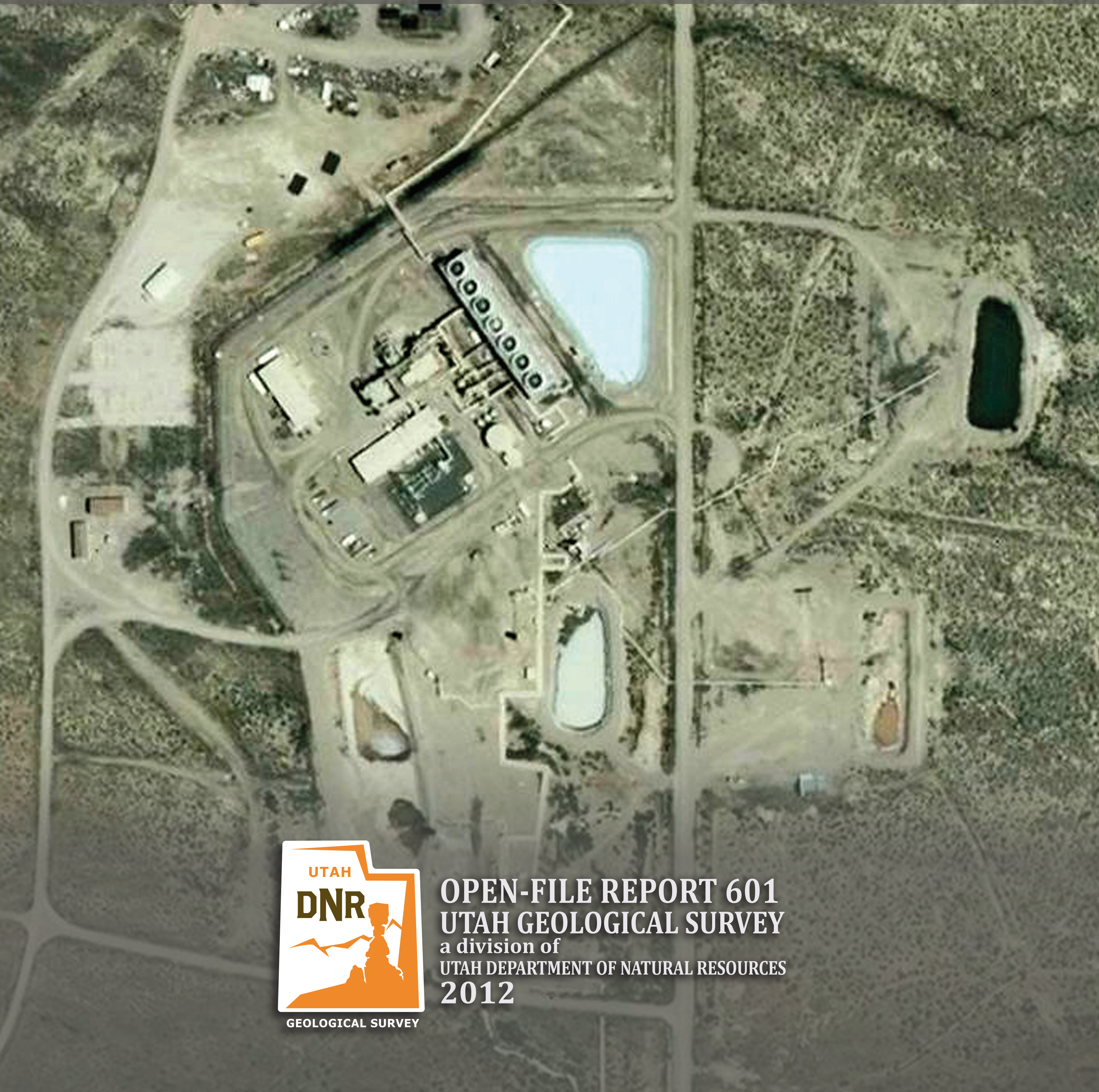
SUBSIDENCE IN SEDIMENTARY BASINS DUE TO GROUNDWATER WITHDRAWAL FOR GEOTHERMAL ENERGY DEVELOPMENT

by Mike Lowe



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Cover photo: *Dixie Valley geothermal plant aerial image from http://gisweb.unr.edu/geothermal/*

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PUBLICATIONS
contact
Natural Resources Map & Bookstore
1594 W. North Temple
Salt Lake City, UT 84116
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email: geostore@utah.gov

UTAH GEOLOGICAL SURVEY
contact
1594 W. North Temple, Suite 3110
Salt Lake City, UT 84116
telephone: 801-537-3300
website: geology.utah.gov

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ABSTRACT

Land subsidence can be caused by a variety of processes, but most land subsidence in the United States is associated with aquifer compaction caused pressure decline associated with groundwater withdrawal. In basin-fill aquifers, most of the aquifer compaction is due to the slow dewatering and compression of fine-grained sediments. Once the fine-grained units begin to compress and lose porosity, compaction becomes permanent, overall water storage in the basin fill is reduced, and land subsidence occurs. Land subsidence may result in various types of land-surface movements that can potentially cause problems if human development exists within the subsiding area. Geothermal development can and has caused aquifer compaction, such as in Dixie Valley, Nevada, where shallow groundwater withdrawal has occurred; subsidence has not been an issue for geothermal development of deeper aquifer systems in the Basin and Range Province. Land subsidence can also be caused by contraction as fractured rock reservoirs cool, such as in The Geysers geothermal area of California, but this mechanism is of less concern in deep sedimentary basin settings.

Land subsidence can be avoided by re-injecting all production water back into the aquifer it was withdrawn from so that pressure changes are minimized. Where land subsidence associated with geothermal energy production does occur, it can be reduced through monitoring combined with aquifer management. Monitoring may include the use of InSAR, use of LiDAR, and establishing and monitoring a high-precision GPS/GNSS (Global Navigation Satellite System) network of survey benchmarks.

With fractured rock aquifers at depth below thick unconsolidated deposits in deep sedimentary basins, the potential for subsidence can be mitigated by pumping all geothermal fluids back into the aquifer they are pumped from after heat extraction to prevent large-scale pressure decline. Where producing aquifers are beneath thick overlying unconsolidated deposits, thermal contraction of the fractured rock aquifer is unlikely to result in significant land surface subsidence due to bridging effects.

To avoid land subsidence in unconsolidated basin-fill settings, aquifers must be managed to balance groundwater recharge and groundwater discharge at both local and basin-wide scales. Ways to accomplish this goal include (1) ensuring all water used for geothermal heat extraction is pumped back into the aquifer, (2) replacing water lost from the aquifer during geothermal energy development by increasing groundwater recharge to the basin-fill aquifer through conjunctive management of groundwater and surface-water resources and importation of water from other basins, (3) dispersing high-discharge wells to reduce localized land subsidence, and (4) reducing overall groundwater withdrawals in the basin. Best management practices for the basin-fill aquifers used for geothermal development will likely include the application of an assortment of the aquifer management practices, and will likely take into consideration water pumped from the targeted aquifer for other purposes (municipal, domestic, irrigation).

INTRODUCTION

This report is part of a larger study of geothermal power potential of deep sedimentary basins, with emphasis on the eastern Great Basin. The goal herein is to review the potential causes of subsidence in sedimentary basins and provide recommendations for avoiding or minimizing subsidence.

CAUSES AND EFFECTS

Land subsidence, the lowering of the Earth's surface due to subsurface movement of earth materials, can be caused by aquifer-system compaction, drainage of organic soils, underground mining, hydrocompaction, natural compaction, sinkhole formation, and the thawing of permafrost (National Research Council, 1991). In the United States, more than 80 percent of the land subsidence, affecting more than 17,000 square miles in 45 states, has occurred because of groundwater withdrawal (Galloway and others, 1999), including groundwater withdrawal for geothermal development (Narasimhan and Goyal, 1984; Blackwell and others, 2007). Land subsidence can also be caused by contraction as fractured rock reservoirs cool (Mossop and Segall, 1997), but this mechanism is of less concern in deep sedimentary basin settings, so the focus herein is on unconsolidated aquifers.

In sedimentary basins, groundwater in unconsolidated aquifers is pumped from the pore spaces between sand and gravel grains, causing a lowering of pore-water pressure (Leake, 2004). The decrease in pore pressure results in an increase in the effective stress in the high-permeability low-compressibility coarse-grained aquifers and time-dependent pore-pressure reduction in the low-permeability high-compressibility fine-grained aquitards, and this increase in effective stress is equal to the decrease in fluid pressure (Poland, 1981). Because fluid pressure within the pores of a granular matrix helps support overlying aquifer material, a reduction in pore-water pressure causes an increase in overburden stress (weight) to the aquifer matrix, causing the aquifer matrix to change volume (compact) (Galloway and others, 1999). Compaction of the aquifer material is immediate, elastic (Galloway and others, 1999) and therefore largely recoverable if the pore-water pressure is restored, and the change in aquifer volume is small (Poland, 1981). If the aquifer has silt and clay beds (aquitards) within or adjacent to it, the lowered pore-water pressure in the sand and gravel causes the slow drainage of water from the pore spaces in the silt and clay beds as pore-water pressures in the aquifers and aquitards decay towards equilibrium (Poland, 1981), allowing the fine-grained particles to compress or compact (Leake, 2004) (figure 1). Reaching pore-water pressure equilibrium between aquifers and aquitards may take months or years (Poland, 1981), and thick clay layers may take hundreds of years to reach equilibrium (Green, 1964). Thus, the resulting compaction may continue long after groundwater withdrawals are brought back into equilibrium with groundwater recharge, or cease completely.

Once the fine-grained units begin to compress and lose porosity, compaction becomes permanent, overall water storage in the basin fill is reduced, and land subsidence occurs (Galloway and others, 1999). The overall aquifer compaction occurs mainly in the fine-grained sediments and is small to negligible in sand and gravel beds (Green, 1964). In confined aquifer systems undergoing large-scale potentiometric head reductions, the volume of water yielded from irreversible compaction of fine-grained aquitards is approximately equal to the volume of land subsidence, and commonly ranges from 10 to 30% of the total volume of water withdrawal (Galloway and others, 1999). The relation between potentiometric-surface decline and land subsidence is largely a function of total basin fill thickness, composition, and compressibility (Arizona Land Subsidence Group, 2007). In some areas of Arizona, a potentiometric-surface decline of about 300 feet produced only 0.6 feet of subsidence (Arizona Land Subsidence Group, 2007). In other areas, a similar potentiometric-surface decline generated as much as 18 feet of subsidence (Arizona Land Subsidence Group, 2007). Sediments with a high clay content, such as those found in playa settings, have high compressibility.

Groundwater withdrawal sufficient to cause significant potentiometric-surface declines and the resulting dewatering of fine-grained basin-fill units can result in the formation of a "subsidence bowl" (Viets and others, 1979) (figure 2), in the vicinity of, but not necessarily centered around, the area of large-scale groundwater withdrawal (Bell and others, 2002). When there are multiple points of groundwater withdrawal, secondary subsidence bowls may develop within the larger, principal subsidence bowl (Bell and others, 2002). As a subsidence bowl develops, various types of land-surface movements occur, usually beginning with vertical settlement, followed by tilting of the land surface, and, finally, horizontal strains in the land surface that can result in the formation of earth fissures (Viets and others, 1979) (figure 2). If infrastructure associated with human development exists within the subsidence bowl, these land-surface movements can result in a variety of potential problems, including (1) changes in elevation and slope of streams, canals, and drains, (2) damage to bridges, roads, railroads, storm drains, sanitary sewers, water lines, canals, and levees, (3) damage to private and public buildings, and (4) failure of well casings from forces generated by compaction of fine-grained materials in aquifer systems (Leake, 2004).

Earth fissures, linear cracks in the ground that initiate at depth due to differential compaction and extend from the compressing layers up to the ground surface (Galloway and others, 1999), can exacerbate problems within the subsidence bowl. Earth fissures form in response to horizontal stresses that develop when land subsidence causes different parts of a sedimentary basin to compact by different amounts (Leake, 2004; Arizona Division of Emergency Management, 2007), and may range from a few feet to several miles long and from hairline cracks to tens of feet wide (Carpenter, 1999). Earth fissures typically form along the edge of basins, near exposed or shallow bedrock that may be related to faults, or over zones of changing basin-fill facies (Arizona Land Subsidence Group, 2007). Some earth fissures exhibit differential displacements of several inches to several feet (Carpenter, 1999), potentially damaging structures if they occur in developed areas. Earth fissures can be enlarged by erosion when they intercept surface water (Viets and others, 1979), which could potentially carry surface sources of pollution to the groundwater aquifer.

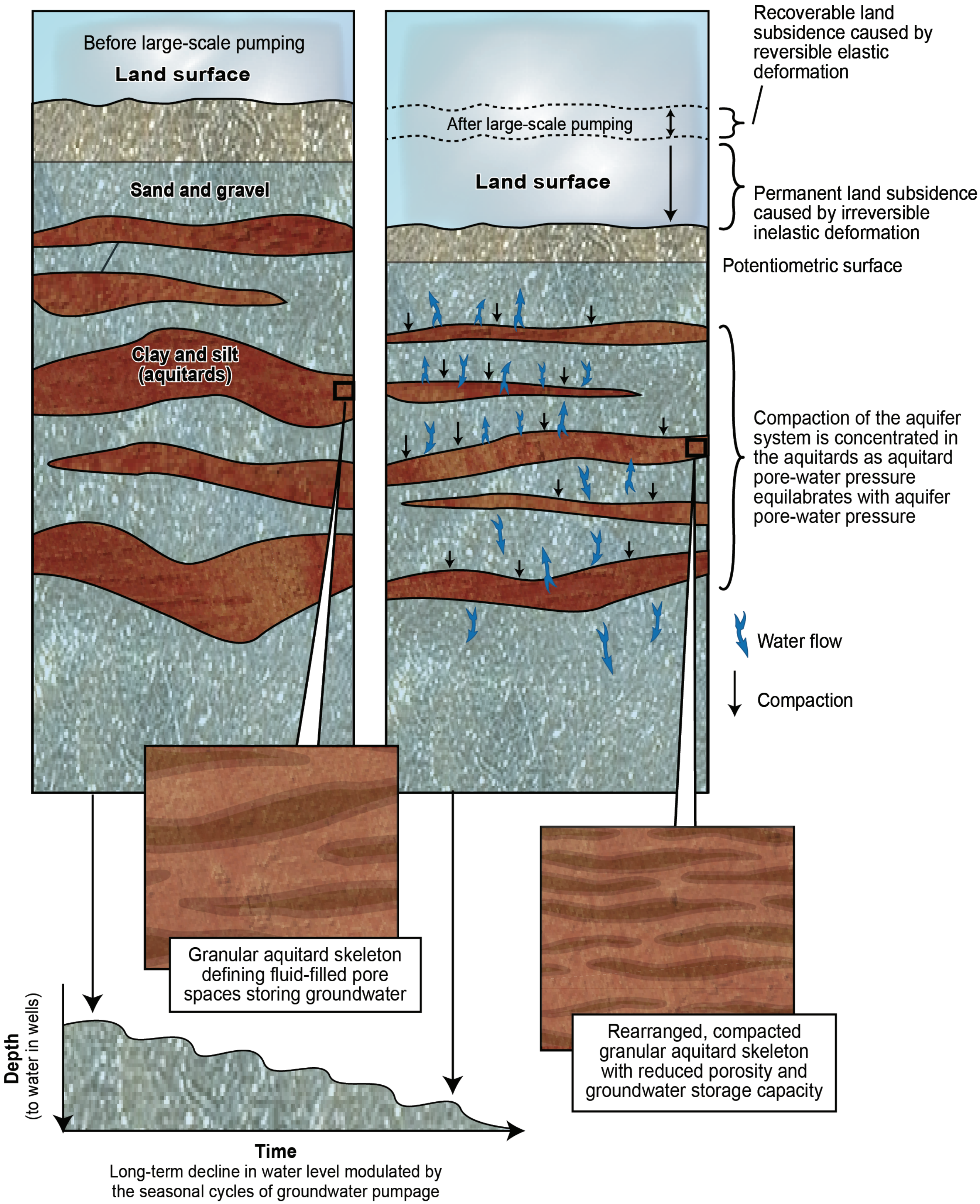

Figure 1. *Schematic diagram of land subsidence due to groundwater withdrawal (modified from Galloway and others, 1999).*

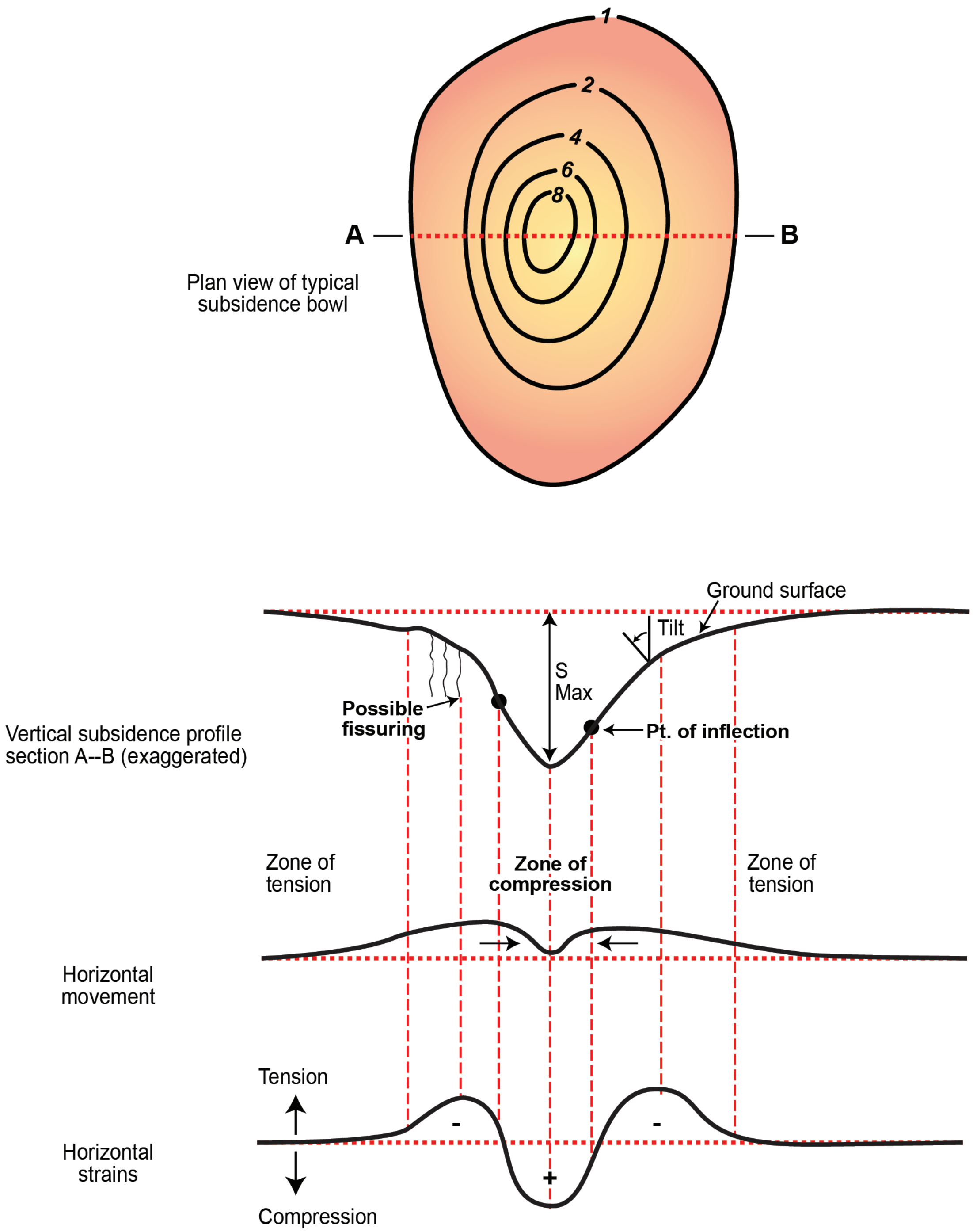

Figure 2. *Schematic diagram of land-surface movements associated with subsidence bowls (modified from Viets and others, 1979). S max is maximum vertical subidence.*

SUBSIDENCE RELATED TO DEVELOPMENT OF GEOTHERMAL RESOURCES—TWO EXAMPLES

Introduction

Although land subsidence associated with geothermal development is uncommon, the following are two cases where it has occurred.

The Dixie Valley Geothermal System, Nevada

Dixie Valley hosts one of the hottest and largest geothermal system in the Basin and Range Province, and the production of about 63 megawatts from Oxbow power plant in the valley over the last 25 years is significantly greater than that of any other geothermal system that is not associated with recent magmatic activity (Blackwell and others, 2007). Like many Basin and Range geothermal systems, the Dixie Valley geothermal field had few surface thermal manifestations prior to development, although the Senator fumarole was present high on the Senator alluvial fan near the Stillwater range front, adjacent to what has become the production well field (Allis and others, 1999).

The Dixie Valley geothermal system is an approximately 20-mile-long area located along the historically active Dixie Valley fault zone on the east side of the Stillwater Range between the Dixie Valley Producing Field and Dixie Hot Springs (Blackwell and others, 2007). Based on well cuttings from a well on the Senator alluvial fan, the aquifer hosting the geothermal system is mostly alluvium (alluvial-fan and silicified landslide deposits), although in-place bedrock might be present below 470 feet in depth (Allis and others, 1999). Poorly consolidated lacustrine/playa deposits interfinger with the alluvium at the toe of the fan (Foxall, 2003). Many production, injection, and exploration wells (8000–11,000 ft deep), as well as various geological and geophysical data, have been used to help delineate the system (Blackwell and others, 2007). The conceptual model of the geothermal system is one of hot water flowing up the main bounding fault of the Stillwater Range within a localized zone beneath the Senator fumarole and then discharging laterally into the valley along permeable zones lower in the Senator alluvial fan (Foxall, 2003). Fluid temperatures are 225°C to 245°C at depths of around 8200 feet and over 265°C at depths of about 9800 feet (Blackwell and others, 2007).

Pressure drawdown in the Dixie Valley geothermal reservoir has caused an increase in steam-heated thermal activity around the Senator fumarole, ground cracking on the Senator alluvial fan, and subsidence to the east of the fumarole (Allis and others, 1999). At production depths (7000–9000 ft) fluid pressure may have been reduced by as much as 50 bars (Allis, Utah Geological Survey, verbal communication, October 17, 2012), while pressure reduction in the main outflow zone (an aquifer about 30 ft below land surface) is estimated to be about 2 bars (Fozall, 2003). The land subsidence occurred where the relatively competent alluvial material merges with less competent lacustrine/playa deposits along the toe of the Senator alluvial fan, resulting in the formation of a small subsidence bowl where runoff water now ponds in its center and ground cracking on the fan itself (Allis and others, 1999). Synthetic aperture radar data indicate subsidence rates in the bowl may have been locally as high as 0.3 feet per year (Foxall, 2003) during the early 2000s.

The Geysers Geothermal Field, California

The Geysers in northwestern California is a vapor-dominated hydrothermal-type geothermal system that began producing electric power in 1960 when a 12.5-megawatt generating plant went on line using 250,000 pounds per hour of steam supplied by four wells (Narasimhan and Goyal, 1984). With the addition of more wells to the production line over the next several decades, the Geysers became the largest producer of geothermal power in the world, generating nearly 2 gigawatts of electric power at peak production in the mid-1980s (Mossop and Segall, 1997). Power production from the nearly 40-square-mile reservoir area has since been declining (Mossop, 2001) due to steam pressure decreases that have continued despite attempts to augment natural recharge with artificial recharge through injection (Nielson and Brown, 1990). Recent reviews of the performance of the The Geysers reservoir and its response to large-scale cold water injection are given by Beall et al. (2010), Beall and Butler (2010) , and Enedy and Butler (2010).

The geothermal reservoir is hosted by highly fractured Franciscan graywacke, probably of Jurassic to Cretaceous age, and Quaternary silicic intrusive rock (felsite) and capped by 1000 to 3000 feet of low-permeability, metamorphic mélange (Mossop and Segall, 1997). The structural framework of The Geysers geothermal field is extremely complex due to thrust faulting that took place along northwest-trending fault zones that dip to the northeast (Nielson and Brown, 1990), and the area remains one of the most seismically active regions in northern California (Mossop and others, 1997) due to strike-slip faulting (Nielson and Brown, 1990). The Franciscan greywacke is very dense and has low primary permeability, so the steam is produced from the open fractures and fault zones (Narasimhan and Goyal, 1984) resulting from the region's complex tectonic history. The steam-producing fractures are relatively flat and generally random in orientation (Nielson and Brown, 1990). There are two producing zones within the reservoir rock: a shallow zone at about 2100 feet, and a deeper, primary zone between 2500 and 5000 feet in depth (Narasimhan and Goyal, 1984). Production from The Geyser geothermal field relies on boiling of immobile water to generate mobile steam.

Geothermal energy production at The Geysers has resulted in both subsidence and induced seismicity (Narasimhan and Goyal, 1984). The phase change from hot water to vapor absorbs large amounts of heat and therefore lowers the reservoir temperature, causing the cooling reservoir to contract and resulting in land subsidence at the surface (Mossop and Segall, 1997). GPS surveys in the 1970s documented that The Geysers geothermal field was subsiding, with a maximum rate of about 0.15 feet per year between 1973 and 1977 (Mossop, 2001), and that the area of greatest subsidence appeared to be centered near the area of the most active steam extraction at that time (Mossop and others, 1997). Two types of land-surface movements accompanied the subsidence: (1) a downward local tilt of about 1.4 inches toward the west-northwest, and (2) vertical land-surface lowering of as much as 5 inches near one of the power plants. Despite reinjection of steam condensate amounting to about 25% of daily steam output back into the reservoir beginning in 1969 (Narasimhan and

Goyal, 1984), the rate of subsidence for the 1977–1996 period remained close to 0.15 feet per year (Mossop, 2001) and maximum subsidence of nearly 3 feet was measured within the subsidence bowl about 1.2 miles north of the above-mentioned power plant (Mossop and others, 1997). Meanwhile, earthquake activity (M ≥ 2) had increased from about 25 events per year during 1962–1963 to 47 events per year during peak production (1975–1977) (Marks and others, 1979). Mossop (2001) found there was a correlation between this increased microearthquake activity and both steam production and fluid injection (Mossop, 2001).

BEST MANAGEMENT PRACTICES FOR MONITORING AND REDUCING LAND SUBSIDENCE DUE TO DEVELOPMENT OF GEOTHERMAL RESOURCES IN DEEP SEDIMENTARY BASINS

Introduction

Development of geothermal resources in deep sedimentary basins could involve pumping from either unconsolidated basin fill deposits or underlying fractured rock aquifers. With fractured rock aquifers at depth below thick unconsolidated deposits, the potential for subsidence can be avoided or mitigated by pumping all geothermal fluids back into the aquifer they are pumped from after heat extraction to minimize large-scale pressure changes and prevent aquifer compaction. Because of the thick overlying unconsolidated deposits, thermal contraction of the fractured rock aquifer is unlikely to result in significant land surface subsidence. While many of the best management practices described below, especially monitoring (appendix), may need to be considered in areas where development of fractured-rock geothermal resources occurs, the focus of this section is on geothermal development of shallow unconsolidated basin-fill aquifers. These best management practices may be less applicable to development of deep unconsolidated aquifer systems where natural compaction has already occurred and the potential for additional compressibility is low.

Reducing Land Subsidence Through Aquifer Management Practices

Potentiometric-surface declines that could lead to land subsidence occur when average annual groundwater discharge exceeds average annual groundwater recharge, causing concomitant land subsidence and earth fissure formation as near-surface fine-grained layers in the basin-fill deposits dewater and compress. To avoid land subsidence, basin-fill aquifers must be managed to balance groundwater recharge and groundwater discharge at both local and basin-wide scales. There are several ways to accomplish this goal, including (1) ensuring all water used for heat extraction is pumped back into the aquifer, (2) replacing water lost from the aquifer during geothermal energy development by increasing groundwater recharge to the basin-fill aquifer through conjunctive management of groundwater and surface-water resources and importation of water from other basins, (3) dispersing high-discharge wells to reduce localized land subsidence, and (4) reducing overall groundwater withdrawals in the basin.

Ensuring No Net Loss of Fluids During Geothermal Development

To the extent possible, all fluids used during the heat extraction process should be injected back into the same zone of the aquifer they were withdrawn from. This will prevent the pore-water pressure reductions that lead to the dewatering and compressing of fine-grained layers, resulting in land subsidence.

Increasing Recharge to the Basin-Fill Aquifer

Increasing groundwater recharge to aquifers with historically declining hydraulic heads through conjunctive management of groundwater and surface-water resources has proven to be a powerful tool in preventing or reducing aquifer compaction (Reichard and Bredehoeft, 1985; Holzer, 1989; Swanson, 1996; Galloway and others, 1999; Onsoy and others, 2005; Utah Division of Water Resources, 2005). Conjunctive management of groundwater and surface-water resources through aquifer storage and recovery (ASR) projects in sedimentary basins offers a potential partial solution to problems associated with water-level declines in the basin-fill aquifer so long as the recharged water is in hydraulic connection with the producing zone of the aquifer. Not only would such projects help stabilize water-level declines, they would also provide water planners and managers with increased flexibility to managing the basin's water supply and provide a source of supplemental water.

Artificial groundwater recharge has long been used to enhance groundwater quality, reduce pumping lifts, store water, salvage storm-water runoff, and reduce aquifer compaction in subsiding areas (Clyde and others, 1984; Pyne, 1995; Galloway and others, 1999). ASR projects involve storing water in an aquifer by artificial groundwater recharge when water is available, and recovery of the stored water from the aquifer when water is needed (Pyne, 1995). Basically, groundwater aquifers are used as water-storage facilities rather than constructing surface-water reservoirs. Artificial groundwater recharge can be accomplished by surface spreading or ponding (such as in rapid infiltration basins) where surficial deposits are highly permeable, or by using wells to inject surface water into an aquifer where surface deposits are less permeable (Clyde and others, 1984). Although loss of stored water through artificial groundwater recharge does occur, principally due to water moving vertically or laterally out of the target aquifer before recovery, the sometimes significant loss of water through evaporation in surface-water storage facilities is avoided (Clyde and others, 1984).

The most beneficial areas for artificial groundwater recharge in a sedimentary basin, using either surface-spreading/ponding techniques or injection wells where appropriate, are areas experiencing the greatest land subsidence. Both perennial and some larger ephemeral streams may be used to provide water for artificial groundwater recharge. Water imported from other basins could also be used as a source of artificial groundwater recharge, assuming water rights in those basins may be obtained (Reichard and Bredehoeft, 1985; Galloway and others, 1999; Onsoy and others, 2005). It should be recognized that importing water from other basins may reduce land-development opportunities or may cause subsidence and other related issues in the basins from which the water is obtained. If the basin-fill aquifer is recharged via surface spreading or ponding, the recharge sites should be located in primary recharge areas, where thick clay layers that may inhibit subsurface water flow are absent in the basin fill. Injection wells may be located where needed. In both recharge methods, it is important to establish a connection between the recharge zone and the zone from which geothermal fluids are extracted.

Dispersing High-Discharge Wells

Basin-fill compaction and associated land subsidence and earth fissures can be stopped or reduced by locating or relocating high-discharge wells (geothermal, municipal, and high-discharge irrigation) in areas that will minimize subsidence. Optimization models coupled with groundwater-flow models can be used to determine where these wells would best be located (Leake, 2010). Campbell and Jensen (1975, as reported in a Water Well Journal editorial) recommended evaluating the feasibility of redistributing pumping loads in the Houston, Texas area from the vicinity of subsidence areas to more distant locations. In the Owari Plain of Japan, short-term and local changes in head are considered when regulating groundwater pumping to prevent land subsidence (Daito and others, 1991).

Reducing Overall Groundwater Withdrawals

Limiting the amount of groundwater extracted from an aquifer so that stored water will not be significantly depleted is the basis for the water-resource management concept known as “safe yield” (Galloway and others, 1999). To avoid groundwater mining, the volume of water withdrawn from an aquifer cannot significantly exceed natural and artificial recharge to the aquifer—the concept of safe yield is usually applied using average annual values of recharge and discharge. Given climatic variability, it may be necessary to manage subsidence-prone areas near geothermal projects even more conservatively to avoid increasing the rate and/or area of subsidence during drought periods. It may be possible to manage subsidence-prone areas using the “optimal yield” concept, in which groundwater discharge is allowed to vary from year to year, or even seasonally, depending on the state of the aquifer system and the availability of local and imported water supplies. This concept incorporates the dynamic nature of the groundwater system and allows water managers to adapt to variations in water supply and use (Galloway and others, 1999).

Basin-wide groundwater withdrawals could be reduced by acquiring and retiring existing water rights, although, we did not find any case histories of this being done for geothermal development in areas with aquifer-compaction-related problems. However, groundwater withdrawals have been reduced in other areas by regulating groundwater pumping (Holzer, 1989) and/or groundwater price (Bangkok City, 2001).

In Texas, which applies the principles of English common law, groundwater is the absolute property in perpetuity of the overlying private landowner (Brah and Jones, 1978; unlike many states where groundwater is considered public property, and the State Engineer grants individuals the right to use allotted amounts). When land subsidence due to groundwater mining developed in coastal areas of the Houston-Galveston region beginning in the 1950s, there was little incentive for private groundwater users to reduce reliance on relatively inexpensive groundwater resources and arrest the subsidence, as they themselves did not incur the subsidence-related costs (Holzer, 1989). In the 1970s, individuals and groups affected by the land subsidence attempted to mitigate the subsidence problem by focusing on ways to turn incentives for groundwater pumping into disincentives (Holzer, 1989). They considered four alternatives: (1) implementation of a surcharge on groundwater pumping, (2) creation of a regional water authority through legislation, (3) formation of a regional underground water conservation district under the Texas Water Code, and (4) creation of a local government agency to regulate pumping (Brah and Jones, 1978). Alternative four was implemented in 1975 by authorization of the Harris-Galveston Coastal Subsidence District (HGCSD) by the Texas State Legislature. The HGCSD was authorized to regulate groundwater pumping by issuing 1- to 5-year permits to all major production wells in the district. The objective of awarding the permits, for which fees are collected to fund the district, was to reduce groundwater withdrawal to an amount that would restore and maintain sufficient artesian pressure in the aquifer to halt subsidence (Holzer, 1989). Conversion of water users from groundwater to surface-water sources made available by local water agencies, as encouraged by the HGCSD, has contributed to water-level recoveries and the slowing of the rate of subsidence in coastal areas of the Houston-

Galveston region (Strause, 1984).

The first generally recognized occurrence of subsidence caused by groundwater withdrawal in the United States was in 1933 in the Santa Clara Valley, California (Tolman and Poland, 1940; Ingebritsen and Jones, 1999); subsidence in this formerly agricultural (now largely metropolitan) area eventually affected more than 230 square miles of land (Poland and Green, 1962) and locally reached a maximum of 12.9 feet (Poland, 1977). Initial response to the subsidence included formation of the Santa Clara Valley Water Conservation District (SCVWCD), which was chartered under California law with responsibility for mitigating the groundwater overdraft problem. Subsequently, the SCVWCD constructed groundwater recharge facilities along the valley margins in 1935 and 1936 (Holzer, 1989). The groundwater recharge facilities combined with abnormally high rainfall temporarily halted water-level declines and slowed subsidence during the early 1940s (figure 3 in Poland, 1977), but groundwater withdrawals largely associated with industrial and urban activities following World War II resulted in new groundwater-level declines and associated subsidence (Holzer, 1989; Ingebritsen and Jones, 1999). These new water-level declines led to the recognition that major imports of water were needed to meet long-term water demands in Santa Clara Valley, and the South Bay Aqueduct System was constructed as a result (Holzer, 1989). Groundwater users were encouraged to switch to this new surface-water source by a tax on groundwater pumpage implemented in 1964 that removed the economic incentive to use groundwater (Holzer, 1989). The SCVWCD has since used the approach of lumping all water resources into a common pool and distributing water costs according to water use rather than water source (Holzer, 1989). This approach led to the recovery of water levels in the 1970s (Poland, 1977, figure 3) and the halting of subsidence as of 1974–75 (Poland, 1977).

Groundwater withdrawals can also be reduced by implementing water conservation measures, potentially freeing up water for use in geothermal development. Such measures could include (1) incentive pricing, (2) outdoor watering guidelines and ordinances, (3) landscape guidelines and ordinances, (4) commercial and residential water audits, (5) installation of meters on water connections, (6) retrofit, rebate, and incentive programs, and (7) leak detection and repair programs (Utah Division of Water Resources, 2001). Incentive pricing (for the public supply consumer rather than the groundwater pumper) should be designed to reward efficiency and discourage waste of groundwater resources. The Utah Division of Water Resources (2001) outlines several strategies for accomplishing this goal. Because 67% of residential water is consumed for outdoor use, overall water consumption could be reduced significantly by implementing strategies such as supplying only the amount of water needed by plants to produce maximum growth and maintaining a sprinkler uniformity of 60% (Utah Division of Water Resources, 2001). Requiring xeriscaping through ordinances or legislation (as implemented in Florida, Nevada, and Texas) or through monetary incentives (as implemented in Las Vegas, Nevada, and Glendale, Arizona) can significantly reduce overall water use (U.S. Environmental Protection Agency, 2010). Water audits, metering, retrofitting (such as replacing standard toilets with low-flow toilets), and leak detection and repair are also important ways to reduce groundwater withdrawals by reducing water use (Utah Department of Natural Resources, 2001).

Aquifer Management Recommendations

Best management practices for the basin-fill aquifers used for geothermal development will likely include the application of an assortment of the aquifer management practices summarized above, and will likely take into consideration water pumped from the targeted aquifer for other purposes (municipal, domestic, irrigation). Keeping discharge in basin-fill aquifers used for geothermal development in balance with recharge so the aquifer can be managed using either “safe yield” or “optimal yield” concepts may be the best management practice for avoiding aquifer compaction and associated land subsidence and earth fissure development.

SUMMARY

Land subsidence, the lowering of the Earth’s surface due to subsurface movement of earth materials, can be caused by a variety of processes, but most land subsidence in the United States is associated with aquifer compaction caused by groundwater withdrawal. In basin-fill aquifers, most of the aquifer compaction is due to the slow dewatering and compression of fine-grained sediments. Once the fine-grained units begin to compress and lose porosity, compaction becomes permanent, overall water storage in the basin fill is reduced, and land subsidence occurs. Land subsidence may result in the formation of a subsidence bowl in the vicinity of, but not necessarily centered around, the area of large-scale groundwater withdrawal. As a subsidence bowl develops, various types of land-surface movements occur, usually beginning with vertical settlement, followed by tilting of the land surface, and, finally, horizontal strains in the land surface that can result in the formation of earth fissures. If human development exists within the subsidence bowl, these land-surface movements can result in a variety of potential problems. Geothermal development can and has caused aquifer compaction, such as in Dixie Valley, Nevada, where shallow groundwater withdrawal has occurred; subsidence has not been an issue for geothermal development of deeper aquifer systems in the Basin and Range Province. Land subsidence can also be caused by contraction as fractured rock reservoirs cool, such as in The Geysers geothermal area of California, but this mechanism is of less concern in deep sedimentary basin settings.

Land subsidence can be avoided by re-injecting all production water back into the aquifer it was withdrawn from so that pressure changes are minimized. Where land subsidence associated with geothermal energy production does occur, it can be reduced through monitoring combined with aquifer management. Monitoring may include the use of InSAR, use of LiDAR, and establishing and monitoring a high-precision GPS/GNSS (Global Navigation Satellite System) network of survey benchmarks.

With fractured rock aquifers at depth below thick unconsolidated deposits in deep sedimentary basins, the potential for subsidence can be mitigated by pumping all geothermal fluids back into the aquifer they are pumped from after heat extraction to prevent aquifer compaction. Because of the thick, overlying unconsolidated deposits and the low compressibility of sediments at depth, thermal contraction of the fractured rock aquifer is unlikely to result in significant land surface subsidence. Monitoring for subsidence and implementing other aquifer management tools may still be considered in fractured-rock settings.

To avoid land subsidence in unconsolidated basin-fill settings, aquifers must be managed to balance groundwater recharge and groundwater discharge at both local and basin-wide scales. Ways to accomplish this goal include (1) ensuring all water used for geothermal energy extraction is pumped back into the aquifer, (2) replacing water lost from the aquifer during geothermal energy development by increasing groundwater recharge to the basin-fill aquifer through conjunctive management of groundwater and surface-water resources and importation of water from other basins, (3) dispersing high-discharge wells to reduce localized land subsidence, and (4) reducing overall groundwater withdrawals in the basin. Best management practices for the basin-fill aquifers used for geothermal development will likely include the application of an assortment of the aquifer management practices, and will likely take into consideration water pumped from the targeted aquifer for other purposes (municipal, domestic, irrigation). Keeping discharge in basin-fill aquifers used for geothermal development in balance with recharge may be the best management practice for avoiding aquifer compaction and associated land subsidence and earth fissure development.

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APPENDIX

Techniques for Monitoring for Land Subsidence

Introduction

The potential for land subsidence exists for any process involving large-scale extraction of groundwater, including geothermal energy development of shallow aquifers. Because it is easier to implement best management practices to reduce land subsidence if the problem is identified early during the life of the project, Lund and others (2012), from which this section is excerpted, recommend that monitoring for land subsidence be an integral part of ongoing operations where net withdrawal of groundwater occurs and there is a risk of impact to infrastructure associated with human development. Three methods can help determine (1) the existence and extent of subsidence, (2) the rate and variability of land subsidence within the subsidence bowl if subsidence is occurring, and (3) the locations of any earth fissures associated with the subsidence, if subsidence is occurring. The three methods are interferometric synthetic aperture radar (InSAR), light detection and ranging (LiDAR) technology, and establishing and monitoring a high-precision GPS/GNSS (Global Navigation Satellite System) network of survey benchmarks sited using the results obtained from the preceding two technologies. Initially, until significant subsidence is detected, InSAR may be the most cost-effective monitoring method.

InSAR

Synthetic aperture radar (SAR) is a side-looking, active (produces its own illumination) radar imaging system that transmits a pulsed microwave signal toward the Earth and records both the amplitude and phase of the back-scattered signal that returns to the antenna (Arizona Department of Water Resources [ADWR], no date). Interferometric synthetic sperture radar (InSAR) is a technique that utilizes interferometric processing to compare the amplitude and phase signals received during one pass of the SAR platform (typically Earth-orbiting satellites) over a specific geographic area with the amplitude and phase signals received during a second pass of the platform over the same area, but at a different time (ADWR, no date). Surface displacement measurements of less than a half inch over an area of several tens of square miles have been routinely demonstrated in subsidence applications using InSAR techniques. More advanced applications of InSAR can measure local displacement rates on the order of a few millimeters per year (Skaw, 2005). The amount and pattern of deforma¬tion in an interferogram are shown by using the color spectrum to indicate areas of greater or lesser deformation.

The ADWR routinely uses InSAR to monitor several active land subsidence basins around Arizona (ADWR, no date), and has also been used to look at active land subsidence in Cedar Valley, southwestern Utah (Lund and others, 2012). Repeated InSAR applications show the spatial extent, deformation rates, and time-series history of the basins. The subsidence measurements are assisting ADWR in its efforts to educate the public and local government agencies on the reality and severity of the land-subsidence hazard. County and local governments have realized the importance of InSAR to their own monitoring efforts, and have entered into agreements with ADWR to ensure that SAR data are collected, processed, and analyzed for areas critical to each group's monitoring needs (ADWR, no date). In addition, water resource managers, engineers, hydrologists, geologists, and other scientists have used InSAR data to identify and evaluate areas of subsidence, uplift, earth fissures, faults, and other features related to groundwater mining (Skaw, 2005).

For subsidence monitoring, InSAR's chief advantage is that it offers wide-area continuous coverage at a reasonable level of accuracy at better cost efficiency than traditional surveying techniques (Skaw, 2005; note Skaw reports measurements in the metric system). A standard InSAR frame covers an area of approximately 10,000 km^2 (~3861 mi^2) at a pixel resolution of about 25 meters (~82 ft)—or 8,000,000 discrete point measurements within the 100 km by 100 km (62 mi by 62 mi) frame. The cost to perform static GPS/GNSS surveys with the same vertical accuracy but at 1/1000th the resolution would conservatively cost $500,000 for the two surveys required to measure change, making the cost per point measurement to produce an InSAR change map using currently available satellite data less costly by many orders of magnitude than conventional surveying technologies (Skaw, 2005). In short, InSAR provides an accurate and cost efficient way to determine the horizontal and vertical extent of land subsidence and subsidence rate variability within a subsiding area to an accuracy of about 1 centimeter.

LiDAR

LiDAR is a remote sensing laser system that measures the properties of scattered light to accurately determine the distance to a target (reflective surface). LiDAR is similar to radar, but uses laser pulses instead of radio waves, and is typically collected from planes or helicopters. LiDAR produces a rapid collection of points (typically more than 70,000 per second) that results in very dense and accurate elevation data over a large area (National Oceanic and Atmospheric Administration [NOAA], 2008). The resulting highly accurate, georeferenced elevation points can be used to generate three-dimensional representations of Earth's surface and its features (NOAA, 2008). After processing, LiDAR data can be used to produce a "bare-earth" terrain model, in which vegetation and manmade structures are edited out. LiDAR has several advantages over traditional photogrammetric methods; chief among them are high accuracy, high point density, large coverage area, and the ability to resample areas quickly and efficiently, which creates the ability to map discrete elevation changes over time at a very high resolution (NOAA, 2008).

LiDAR is used extensively in base mapping, natural resource management, floodplain mapping, transportation and utility corridor mapping, urban planning, and in many kinds of geologic investigations. For example, LiDAR has been used to identify previously unrecognized faults (Harding and Berghoff, 2000) and landslides (Oregon Department of Geology and Mineral Industries, 2006; Schulz, 2007), and to measure subtle amounts of uplift at Mount St. Helens (National Aeronautics and Space Administration, 2004; U.S. Geological Survey, 2004). LiDAR offers two important advantages over conventional aerial photography for mitigating land-subsidence and earth-fissure hazards. First, high-resolution, bare-earth LiDAR images can be used to identify and map currently unrecognized earth fissures that are not apparent on conventional aerial photography. Second, repeat LiDAR surveys can be used to generate accurate displacement maps to define the boundaries of subsidence areas, and may allow monitoring of existing earth fissure growth and new fissure formation.

LiDAR costs vary based on project specifications. A 500-square-mile project area with 3-meter (~9.8 ft) point spacing over flat to moderate terrain may cost $200-300 per square mile (Fugro Earthdata, Inc., no date; note Fugro Earthdata reports some measurements in the metric system and others in the English system). LiDAR acquired in 2006 for the Wasatch Front area cost $141,000 for ~1300 square miles (~$108/sq. mile) (Rick Kelson, Utah Automated Geographic Reference Center, verbal communication, 2011). These estimates assume a contiguous, roughly rectangular project block. The location, type of terrain, vegetation cover, and time of year can also affect pricing (Fugro Earthdata, Inc., no date).

High-Accuracy GPS/GNSS Survey Network

Following acquisition of InSAR and LiDAR data to better define the boundaries of subsiding areas and earth fissure locations, that information should be used to establish a network of high-accuracy GNSS survey monuments in areas of subsidence and fissure "hot spots." Periodic resurveying of the benchmarks using the U.S.-based GPS system and other available GPS systems would permit repeated high accuracy (1–5 mm horizontal/vertical) subsidence monitoring in areas most relevant to best aquifer management practices and hazard mitigation.

The National Geodetic Survey (NGS) has established permanent GPS monitoring stations in subsiding areas of some western states. If an area of interest lacks permanent monitoring stations, the NGS should be contacted to determine the extent of their interest and willingness to install permanent GPS monitoring stations.