin and the region west of Black Mesa to the Grand Canyon.

The R Aquifer's lower confining unit was interpolated from depth to Precambrian basement rock (Butler, 1991). This data set is extensive covering the Colorado Plateau of the Four Corner States with 1,232 depth measurements below the R Aquifer in Arizona. There were no areas of the R Aquifer that were not included in these data.

The Basin and Range basin-fill aquifers' lower confining units were modeled from depth to basement rock produced by the Arizona Geologic Survey (2007) mainly from gravity data supplemented in some areas by geomagnetic and seismic data. All of the basin-fill aquifers of Arizona are included in this data set resulting in a good interpolation of these aquifers.

Except for some areas of the C Aquifer as noted above, the bottom aquifer surface as modeled in this assessment should be representative of the lower confining units of the aquifers of Arizona and should result in a reasonable estimate of the well development costs for these aquifers.

Salinity and depth to groundwater

The wind turbine cost estimates were produced only for aquifers with brackish groundwater within 20 km of an annual average wind resource of class 3 or greater and were dependent on the energy requirements of the desalination equipment as a function of feed water salinity, groundwater pumping as a function of depth to water, and an estimate cost per energy output. The estimate cost per energy output was taken as the 2007 average cost for wind projects in the U.S. as calculated by the USDOE (Wiser and Bolinger, 2008). Salinity and depth to water were dependent on the assessment of these parameters in this work.

The TDS concentrations predictions were, in some regions, based on the extrapolation of data where little available data exist. These areas included the northern and western portions of the D Aquifer, northwestern-most portion of the C Aquifer's geographic extent between Cameron and Page, and a large region of the R Aquifer across Northeastern Arizona. The salinity of the Basin and Range basin-fill aquifers were only modeled where sufficient data could

be obtained. Published information on the Colorado Plateau Aquifers notes that the groundwater of these aquifers is predominantly fresh with areas of high salinity. The location of areas with high salinity is generally known and discussed in the literature. These areas are the same as the high salinity areas modeled in this assessment. It may be likely that the areas extrapolated to show high salinity concentrations are over estimating groundwater salinity and that these areas contain predominantly fresh groundwater requiring no desalination. However, there is no data to back this claim, and it may be assumed that the cost estimates based on the interpolations in these areas represent a high value.

The depth to groundwater data was obtained mainly from USGS and ADWR databases (USGS, 2009; ADWR, 2009) providing water levels in wells and springs elevations, but was also derived from various USGS publications containing water-level data not included in the USGS NWIS (Leake *et al*, 2005; Bills *et al*, 2007). These data were limited in extent to areas where groundwater wells are located leaving large areas of the aquifers with no data for interpolation. In these areas, depth to hydrogeologic units was noted from USGS publications containing geologic cross-sections (Billingsley and Wellmeyer, 2002; Billingsley *et al*, 2006b; Billingsley *et al*, 2008; Billingsley and Workman, 2000; Truini and Macy, 2005).

The upper aquifer surface interpolated from these data represents the depth to groundwater in most areas. However, The D and R Aquifers of the Colorado Plateau contain confined regions that were not modeled from depth to groundwater information, but were modeled from depth to upper confining unit information. These regions include all but the southern portion of the D Aquifer and all of the R Aquifer except where well and spring data exist near along the Colorado River and in the Verde Valley. The potentiometric pressure throughout the confined regions of these aquifers would result in a depth to water level above the levels modeled, and in turn, would result in decreased energy required for pumping, decreased wind turbine output, and a lower estimated wind turbine cost. The potentiometric pressure in the D Aquifer's basin center results in a water level approximately 600 ft (180 m) above the top of the aquifer (Truini and Macy, 2005). In the R Aquifer, the potentiometric pressure has been noted as a few hundred to 500 ft (60-150 m) above the top of the aquifer in its western portion south of the Grand Canyon and more than 2,000 ft (600+ m) above the aquifer's top north of Flagstaff (Bills *et al*, 2007). Little is known about its potentiometric pressure north of the Grand Canyon or in Northeastern Arizona. How does this affect the estimated cost of the wind turbine system? A 100 m increase in water level above the top of the aquifer equates to an approximate 2% to 3% decrease in wind turbine capital costs depending on the salinity of the feed water. A high salinity feed water will show a lesser cost savings with decreasing depth to water than would be seen with a low salinity feedwater.

Micrositing Results

As mentioned in the objectives section, after reviewing the areas of the state in which the GIS study indicated may have a potential need to develop saline water resources, the next step was to "microsite" specific conceptual designs for two actual sites. In doing this more specific feasibility study, one question to be addressed was to determine if wind and desalination facilities need to be co-located, or if one could economically develop them in separate places and connect them through the utility grid. Also of interest was to understand if there was any potential to run desalination equipment (e.g., reverse osmosis) directly from wind energy, or if grid-quality AC electricity is required. As presented below, the analysis took into account the

area's resources, the local community's need, and the desire to further broaden the project's findings by comparing a collocated with one non-collocated scenario.

Site Selections

Two sites were selected for micrositings analysis. The community of Dilkon and the city of Holbrook (both in Navajo County, AZ) were selected for collocated and non-collocated study, respectively. Both communities are about a 90 mile drive east of Flagstaff, and are shown on the map in **Figure 27**. Dilkon has a very non-centralized population of about 1,300, and Holbrook has a more centralized population of about 4,900.

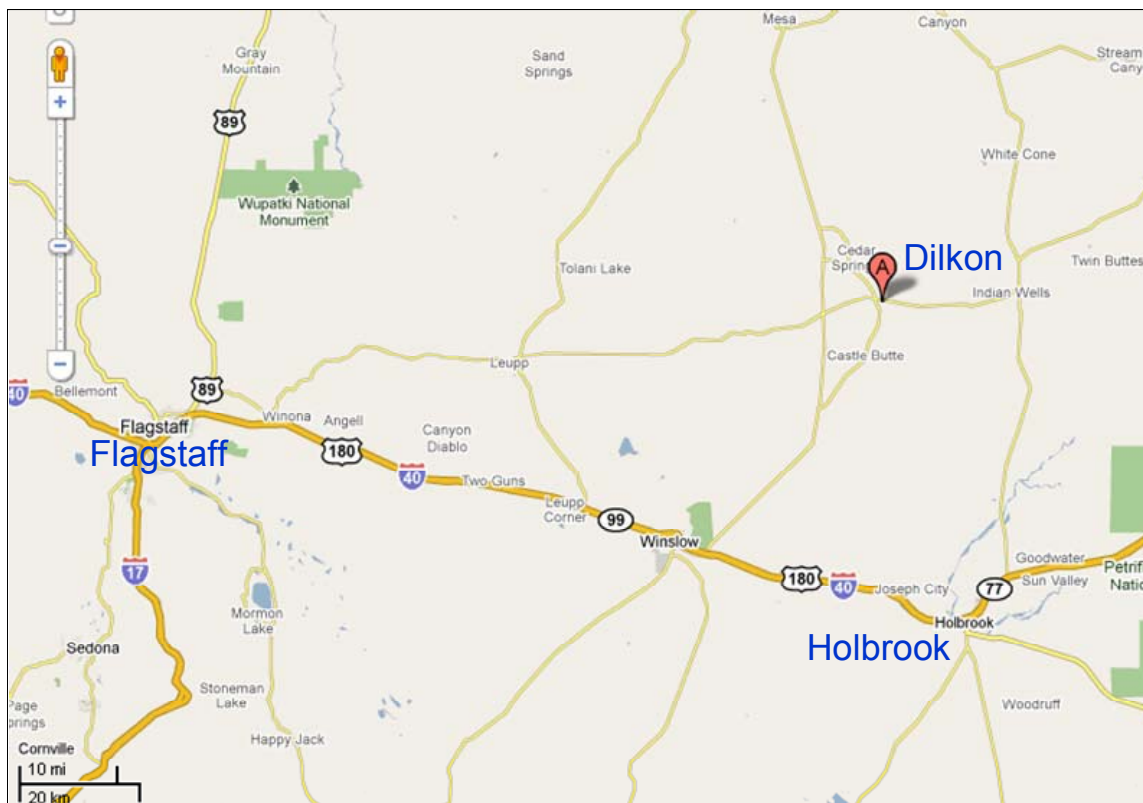


Figure 27: Map of site selections and surrounding area.

Dilkon

The community of Dilkon (also “Dilcon”) was chosen as the collocated site primarily due to its community interest and need, and probable future development. The Bureau of Reclamation actually is currently working in cooperation with the Navajo Nation to investigate development of brackish groundwater to serve rural water users in the surrounding Tolani Lake Chapter (Black, 2009).

Kevin Black, a consultant with the Bureau of Reclamation, approached Northern Arizona University and communicated an interest in collaboration to research groundwater desalination utilizing renewable energy. One very promising desalination application for the region centered on the water requirements of a prospective community hospital that would likely not otherwise be feasible, due to the relatively high local expense of both energy and water. Mr. Black was able to provide the requirements for such a hospital, which were then chosen as a logical target for a micrositings analysis. Additionally, Mr. Black emphasized the importance of such a project

as a *community* water and power source, underscoring the hospital's requirements as project *minimums*. He also estimated the drill depth in the area would require about 1,100 ft and TDS levels of about 7,500 ppm TDS.

Dilkon potentially could make use of Class 3 to Class 4 wind resources (**Figure 28**) within just a few miles (NAU, 2009). Although not off-grid, the community is not near any large transmission lines and its wind generation would most likely be “behind the meter.” It also experiences a marked seasonal lull in wind activity during the late summer when water could be of greatest value. For these reasons, tank storage options were also explored.

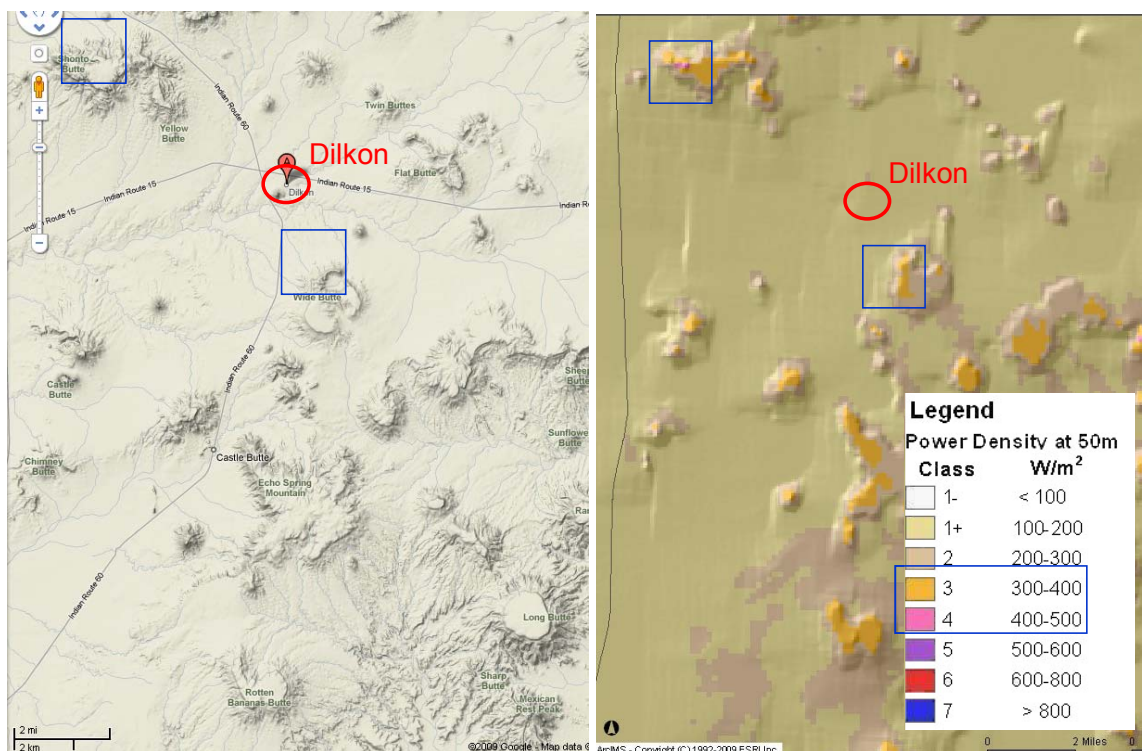


Figure 28: Maps showing ridge formations and wind resources near Dilkon.

Holbrook

The city of Holbrook was chosen as the non-located site. It, too, was selected in part due to probable future development. In fact, a main informational resource for this report was an area construction manager who had been drilling wells specifically for conventionally powered desalination. Other heavily weighted criteria were the close proximity of both roads and transmission lines to some of its closest wind resource.

In his earlier report on wind-powered desalination opportunities in Arizona, Janecek *et al* (2005) also points out Holbrook as a likely area of opportunity. Holbrook is adjacent to a large area of Class 3 wind resource (**Figure 29**). As would most non-located sites, wind generation would likely require the building of transmission lines to tie into the grid, which is potentially more manageable in Holbrook than other areas due to the transmission lines running alongside the wind resource

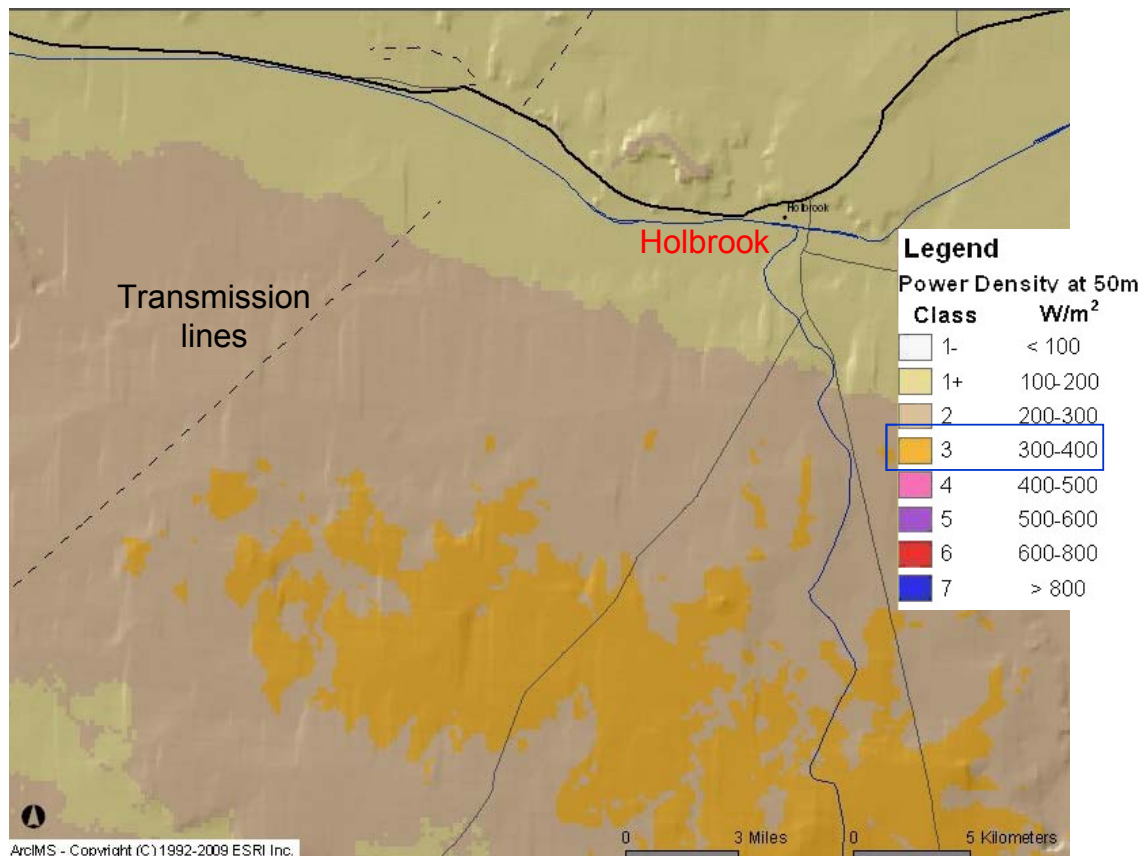


Figure 29: Map showing wind resources south of Holbrook area.

The wind resource of this region has also been studied previously. In a 2007 APS/NAU study, power production data was modeled for the wind resource near Hay Hollow, only 22 miles southeast of Holbrook. This data can be used both to estimate the capacity factor for Holbrook's wind, and to find seasonal trends that might be experienced in the area.

Recent well drilling activity in the area suggests an estimated required drill depth of 550 feet with groundwater salinity approximately 1,000 ppm TDS (Gilardoni, 2009). These TDS levels are notably lower than those of the Dilkon area, which demonstrates one of the main tradeoffs possible with non-collocated facilities.

Wind resources

As mentioned earlier, the Hay Hollow wind resource (**Figure 30**) has previously been modeled for power production data. Eleven years of data were modeled for nine different 36 MW wind plant "strings" spread around the area. Hay Hollow's expected power production was averaged for all 11 years, and for all strings, to determine average generation of about 9.2 MW (out of 36 MW) yielding a capacity factor of about 25.6%. Given the proximity and similarity of geography, this capacity factor would be a realistic expectation for the wind resources immediately south of Holbrook.

This same power production data was also used to explore the seasonal variations that a wind plant might experience in the region. **Figure 31** shows the progression of a rolling 30-day average generation for all 11 years. A late-summer "lull" is immediately evident. While the

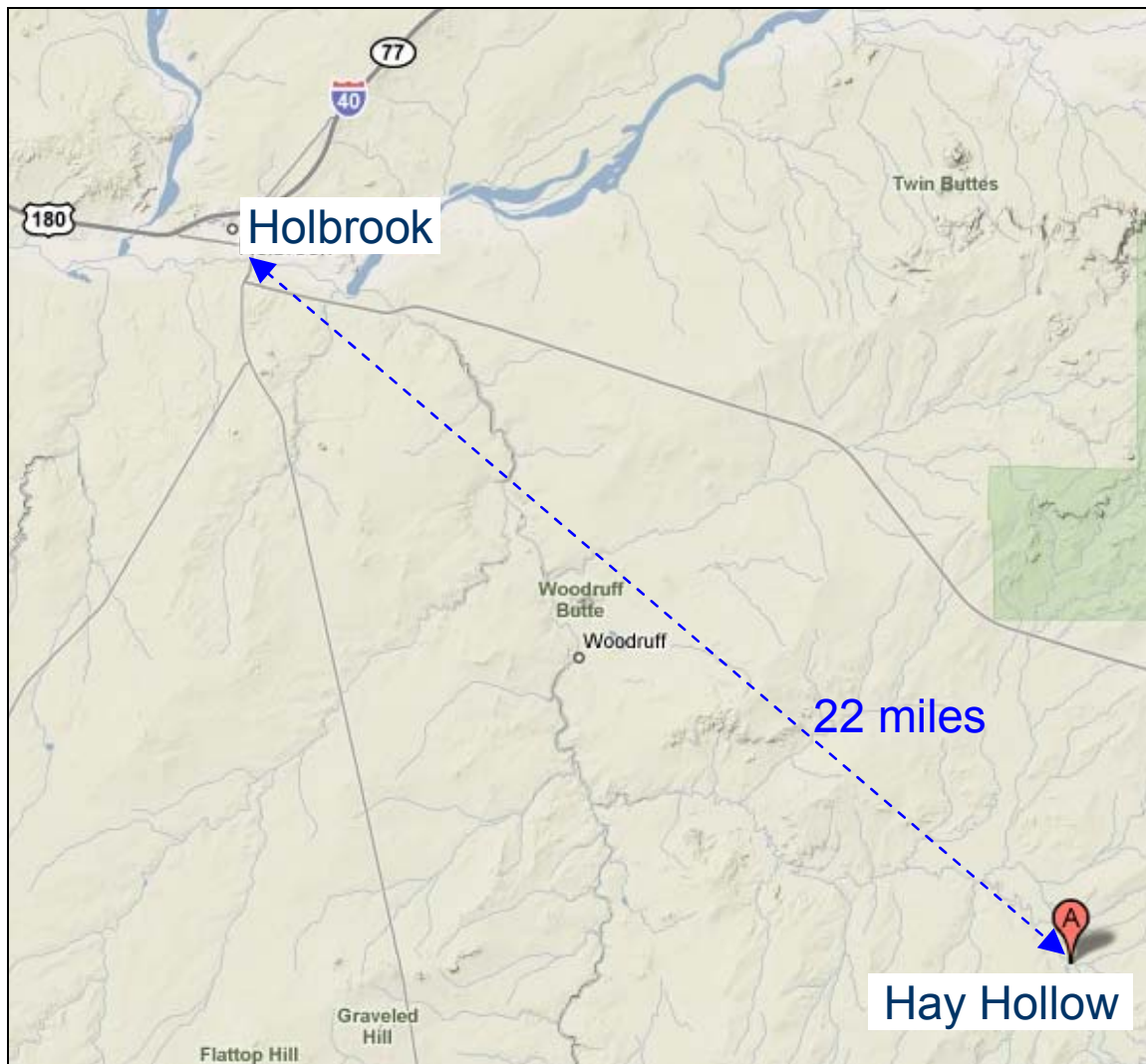


Figure 30: Map of Hay Hollow in relation to Holbrook.

mean 30-day-average for all data is 9.23 MW, several of the years plotted show at least a brief dip below about $\frac{1}{4}$ of that mean.

It is important to note that because each plotted data point represents an average of 30-days worth of generation data, even a single plotted data point below $\frac{1}{4}$ generation represents a full 30-day span with generation producing less than $\frac{1}{4}$ the energy of an average 30-day span. The duration of this annual lull varies from year to year, but as **Figure 31** shows, a number of lulls lasting as much as 60-days do approach the $\frac{1}{4}$ mean generation mark.

Although Dilkon is much farther from Hay Hollow, these trends would be much more regional than site-specific, and of value to both locations. This is fortunate, because due to lack of similar information near Dilkon, the capacity factor for that wind resource was estimated differently.

As mentioned earlier, Dilkon has wind resources of Class 3 and possibly Class 4. Class 3 winds have speeds between about 6.3 m/s and 7.0 m/s, on average, so a conservative estimate of average area windspeed would be 6.5 m/s. This windspeed and the area elevation of about 6,000 ft can be used to determine average power production via use of a table of wind turbine

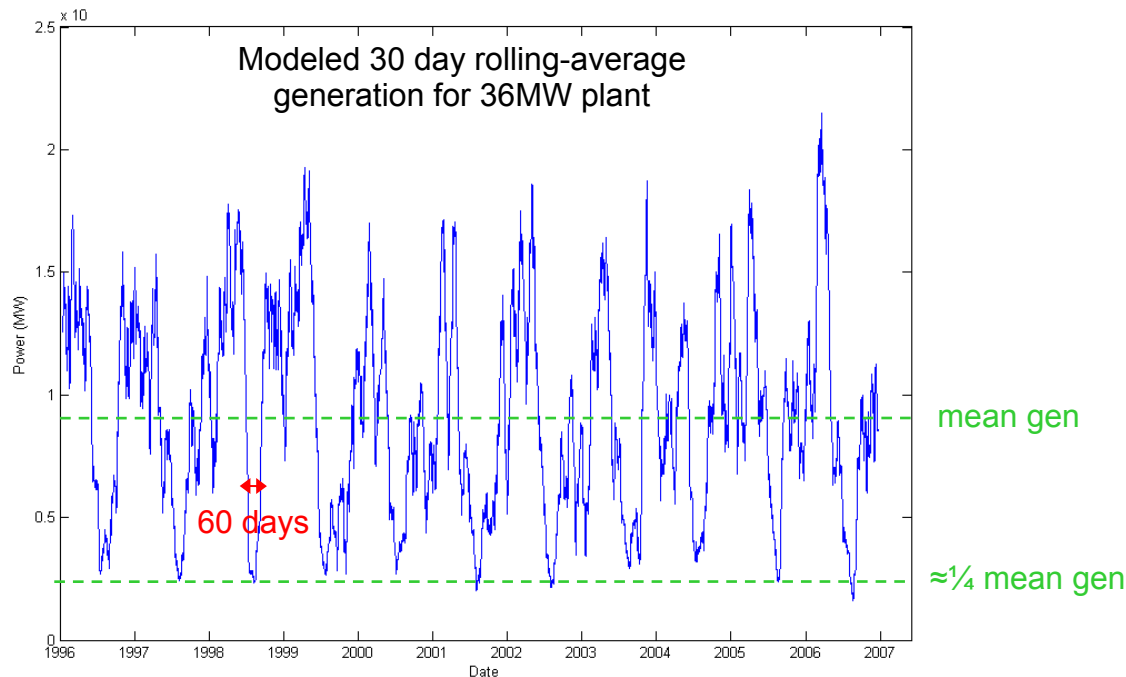


Figure 31: Modeled wind generation at Hay Hollow over 11 years.

power curves. Using the power curves of the same 1.5 MW wind turbine as that used in the Hay Hollow models, the estimated average capacity factor would be about 18%.

Energy requirements

Dilkon

For Dilkon's hospital's water requirements, Mr. Black estimated a need for 15,000 gal/day, requiring about 160 kWh/day for both pumping and R.O. desalination. In terms of most production-level R.O. desalination equipment, this is an extremely small throughput demanding only an extremely light duty cycle. However, as mentioned earlier, the project would ideally eventually be a community-supporting effort (not merely a hospital-supporting effort) and this room for expansion is what Mr. Black is seeking for the community. With a requirement of 160 kWh/day, Dilkon would require an average generation of 6.7 kW from its wind resources. Given the estimated capacity factor for the area of about 18%, that would mean a nameplate capacity of 37 kW would need to be installed.

Holbrook

Holbrook would require much less installed capacity for a similarly equipped desalination operation. Its estimated capacity factor is much greater at 25.6%, and its energy requirements are less. Also, the pumping depth is only about half that of Dilkon, and TDS levels are far below Dilkon's. According to Wittholz *et al* (2008), the estimated energy requirements mentioned earlier in this report, energy required for Holbrook's TDS levels would only be about half that required for Dilkon. So to pump and desalinate the same 15,000 gal/day, Holbrook would require only about half the 6.7 kW required in Dilkon.

For Holbrook to meet the same desalination requirements, given the estimated capacity factor for its wind resource, only a nameplate capacity of 13 kW would need to be installed. The

costs for a single grid-intertie-capable 10 kW Bergey wind turbine, with inverter, tower, and installation are tabulated in Table 7. Potential taxes and credits are not included. To cover Dilkon's 37 kW needs, four such turbines would be required "on average", especially if tank storage is to be considered. For Holbrook's 13 kW needs, two such turbines would likely handle the load, and have capacity to spare for times when generation might be below average. Of course, other turbine configurations could be considered. This is just one possible suggestion.

Table 7: Per-turbine capital costs for 10 kW grid-intertie Bergey. Bergey Retail Price List <http://www.bergey.com/Products/Prices1.htm>. Accessed August, 2009.

10kW Bergey turbine	\$30k
Tubular tower	\$34k
Installation	\$20k
Total per turbine	\$84k

Desalination facility costs

Because a 15,000 gal/day throughput is so small, relative to other installations, the R.O. facility itself is far from any economies of scale, regardless of in what city it is installed. According to Wittholz *et al* (2008), a facility producing a throughput many orders of magnitude greater would still cost about the same, reflecting the use of the same equipment, just with a heavier duty cycle, again lending itself to future expansion to suit the community. Wittholz *et al* (2008) estimates the capital cost for a plant of this order at no more than \$10 million, with a production cost of about \$10,000/year. (Unfortunately, as Wittholz mentions, uniform pricing figures are difficult to assure between installations. This is especially true for the smallest facilities, of which much fewer data points were available.)

Drilling and equipping the well for the facility, however, would vary significantly between the two locations¹. The estimated costs for drilling, equipping, and other needs (e.g.: minimal treatment, emergency power, wellhouse, etc.) are tabulated in Table , below.

Table 8: Well drilling & equipping capital costs.

	Dilkon	Holbrook
Drilling	\$325,000	\$75,000
Equipping	\$50,000	\$28,000
Other (minimal treatment, emergency power, wellhouse)	\$48,000	\$45,000
Total	\$423,000	\$148,000

Extra Concerns

As noted earlier, a tank storage solution for Dilkon should probably be investigated, particularly to cover a 60-day span when generation might run as low as only $\frac{1}{4}$ average generation. This tank would therefore need to cover about $\frac{3}{4}$ of their water needs for a 60-day span, or roughly 650,000 gallons. It was noted earlier that such a 60-day span was a very conservative figure so a tank that large would probably not be required, especially if water usage rates were controlled during the more severe wind "lull" periods.

A 500,000 gallon tank would cost about \$300,000 to ship and build, plus another 15%-20% for site preparation in the type of terrain of the area, for a total of about \$350,000. This is a figure that could vary wildly, depending on installation terrain (it could range well over 100% of build cost just for site preparation) and raw material prices (the price of steel amounts to about 40% of build cost, and has both crashed and skyrocketed alternating in recent years).

The Holbrook area has extra concerns of its own, probably requiring installation of grid intertie lines. These lines are very expensive relative to other capital requirements but the length required could also vary widely, depending on where wind turbines are to be installed, and the type of terrain the lines must run through. For the purposes of this report, a length of 5-miles is probably a good estimate. Line prices are also varied, but between \$10,000-\$15,000 per 300 ft would be a decent estimate. 5 miles of such a line would average about \$1.1 million.

It is important to note for the reasons outlined above that these prices are a first-cut comparative estimate.

Micrositing Conclusions

Total costs for the primary site-dependant requirements are listed below in Table . These could almost be thought of as the opportunity costs for building in sub-optimal locations. As the table demonstrates, each element is clearly more optimal in one location over the other, but the tradeoffs (at least in this theoretical application and comparison) tend to balancing out the total costs.

Table 9: Site-dependant desalination facility capital costs.

	Dilkon	Holbrook
Well drilling	\$423,000	\$148,000
Turbine capital/install	\$336,000	\$168,000
Extra requirements	\$350,000	\$1,100,000
	(tank storage)	(grid tie line)
Sub-total	\$1,109,000	\$1,416,000

Because we assumed the same desalination throughput requirements between the two sites, the actual R.O. facility and operation costs would be essentially the same. The figures below in Table represent the maximums that communities as small as these could expect to need to pay. The facility cost is not tied to the throughput at these levels, as production-level equipment would merely need to run reduced duty-cycles, and would allow for significant future expansion when required.

Table 10: R.O. equipment costs, independent of location.

R.O. facility	< \$10,000,000
R.O. production	\$10,000 (per year)

Because the facility cost is many times more than any of the other individual costs at either of the two sites, it would be crucial for a potential installation to fully analyze its

maximum future desalination requirements, and determine if a smaller, less expensive facility could be built. Fortunately for potential developers, such production-level R.O. equipment is almost completely modular, and could be reduced to a single unit of the smallest capacity, if needed.

Summary and Discussion

The purpose of this study was to assess wind-powered desalination opportunities in the state of Arizona. The maps produced in this assessment show where brackish groundwater was predicted to exist and where these resources may be co-located with wind resources potentially capable of supplying the electrical demand of desalination.

The national assessment was produced from generalized geologic maps and cross-sections and hydrogeologic descriptions of brackish aquifers in the principle aquifer systems of the U.S. (USGS, 2008). The information contained in this reference summarizes local and regional groundwater assessments in a fairly non-technical manner. Its use in this assessment provides results that are limited to a generalized, regional understanding of the location and volume of potential brackish groundwater resources of the U.S. This assessment does not attempt to address the actual availability of these resources. Only a detailed hydrogeologic study of an aquifer that includes well testing can attempt to do this. Given these limitations, 2.9×10^{14} m³ brackish groundwater, approximately ten times the volume of water stored in the Great Lakes, was predicted to exist in U.S. aquifers.

The state-scale assessment focuses on the Colorado Plateau and the Basin and Range basin-fill aquifers of Arizona. This assessment was also meant to provide a regional estimate of brackish groundwater resources, but was refined from the national assessment by incorporating groundwater, aquifer, and geologic data from the USGS, Arizona Department of Water Resources, and the Arizona Geologic Survey. This assessment provides a more detailed study of brackish groundwater resources, but, like the national assessment, does not attempt to estimate the actual availability of brackish groundwater resources. Use of this assessment was meant to provide water resource managers in Arizona an approximation of the volume of brackish groundwater resources potentially available and an estimation of the costs associated with desalination using either wind power or grid electricity. To briefly summarize the location and volume of brackish groundwater estimated by the Arizona assessment for comparison to the national assessment and for reference in the discussion, 8.1×10^{12} m³ brackish groundwater was predicted largely in the Gila, San Pedro, Santa Cruz, and Salt River drainage basins of Southern and Central Arizona, in the deepest portion of the D Aquifer, in the C Aquifer along the Little Colorado River Basin, and in the R Aquifer where the R Aquifer is present north of the Defiance Uplift in Northeastern Arizona. Considering Lake Mead and Lake Powell contained 11 million acft (13 billion m³) and 16 million acft (20 billion m³) of water in storage, respectively, in June 2009 (CLIMAS, 2009), the volume of brackish groundwater predicted in Arizona's aquifers represents 400 to 600 times the volume of water stored in these reservoirs. Also for comparison, the volume of brackish groundwater estimated in this assessment represents 2,300 times Arizona's annual allotment of water from the Colorado River under the Colorado River Compact of 1922 (approximately 3.5 billion m³).

Wind resources

The location of wind resources used in this assessment show an average annual wind resource (USDOE, 2008a). For the U.S. assessment, wind resources were correlated to brackish groundwater that directly underlies areas with wind class 3 or greater. For the Arizona assessment, wind resources were correlated to brackish groundwater within 20 km of wind class 3 or greater. In Arizona, wind resources were generally found to be poor to marginal (wind class 1 to 2) and are unsuitable for utility-scale electrical generation with current technology. However, wind class generally increases with altitude and sharp changes in topography producing fair to excellent wind resources (wind class 3 to 5) along ridgetops and valley rims both locally and across large areas. These locations are particularly notable in the Basin and Range Province. Suitable wind fields are also oriented along prominent geographical features such as northeastern rim of Black Mesa, and the southwestern rim of Little Colorado River valley. The largest such field extends from northwest of Cameron on the west rim of the Little Colorado valley southeast to Springerville. Small, localized wind fields are found throughout the eastern end of Grand Canyon National Park, Glen Canyon Recreation Area near Page and northwest and southeast of Kayenta.

The volume of brackish groundwater predicted to exist within 20 km of a class 3 or greater is $6.0 \times 10^{12} \text{ m}^3$ or 74% of the brackish groundwater estimated in Arizona. This leaves 26% of Arizona's brackish groundwater resources that cannot be desalted with co-located wind resources. However, this does not negate the possibility of desalination as a fresh water option. Energy produced in one region can be transmitted via transmission lines to areas with brackish groundwater resources. The energy produced at a remote location can be either from a renewable source such as wind or from a traditional source such as fossil fuel or nuclear. The costs associated with electrical transmission were not considered in this assessment, but can be significant and greatly varied ranging from \$360,000/km to \$4,200,000/km (Janeck et al, 2005).

Communities

Communities in Arizona located near predicted brackish groundwater resources and within 20 km of annual average wind resources of wind class 3 or greater include Bullhead City, Cameron, Douglas, Eagar, Florence, Green Valley, Holbrook, Kayenta, Kingman, Lees Ferry, Oraibi, Page, the greater metro-Phoenix area, Rock Point, Springerville, Tempe, Tuba City, Tucson, Winslow, and Yuma. This list is not all inclusive. The basins where these communities are located may contain other communities that may wish to consider wind-powered desalination as a fresh water option. The wind and brackish groundwater resources potentially available to these communities vary in suitability i.e. depth, salinity, and volume of brackish groundwater and strength of wind resources. The interpolation of the groundwater resources in the northern-most portion of Arizona is speculative due to insufficient data, but the interpolation suggests that these areas should contain moderately- to highly-brackish groundwater at relatively shallow depths. Communities in this region include Lees Ferry, Page, Kayenta, and Rock Point. Although this assessment indicates that these communities may wish to consider wind-powered desalination as a fresh water option due to the proximity of resources, this work does not assess detailed community information that would be needed to determine whether these communities should consider pursuing a more detailed feasibility study of available resources.

Cost estimates

Cost estimates provided in this assessment were meant to provide water resource managers a first approximation of the costs associated with desalination to aid in decisions regarding accommodating the future water demands of their communities.

The capital costs associated with desalination at 10,000 m³/d plant capacity were estimated to range from \$10,500,000 to \$13,400,000 for wind-powered desalination and from \$8,230,000 to \$8,950,000 for desalination using grid electricity. This represents an increase of 28% to 50% for using wind power instead of existing grid electricity. At 50,000 m³/d plant capacity, the estimated capital costs of wind-powered desalination are 41% to 73% higher suggesting that wind-powered desalination becomes a less attractive option with increasing desalination plant capacity. However, the energy requirements of utility-scale desalination typically require a community to build new power generating facilities. If wind power were not used, some other power generating facility may still be required. The cost of such facilities were not considered in this assessment with regard to the cost estimates for desalination using grid electricity, and this additional cost would be significant.

The energy requirements of desalination range from 1.1 to 3.2 kWh/m³ depending on the salinity of feedwater and the depth from which groundwater must be pumped. Given these energy requirements, the energy output of an electricity generating facility must be 0.5 to 1.3 MW for a 10,000 m³/d desalination plant and 2.3 to 6.6 MW for a 50,000 m³/d desalination plant. At a 35% operating capacity, a wind turbine system must be rated at approximately 3 times these outputs, 2 to 4 MW and 7 to 20 MW for 10,000 and 50,000 m³/d desalination plants, respectively. At an average cost of \$1,710/kW, this equates to estimated wind turbine system costs ranging from \$3,400,000 to \$6,800,000 and from \$12,000,000 to \$34,000,000 for 10,000 and 50,000 m³/d desalination plants, respectively. These values are comparable to the costs estimated for desalination of brackish groundwater in Arizona which ranged from \$2,240,000 to \$4,970,000 and from \$11,200,000 to \$24,900,000 for 10,000 and 50,000 m³/d desalination plant capacities, respectively.

The NRC (2008) noted two U.S. inland desalination plants with UPCs of \$0.63 and \$0.43/m³. These values are higher than the range of UPCs for ninety RO desalination plants worldwide, \$0.14 to \$0.38 (Wittholz *et al*, 2008). Because the estimates in this assessment were based on the database provided by Wittholz *et al* (2008), it was expected that the estimates that result in this assessment would be more comparable to the global range than to the two U.S. desalination plants. It was also expected that the per unit cost of water produced by desalination would decrease with increasing desalination plant capacity. The UPC of desalinating brackish groundwater was found to decrease 25% to 33% by increasing the desalination plant capacity from 10,000 m³/d to 50,000 m³/d. Unexpected was a lower UPC for wind-powered desalination compared to desalination using grid electricity considering the annualized capital cost of the wind turbine systems were included in the estimated UPC for wind-powered desalination. The UPC for wind-powered desalination was found to be \$0.15/m³ to \$0.20/m³ less than the UPC for desalination using grid electricity for a 10,000 m³/d desalination plant and \$0.09/m³ to \$0.14/m³ for a 50,000 m³/d desalination plant. These cost decreases also do not take into consideration the capital costs associated with a new power generation facility or transmission lines if such equipment were needed for a desalination plant using grid electricity.

Micrositing

The positive and negative tradeoffs between collocated and non-collocated wind/desal scenarios did nearly balance out for these two particular scenarios. The trends demonstrated therein are that collocated wind/water/population resources will likely be less optimal than non-collocated, but non-collocated resources will need to absorb the extra costs associated with the distances involved (e.g., grid intertie lines). The size (and cost) of the R.O. desalination equipment itself is dependent on the requirements of the local population, and would need to be specifically tailored to their long-term needs before completing a cost-feasibility analysis because pricing is highly variable.