

LAND SUBSIDENCE AND EARTH FISSURES IN ARIZONA



NOTICE
EARTH FISSURE
POSSIBLE ROAD HAZARD
USE CAUTION

35
M.P.H.

Research and Informational Needs
For Effective Risk Management

By
Arizona Land Subsidence Group (ALSG)

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Cover page:

Sign erected in 2006 warning motorists of earth fissure hazard across Dragoon Road in Cochise County near the Apache Power Plant. (photo by Ray Harris)

PREFACE

The Arizona Land Subsidence Group (ALSG) was originally created by interested geological and engineering professionals as a technical forum to discuss the state of knowledge regarding subsidence and earth fissures in Arizona, and to share information and experiences. The Arizona Geological Survey (AZGS) subsequently requested that the ALSG serve as a technical advisory committee for their State-mandated Earth Fissure Mapping Program. The ALSG is a voluntary collaboration of professionals that includes representatives from AZGS, the Arizona Department of Water Resources (ADWR), the Arizona Department of Environmental Quality (ADEQ), the Flood Control District of Maricopa County (FCDMC), the United States Geological Survey (USGS), Pinal County, the University of Arizona, Arizona State University, various utilities serving Arizona, and consulting geoscience and engineering specialists.

This white paper has been created by ALSG to help educate stakeholders and decision makers by describing the geological features and processes of land subsidence and earth fissures, and the hazards they create. This paper presents the current and future technical needs that exist in terms of basic knowledge, available data, and the state of professional practice.

EXECUTIVE SUMMARY

Land subsidence and earth fissures have been part of the landscape of southern and south central Arizona for at least the past seventy years. With urban growth now expanding into former agricultural and undeveloped desert lands, the geologic hazards related to subsidence and fissures are being steadily encroached upon with detrimental and costly impacts. There is a growing need for information and tools to deal with these hazards.

Due to the regional impacts of subsidence and earth fissures, policy-makers are faced with making informed risk management decisions to mitigate impacts of these hazards on public safety and welfare. Unfortunately, a sound technical framework for addressing subsidence-related geological hazards is currently lacking and some Arizona citizens are at risk.

Legislation enacted in Arizona during 2006 targets the identification and public disclosure of earth fissures with the implied intent of mitigating hazards by avoidance. Once maps are prepared and released, however, best practices and possible statutory changes will need to be identified and implemented by state and local policy makers. Currently, there are no technical guidelines or protocols for defining fissure zones or for developing nearby lands. In defining fissure zones, potential concerns include: development restrictions (i.e., building and infrastructure setbacks from the fissure); mitigation techniques; and potential future fissure development. With few exceptions little is being done to (a) gain knowledge of the origin, mechanics, and behavior of land subsidence and earth fissures; (b) identify areas of potential earth fissure development and the magnitude of effects; (c) address groundwater withdrawal in such a way as to impede future earth fissure formation; and (d) develop engineering practices and mitigation measures needed to address associated hazards and to substantially reduce risks.

Arizona's new Earth Fissure Mapping Program represents an important first step in meeting the State's responsibility for public safety and welfare. What is needed now is a comprehensive program to address earth fissures phenomenologically. It is important to know where fissures will next appear; how they evolve and how fast they propagate; what the impact to structures/infrastructure is; and what engineering solutions can be applied to reduce risks. If Arizona limits its efforts to mapping earth fissures, we can anticipate more damage to structures and infrastructure, with related economic losses, and, more importantly, a burgeoning threat to human health and safety.

As groundwater mining continues, land subsidence and earth fissures will continue to threaten the Arizona public. These geohazards can result in damage to structures designed and constructed to house, serve, and protect the general public as well as public infrastructure including roads, dams, canals, bridges, and utilities. A few specific examples of damage and human safety threats are bulleted below.

- Luke Air Force Base and Vicinity (1992) - Dysart Drain flow reversal with 100 homes flooded, base closure for 3 days, and about \$3 million in damage.

- CAP Canal in Scottsdale (1999 to present) – Up to 1.5 feet of subsidence threatening the canal's maximum flow capacity, resulting in raising canal lining over many years at a cost of more than \$1 million.
- Loop 202 Red Mountain Freeway (2006) – Earth fissure crossing freeway cost \$200,000 to mitigate and no one knows if the measures implemented will work.
- Foothills Residences, Santan Mountains (2006-07) - Fissures opened almost instantaneously after storms, opening dangerous gaping holes in residential yards, crumbling driveways, exposing underground utilities, and destabilizing adjacent lands.
- McMicken Dam (2003-06) – Earth fissures discovered near the dam, requiring removing/replacing a portion of the dam at a cost of several million dollars.

These problems are real and it is only a matter of time before they leave the realm of nuisances and economic costs and enter the realm of human casualties in the form of injury or death (On July 21, 2007, reactivation of the infamous Y-crack near Queen Creek was responsible for the death of a horse that was engulfed in the rapidly widening fissure.).

Currently, geologists and engineers lack adequate field tools or analytical methods to determine where a narrow earth fissure crack will present itself or when that fissure will erode and enlarge (perhaps overnight) into a dangerous chasm. At present, the only mitigation strategy is to know exactly where fissures are so developers can avoid them. This is not always possible, however, and, what is more does nothing to address pre-existing structures. Site-specific mitigation measures are mostly empirical, untested, and do not assess risk. Risk assessment and mitigation strategies for protecting facilities from damage must be researched and developed.

ALSG offers the following recommendations to address these issues:

1. Encourage research into the processes that cause horizontal movement, tension, cracks, and fissuring by establishing subsidence and earth fissure research centers at Arizona's state universities.
2. Establish a long-term monitoring program to track the occurrence, evolution, and distribution of subsidence and fissuring.
3. Create a distributed network that can integrate inter-operable online sources for communicating data and new strategies for handling subsidence-related hazards. The University of Arizona's, online Geotechnical, Rock and Water Resources Library is a model to emulate.
4. Partner with neighboring states who are experiencing similar problems. Mitigation strategies recommended for the Las Vegas Valley can provide valuable insight for Arizona.
5. Integrate new knowledge into subsidence and earth fissure publications and mapping products.

Dedicated scientific research is needed to understand the processes of subsidence and earth fissuring and develop engineering practices to identify and mitigate associated hazards. Arizona needs local and state governmental leaders, business leaders, and community activists to step forward and accept a leadership role here. At present, the best that the geoscience community can do is advise against building near earth fissures. This, of course, does little to help land and home owners whose property values are undermined by the presence of nearby fissures. Research and data gathering offer the best hopes for optimal land utilization while providing a rational way to protect facilities and property owned by Arizonans.

LAND SUBSIDENCE & EARTH FISSURES IN ARIZONA

1 INTRODUCTION

Land subsidence and earth fissures have been observed for at least the past seventy years in southern and south-central Arizona. With urban growth now expanding into former agricultural and undeveloped desert lands, the geologic hazards related to subsidence and fissures are being steadily encroached upon with detrimental and costly impacts. As public awareness of the presence of these geological features and processes grows, so too does the need for information and tools to identify and mitigate the associated hazards.

The Arizona Land Subsidence Group (ALSG) was originally created by interested geological and engineering professionals as a technical forum to discuss the state of knowledge regarding subsidence and earth fissures in Arizona, and to share information and experiences. The Arizona Geological Survey (AZGS) subsequently requested that the ALSG serve as a technical advisory committee for their State-mandated Earth Fissure Mapping Program. The ALSG is a voluntary collaboration of professionals that includes representatives from AZGS, the Arizona Department of Water Resources (ADWR), the Arizona Department of Environmental Quality (ADEQ), the Flood Control District of Maricopa County (FCDMC), the United States Geological Survey (USGS), Pinal County, the University of Arizona, Arizona State University, various utilities serving Arizona, and consulting geoscience and engineering specialists.

The chief benefit of the ALSG to date is a universal recognition amongst its participants of serious deficiencies regarding our scientific understanding of the mechanisms of ground subsidence and earth fissure formation. Major work is needed to improve modeling, monitoring and mitigation of these geohazards. Shortcomings in these areas are compounded by the lack of data and by a ready means to acquire data for performing geological analyses and designing mitigation techniques. Due to the regional impacts of subsidence and earth fissures, policy makers are faced with making risk management decisions on behalf of public safety and welfare. But for policy makers to make informed decisions and develop effective policy, they must be guided by a scientific and engineering community well-versed in the formative processes of earth fissures and with experience mitigating the associated hazards. A sound technical framework for addressing hazards is lacking and some Arizona citizens are at risk.

Once the technical deficiencies were recognized, the ALSG turned its attention to identifying effective means of implementing research, compiling relevant information, and disseminating data. It quickly became obvious that Arizona's regulatory agencies, private consultants, and utility corporations are not the logical choice to administer the long-term funding, structuring or implementation of basic research. This is the function of a research institution or university; organizations with ready access to qualified scientists and engineers, and the capacity to seek financial and technical support from the community at large.

The following discussion is designed to help educate stakeholders and decision makers by: (a) describing the geological features and processes of land subsidence and earth fissures; (b) detailing the nature of associated geologic hazards; (c) addressing the technical needs that currently exist; and (d) matching technical needs with resources of government agencies and research institutions or universities.

2 LAND SUBSIDENCE AND EARTH FISSURES AS A GEOLOGIC PROCESS

Land subsidence and earth fissure formation in Arizona are the result of substantial groundwater withdrawal from aquifers in sedimentary basins. Subsidence frequently results in bowl-shaped depressions, with loss of elevation greatest in the center and decreasing towards the perimeter. Earth fissures, the most spectacular manifestation of subsidence-related phenomena, occur about the margins of alluvial basins, near exposed or shallow buried bedrock, or over zones of changing alluvial characteristics (facies) in basins where differential land subsidence has occurred.

Subsidence

Since 1900, groundwater pumping in south-central Arizona for irrigation, mining, and municipal use has greatly outstripped recharge, in some places by a factor of 500 times. (Schumann and Cripe, 1986). A total area of more than 3,000 square miles is affected by subsidence, including the expanding metropolitan areas of Phoenix and Tucson and rapidly growing northern Pinal County (Carpenter, 1999). In the past, groundwater was withdrawn primarily from agricultural irrigation wells. Today, municipal wells also extract groundwater, and as a result, groundwater levels continue to decline in many areas. In places where agriculture is being phased out in favor of residential and commercial users and where groundwater recharge programs using Central Arizona Project (CAP) Colorado River water occur along with use of reclaimed wastewater, groundwater levels are stable or on the rebound. In Arizona, however, groundwater still accounts for 40% of all water use.



Fig. 1 - Differential displacement along fissure near Hunt Hwy in Pinal County (photo by Ken Euge)



Fig. 2 - Irrigation canal in west Maricopa County broken and offset by subsidence (photo by L. Fellows)

Land subsidence was first verified in south-central Arizona in 1948 (examples of differential movement from land subsidence are shown in Fig. 1 and Fig. 2). By the late 1960s, studies showed substantial subsidence near Eloy, at Higley Road south of Gilbert, and at Luke Air Force Base. In general, the areas of greatest subsidence corresponded with areas of greatest water-level decline (Schuman and Poland, 1969). By 1977, an area of nearly 625 square miles had subsided around Eloy, with maximum subsidence on the order of 12.5 feet. Stanfield

showed subsidence over 425 square miles, with a maximum subsidence of 11.8 feet (Laney et al., 1978). Near Queen Creek, an area of almost 230 square miles subsided more than 3 feet. In northeast Phoenix, as much as 5 feet of subsidence occurred between 1962 and 1982.

The relationship between groundwater-level decline and subsidence in Arizona's sedimentary basins is complex and varies within and between basins as a function of total aggregate thickness, composition, and compressibility. In the Harquahala Plain, only about 0.6 feet of subsidence occurred in response to about 300 feet of water-level decline; in contrast, near Willcox more than 5 feet of subsidence occurred in response to just 200 feet of water-level decline (Holzer, 1980; Strange, 1983; Schumann and Cripe, 1986). By 1992, ground-water level declines of more than 300 feet generated land subsidence of as much as 18 feet about 20 miles west of Phoenix on and near Luke Air Force Base (Carpenter, 1999).

Records of land subsidence in southern Arizona are spotty. Accurate, long-baseline level surveys provide some historical records of land subsidence. The advent of Global Positioning Systems (GPS) facilitates some more recent studies of subsidence. Current state-of-the-practice measurements of land subsidence are extracted from time-series satellite radar images. While images and GPS data provide spatially dense measurements that are accurate over large areas (earliest data are from 1992) only subsequent subsidence can be measured. And, unfortunately, image data are expensive and not readily available for many affected areas of Arizona.

Earth Fissures

Earth fissures are cracks, seams, or separations in the ground caused by tensional forces related to differential land subsidence (Fig. 1 and Fig. 3). As related to groundwater pumping, tensional forces tend to occur (though not always) in transition areas between subsidence zones and more rigid underground formations (e.g., bedrock) where surficial sediments experience differential settling. The difference in magnitude of subsidence across transition areas produces down-drag and tensional forces in the sediment column. Tensional cracks (i.e., earth fissures) occur where the sediment properties and stresses result in a subsurface rupture or separation.



Fig. 3 - Incipient fissure cracking near Bowie, Arizona (photo by Ken Euge)

The formation of Basin and Range physiography in southern and south-central Arizona results in steeply sloping bedrock surfaces that extend surface-ward from great depths. These bedrock surfaces may be buried beneath sediment and are generally not reflected in the surface morphology or topography. Nonetheless, bedrock plays a major role in controlling the location and geometry of many subsidence zones and thereby greatly influences the formation of most earth fissures.

Along the perimeter of a subsidence bowl, earth fissures commonly exhibit characteristic and similar surface expressions of orientation, length and width. In general, fissures are discrete rupture features with vertical offsets across the fissure of less than a foot. While the surface trace of a fissure can be miles long and the fissure might extend to depths of hundreds of feet, they are rarely more than a few feet wide. Sometimes, subsurface geometry can result in a “Y” shaped network of fissures.

Fissure Gullies

Because they commonly parallel nearby mountain fronts, earth fissures cut across surface drainage features. Surface runoff or flow intercepted by an earth fissure has a vertical or near-vertical pathway to the subsurface groundwater table. The high gradient contributes to erosive forces that move sediments downward into the fissure. As near-surface sediments are transported downward, erosion and caving at the surface creates a gully feature. The volume of water, erodability of sediments, size of the fissure rupture, and other geohydrologic parameters yield a unique result for each fissure. Resulting gullies can vary from slightly eroded fissures to gullies that are tens of feet wide and tens of feet deep (Fig. 4 and Fig. 5).



Fig. 4 - Rogers fissure in the Harquahala Plain, central Arizona (photo by Ray Harris)



Fig. 5 - Fissure gully near Picacho, Arizona (photo by S.R. Anderson, USGS)

Fissure gullies develop over time as intercepted runoff drains into a fissure and drainage patterns change in the affected area (the time factor here is not well constrained and is probably a complex function of fissure orientation, local topography, and precipitation volume and rate). Erosion tends to contour the fissure surface so that over time the fissure assumes the appearance of a drainage gully; this transformation may impede identification of older, inactive fissures. Additionally, erosion by channelized waters can enlarge fissure gullies over time producing an erosion bowl that can look like a localized subsidence feature.

In agricultural areas, fissures and fissure gullies are often obscured by cultivation. Reactivation of fissures can recur, only to be obscured again by cultivation. In some cases, farmers periodically fill fissures with soil and other materials because the gully formation processes are persistent. Such fissures are commonly known only to the farmers who cultivate the fields.

Gullies can also appear to form in the course of a single storm event; while in reality, the formative process may be decades in the making. In August 2005, monsoon runoff pooled along the trace of a fissure near the intersection of Happy Road and 195th Street, south of Queen Creek in southeast Maricopa County. Runoff entered the fissure and overnight created a gully 15 ft wide and up to 25

ft deep, cutting across several driveways, blocking access and exposing buried utilities (Fig. 6 and Fig. 7). The location of this fissure had been known for decades and efforts to remediate with backfill clearly failed.



Fig. 6 & 7 - Photos taken on two consecutive days south of Queen Creek, Arizona. The fissure gully in the second photo formed during a single, heavy rain storm (photos from AGIC newsletter, 2007).

3 IMPACTS OF LAND SUBSIDENCE AND EARTH FISSURES

Land subsidence and earth fissures will continue to recur in Arizona, presenting a danger to the public. Subsidence can measurably change or reverse basin gradients causing localized flooding and adversely impact or even rupture long-baseline infrastructure such as canals, sewer systems, gas lines and roads, leading to expensive repairs. A change in the gradient of a sewer line, storm drain, or aqueduct can interrupt flow causing it to slow, clog, overflow or reverse. Valley-wide subsidence and local subsidence bowls do not present the most significant present or potential hazard (Bell and Price, 1993). Formation of subsidence bowls, however, triggers vertical and horizontal differential movement in unconsolidated basin-fill sediments. This in turn leads to the greatest subsidence-related hazard, the formation and growth of earth fissures!

Hazards associated with earth fissures (Table 1) are generally more local and include damage to homes and buildings, roads, dams, canals, sewer and utility lines, as well as providing a conduit for contaminated surface water to rapidly enter groundwater aquifers.

Table 1. Hazards Directly Associated with Earth Fissures	
<ul style="list-style-type: none"> • Cracked or collapsing roads • Broken pipes & utility lines • Damaged or breached canals • Cracked foundation/separated walls • Loss of agricultural land • Livestock & wildlife injury or death 	<ul style="list-style-type: none"> • Severed or deformed railroad track • Damaged well casing or wellhead • Disrupted drainage • Contaminated groundwater aquifer • Sudden discharge of ponded water • Human injury or death

(After Pewe, 1990; Bell & Price, 1993; and Staff, 1993)

Abridged Case Studies of the Impact of Subsidence and Earth Fissures

Since the 1950s the formation of subsidence-related earth fissures has greatly increased in Arizona, with hundreds now identified in the alluvial basins of southern Maricopa, western Pinal, eastern Pima and northern Cochise Counties; the majority cropping out in Pinal and Maricopa Counties (Gelt, 1992). The following abridged case studies describe some of the historic problems caused by subsidence and earth fissures in Arizona.

Earth fissures occur in three areas of differential subsidence on and near the Luke Air Force Base. Subsidence near the base led to flow reversal in a portion of the Dysart Drain, an engineered flood conveyance. On September 20, 1992, surface runoff from four inches of precipitation caused the sluggish Dysart Drain to spill over flooding the base runways, damaging more than 100 homes, and forcing the base to close for 3 days. Total damage was on the order of \$3 million (Schumann, 1995).

Sections of the CAP canal in Scottsdale traverse an area that has subsided up to 1.5 feet over a 20-year period, threatening the canal's maximum flow capacity. In response, CAP raised the canal lining 3 feet over a one-mile segment of affected area at a cost of \$350,000. A second and much larger subsidence area was later identified near the Scottsdale Airpark. Plans for raising the canal lining will cost an estimated \$820,000. Recently, a third subsidence area has been identified east of the Scottsdale Airpark in the Scottsdale WestWorld area. This happened in spite of the fact that during the original design phase, CAP Engineers showed considerable foresight in mapping a route to minimize the likelihood of encountering zones of subsidence (Gelt, 1992).

The effect of subsidence on well casings can be curious as well as destructive. As land subsides, casings from deep wells may seem to rise into the air, as if they were growing from the ground. The casing is not rising, of course, but the earth is sinking. Well cases can also collapse under the pressure of subsidence necessitating expensive repairs and even the replacement of wells (Gelt, 1992).

Land surveyors experience difficulties because of subsidence. They may have difficulty closing traverses in certain areas of the state. Bench marks in subsidence areas may settle while those

on bedrock do not. Survey data quickly become obsolete. Baseline elevations have been modified numerous times (Gelt, 1992) leading to a costly elevation modernization program in Arizona.



Fig. 8 - Earth fissure damage to residence in Nevada (photo by John Bell)

Compaction from land subsidence is, to a large degree, an irreversible process. And once the sediments compact, the storage capacity of the aquifer is permanently diminished. Even if the water table rises, the land surface does not rebound substantially and the potential for aquifer recharge is reduced.

Estimates of permanent groundwater storage losses in the Lower Canada del Oro sub-basin in Pima County are on the order of 4 million cubic meters (Pool, 1999).

Fissures may intercept surface runoff within surface drainages during floods or accidental fluid releases. The open and pervasive nature of fissures is such that they potentially provide a ready conduit for the delivery of contaminants to subjacent aquifers. By way of example, fissures northwest of Snowflake, Arizona, (probably caused by geologic processes of salt dissolution deep in sedimentary rock) captured about 6,000 acre-feet of paper mill effluent water in 1960 and an additional 1,500 acre-feet of effluent water in 1984.

The problems encountered with subsidence and earth fissures in Arizona will increase as groundwater continues to be withdrawn at unsustainable levels. More damage to structures and infrastructure can be expected with ever increasing economic losses, and, more importantly, a burgeoning threat to human health and safety, too. Fig. 8 and Fig. 9 show the all too real effects of the confluence of earth fissures and development. Las Vegas has one of the worst earth fissure problems in the country. The Windsor Park subdivision in North Las Vegas was so severely impacted by fissures that 240 homes were repaired or replaced at a cost of \$12 to \$13 million (Bell, et al., 1992). The involvement of local governmental and business leaders, along with the industries and engineers that serve our public by designing and constructing infrastructure is required to mitigate the impact of subsidence-related phenomenon.



Fig. 9 – Fissure gully crossing below above-grade pipe at a mine facility in Nevada (photo by AMEC presented in 2004 ADOT workshop)

Cost of Mitigation

In constructing new facilities or infrastructure, fissures must either be avoided or mitigated. Nine fissures were crossed during construction of the CAP canal system, necessitating corrective measures. Several methods were evaluated, from bridging fissures with gravel to rerouting drainage. Using gravel to bridge threatening fissures was only marginally successful. The most effective method combined sealing the fissure and rerouting drainage to prevent surface flows



Fig. 10 - Central Main Lateral Canal of the CAP crossing the Picacho earth fissure (fissure shown as a dark line) (photo by Michael Carpenter)

from eroding fissures into large, destructive gullies. Canal linings were also constructed with steel reinforced concrete to bridge fissures that re-opened (Fig. 10).

Similar measures were recently undertaken where the Loop 202 Red Mountain Freeway crosses existing earth fissures in East Mesa (Fig. 11). In addition to a steel-reinforced concrete roadway section, builders placed layers of densely packed earth, geotextiles and geogrid screens to bridge a 65-foot wide roadway path above fissures at a \$200,000 cost to the state. Drainage pipes alongside the freeway were also cased to prevent possible future damage.

In 2003, FCDMC studies of earth fissures and surface flow conditions indicated a high probability for further earth fissure development near the south end of McMicken Dam near the foothills of the White Tank Mountains west of Phoenix. The engineered solution constructed in 2006 involved removing that part of the existing dam segment situated in an area that held a high potential for

earth fissures. The removed segment of the dam was replaced with a realigned soil-cement dam segment complemented by a surface water basin located outside of the susceptible area. The total project cost was on the order of several million dollars. Other county flood retention structures are located in areas of significant subsidence and are in various stages of mitigation.

Such mitigation measures are not typical. More often an old fissure is backfilled with dirt and debris which does little to mitigate the hazard and serves only to conceal the feature from prospective land or home buyers. This was the case along the foothills of the Santan Mountains when in 2005 heavy local rains washed construction debris down into the buried voids, left gaping holes in yards, cut across driveways, and exposed underground utilities and destabilized adjacent lands. The emotional toll on the landowners far exceeds the cost of refilling the holes. When asked to comment about the earth fissures in her Santan foothills neighborhood, homeowner Joan Etzenhouser said, "I didn't know what it was. I've had people come out, confirm that I have fissures. And I have one running under my home. And I don't know what effect it has on the value of the property. I suspect it's not a good thing."



Fig. 11 – Earth fissure cracks below Loop 202 Freeway construction in Mesa, AZ (photo by Ray Harris)

4 IMPACTS ON SUSTAINABILITY AND GROWTH IN ARIZONA

The CAP canal system completed in the mid 1980s provided Arizona with a supplemental water supply that lessened the demand and overdraft of groundwater, slowing subsidence and fissure development. This surplus could diminish in the future leading to renewed groundwater mining and thereby increasing the potential for new subsidence and fissure occurrence.

According to the University of Arizona's *Climate Assessment for the Southwest* (CLIMAS), an expanding population and a warming climate are converging to drive up water demand (Lenart, 2006). Moreover, Arizona is prone to multi-year and multi-decade drought as a result of long-term variations in Pacific Ocean circulation and, perhaps, Atlantic Ocean circulation, too (Garfin, 2006). Between 2005 and 2035, projections for Maricopa, Pinal and Pima counties show the population doubling. The estimated 9.6 million people in the three-county area will contribute to a projected near doubling of water demand during that same time frame. From 2000 to 2050 the state population is expected to triple, adding even more pressure on our finite water resources (Fig. 12).

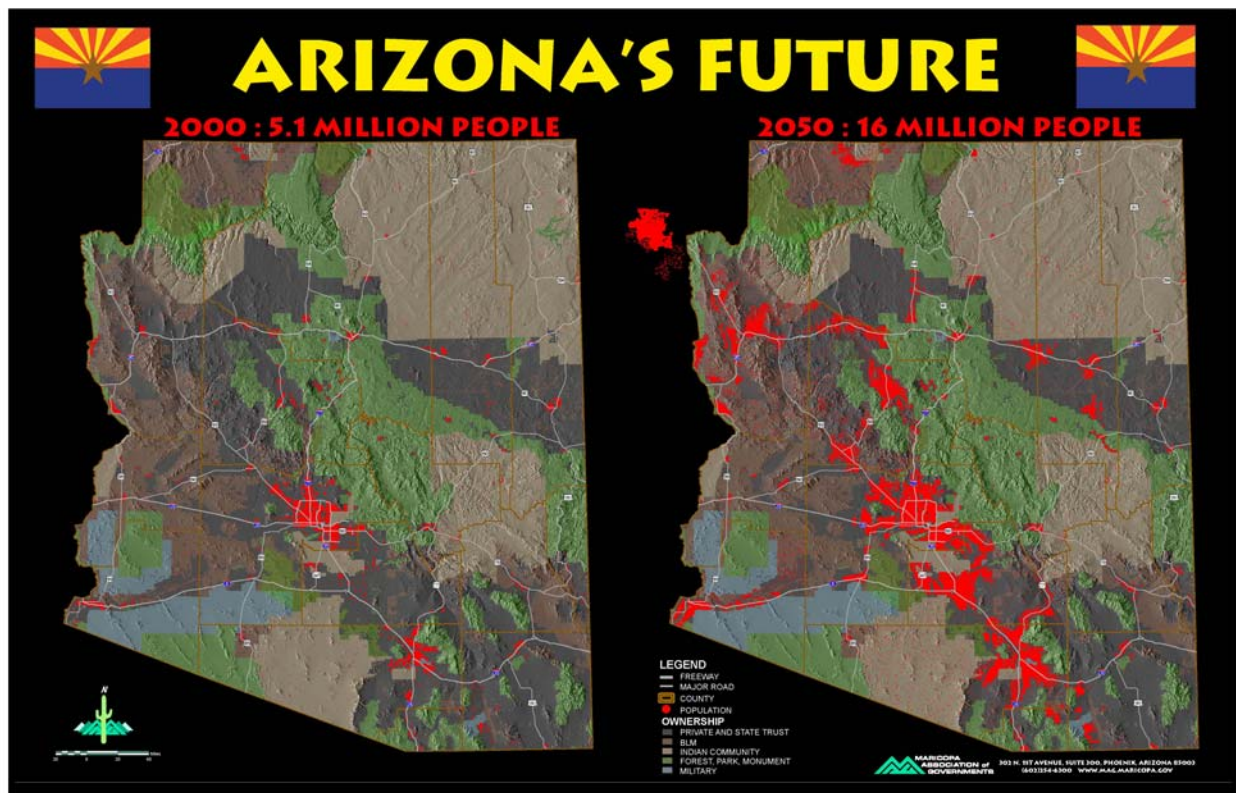


Fig. 12 – Arizona population growth projections: 2000 to 2050
(source: Maricopa Association of Governments)

CLIMAS notes that given current water resources, the central Arizona region can support only about 8.5 million people. Beyond that population there is a need to secure additional non-potable sources such as agricultural water and wastewater effluent. Securing additional water sources, including from the Colorado River allocations to agriculture, is one possible alternative. Water managers are pursuing the prospect of treating wastewater effluent, among other sources, to keep up with the growing demand for potable water. If drought conditions continue

and surface water supplies for the state diminish, local communities are expected to pump additional groundwater. This in turn could lead to renewed subsidence and fissuring in existing subsidence areas, and the advent of new subsidence bowls in presently undeveloped basins that experience future development.

Alternately, new home construction may be curtailed by concerns about subsidence-related groundwater use. Pima County is considering a new policy that could limit housing additions outside of established municipalities while requiring water conservation technology in new houses and restricting digging new wells (Metzler, 2006). The County is considering taking into account the impact of any groundwater pumping on the surrounding areas, including existing wells and the natural environment, when deciding whether to grant a re-zoning or a comprehensive plan (208 Plan) amendment. Because shallow groundwater pumping is limited due to ecosystem impacts, deep wells and a robust conservation program may be the only viable options.

The State of Arizona has historically implemented rules that require new subdivisions and communities to demonstrate 100-year availability and legal authority of water supplies. Recent growth projections for the state have led lawmakers to require local communities to plan and prepare for drought and associated water supply issues. Additionally, the Arizona Department of Water Resources (ADWR) is in the final rulemaking process for revisions to the Assured and Adequate Water Supply for the Pinal Active Management Area (AMA) due largely to the projected shift from agricultural to residential land use. ADWR is also in the process of reviewing public comments for the upcoming *Draft Substantive Policy Statement: Hydrologic Studies for Assured and Adequate Water Supply Applications*, which would apply to the entire state.

Because Arizona's water suppliers are planning for possible enhanced groundwater pumping in the future, and because there is a mechanistic link between groundwater pumping, land subsidence and fissuring, the ALSG strongly recommends that Arizona's stakeholders and decision makers take action now to protect home and property owners from these geologic hazards that could worsen in the future.

5 ADDRESSING EARTH FISSURES IN ARIZONA

Land subsidence and earth fissures are important issues for the State of Arizona. That legislative leaders recognized this is evinced by House Bill (HB) 2639 passed in 2006. Arizona Revised Statute 27-152.01 (created by HB2639) provides the Arizona Geological Survey (AZGS) with funds for mapping earth fissures throughout the state; AZGS is charged with updating their earth fissure database every five years. AZGS began their earth fissure mapping program in September 2006. In June 2007, they released a report and 1:250,000 scale earth fissure planning maps for Cochise, Maricopa, Pima, and Pinal counties (Allison and Shipman, 2007). Subsequently, the AZGS mapping team began detailed mapping of the first of 22 select study areas using high resolution, global positioning system (GPS) receivers. As mapping of study areas is completed, AZGS will submit earth fissure data to the Arizona Department of State Lands (ADSL). The Resource Analysis Division at ADSL is mandated to post earth fissure maps online within 90 days of receiving data from AZGS. Additionally, the Arizona Department of Real Estate (ADRE) is to make these maps available to the public upon request.

This legislation targets the identification and public disclosure of earth fissures with the implied intent of mitigating hazards by avoidance. Once maps are prepared and released, however, best practices and possible statutory changes will need to be identified and implemented by

state and local policy makers. Currently, there are no technical guidelines or protocols for defining fissure zones or for developing nearby lands. In defining fissure zones, potential concerns include: development restrictions (i.e., building and infrastructure setbacks from the fissure); mitigation techniques; and potential future fissure development. With few exceptions, little is being done to (a) gain knowledge of the origin, mechanics, and behavior of land subsidence and earth fissures; (b) identify areas of potential earth fissure development and the magnitude of effects; (c) address groundwater withdrawal in such a way to impede future earth fissure formation; and (d) develop engineering practices and mitigation measures needed to address associated hazards and to substantially reduce risks.

Arizona's State Geologist, M. Lee Allison, noted that HB2639 (2006) directed the AZGS to make available "maps of soils subject to fissures" so that anyone can see if their home or property is at risk (Allison, 2007). But soils and sediments at the surface do not control earth fissures. Fissures initially form at depths of hundreds of feet and are thus independent of surface soil type. The State Legislature acted in 2007 to remedy this and other problems, and their amendment now awaits the Governor's signature.

The members of ALSG recognize that the mapping program funded by the State represents an important step forward in establishing a rational approach to dealing with these issues. But still more needs to be done.

A member of ALSG, Dr. Muniram Budhu of the University of Arizona's (U of A) Civil Engineering Department, has formed the Arizona Geohazards Research Center at the U of A to address the technical needs identified by the group. The ALSG has utilized Dr. Budhu's proposal as a model for testing the potential effectiveness of a university-based research organization in meeting the identified needs. The ALSG has weighed these needs against the likely capabilities of the U of A research center, as a means of judging potential effectiveness. The Arizona Geohazards Research Center does not negate the possibility of other Arizona-based universities leading or participating in the effort. The ALSG is simply identifying the needs and seeking mechanisms to understand and share information regarding the processes of ground subsidence and earth fissure formation.

6 SHORTCOMINGS IN LAND SUBSIDENCE AND EARTH FISSURE SCIENCE

In 1991, the U.S. National Research Council's (NRC) Panel on Land Subsidence recognized three critical gaps in our understanding of subsidence-related phenomena (Galloway et al., 1999): "First, basic earth-science data and information on the magnitude and distribution of subsidence ... to recognize and to assess future problems. These data ... help not only to address local subsidence problems but to identify national problems. ... Second, research on subsidence processes and engineering methods for dealing with subsidence ... for cost-effective damage prevention or control. ... And third, although many types of mitigation methods are in use in the United States, studies of their cost-effectiveness would facilitate choices by decision makers."

Modeling and Monitoring

The geologic principals that govern land subsidence and earth fissure development are not well understood. As a result, geoscientists, geologists and geotechnical engineers have limited tools at their disposal for evaluating and mitigating these geohazards. We are not now in a position to forecast where and when fissures will occur. Moreover, the technical bases on which to

recommend setback distances from earth fissures, or even if setbacks are an effective mitigation or prevention strategy, remains uncertain. As a result, public officials charged with ensuring public safety are unable to meet that charge even as growth continues to encroach on earth fissure areas (Fig. 13 and Fig. 14).

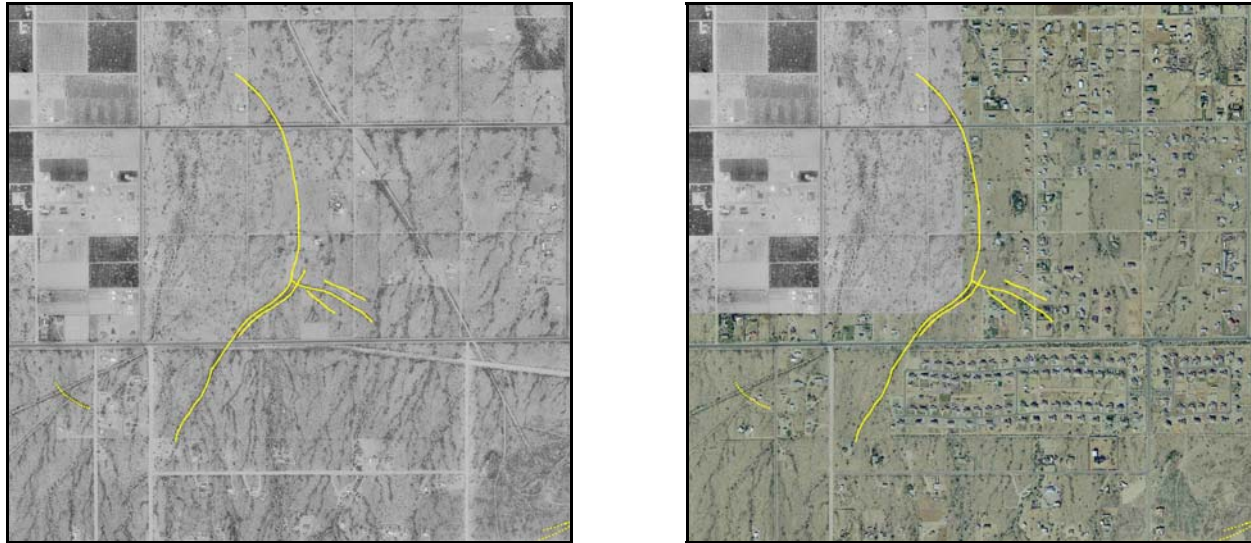


Fig. 13 & 14 - 1997(L) and 2005(R) aerial photos of earth fissure complex (highlighted) in the Chandler Heights area. Note residential growth adjacent to and over fissures (source: Ray Harris).

Earth fissure formation and propagation models are primitive, at best. Current techniques chiefly rely on surface features to detect an earth fissure, and are wholly unable to detect blind fissures. Applied geophysics is proving successful at tracing the subsurface extent of earth fissures. Long-term monitoring of specific fissures at selected at-risk facilities is providing valuable data on local subsidence, surface displacement and strain. But quantitative models characterizing how unconsolidated sediments behave during groundwater mining and basin subsidence are in their infancy.

Only as geologic material subsidence behavior becomes better understood and more predictable will earth fissure prediction become feasible or practical. So many questions remain unanswered. Where will fissures next appear? How do fissures grow and how fast do they propagate? Can fissures be reactivated or further opened after forming wide gullies? What is the risk of failure of infrastructure due to earth fissures? What engineering solutions can be applied to reduce the risk of failure?

In 2005, Maurice Tatlow described efforts by ADWR to address land subsidence using a network of GPS stations scattered throughout the Phoenix area (ADWR, 2005). He concluded that with a sufficient number of discrete GPS stations it is possible to determine where subsidence has occurred and is continuing to occur; installing an effective number of stations, however, would be expensive. Land subsidence, past and present, is an issue in the Phoenix Active Management Area (AMA), the Pinal AMA, the Tucson AMA, and the Willcox Basin. Moreover, it is likely that subsidence is occurring within the Bowie-San Simon area, as well as in other basins where the groundwater table is falling. Land subsidence monitoring requires a long-term commitment of 20 to 50 years. Residual subsidence is difficult to differentiate from active subsidence, and it is equally difficult to determine the immediate cause of subsidence – is it present-day pumping, past pumping, or both? The impact of a single well is hard to determine

and may be masked by variations in the subsurface materials, but the combined impact of many wells over time is evident.

Synoptic satellite imagery provides an alternative to expensive GPS monitoring of large sedimentary basins. The advent of Interferometric Synthetic Aperture Radar (InSAR) satellite imagery provides recourse for temporal monitoring of basin subsidence. For an area of interest radar imagery can be collected over time to create a time-series for making interferograms. An interferogram shows fringe patterns that are related to subsidence occurring over the time interval of the captured images (Fig. 15). InSAR satellite imagery has been used successfully to detect and measure subsidence. Moreover, it has the ability to focus attention to areas where fissures could develop and may provide insight into the causal mechanisms and relations between subsidence and earth fissures. This could lead to tools for identifying at-risk zones, which could in turn result in deploying appropriate prevention or mitigation measures to alleviate impacts before structural damage ever occurs.

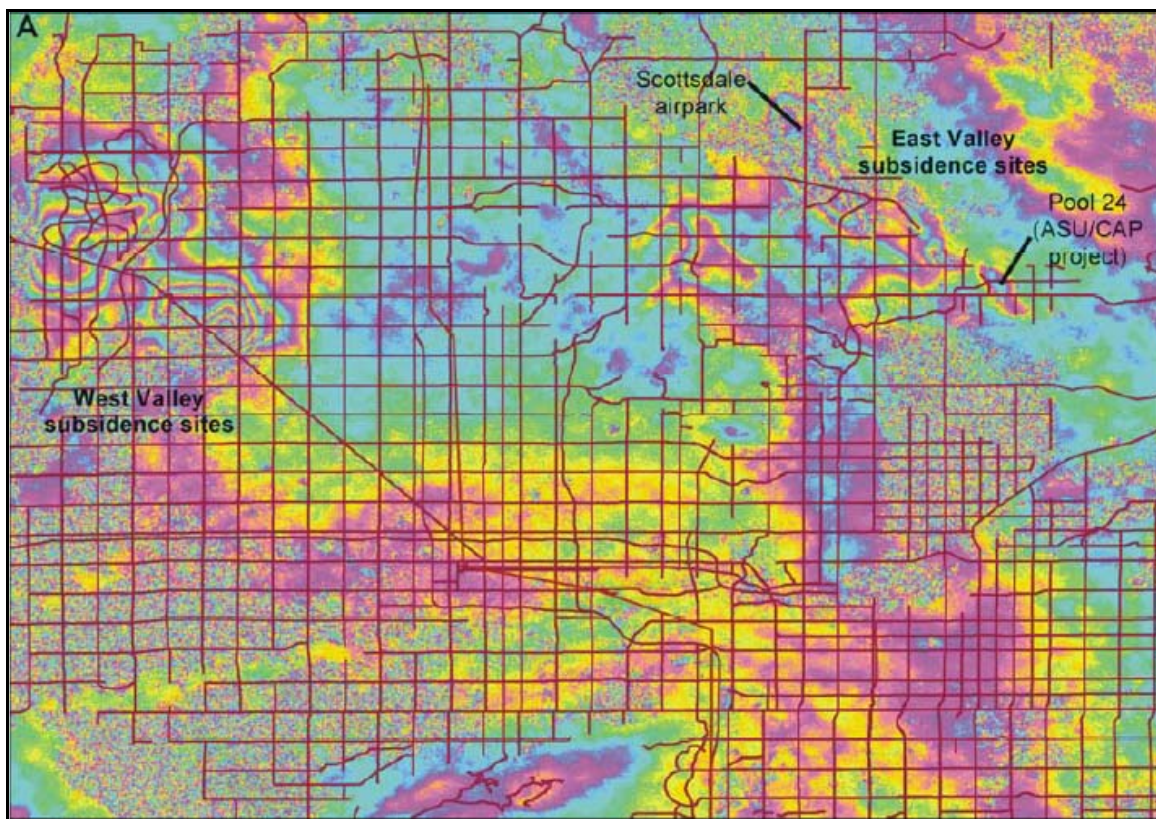


Fig. 15 – InSAR ground-motion map for metro Phoenix showing subsidence bowls in the northwest valley (Surprise) and northeast valley (Scottsdale). Each set of yellow-to-blue fringe colors represents 2.8 cm of subsidence over 1330 days (map developed by M. Tatlow and S. Buckley).

ADWR and a number of local consulting firms have been using InSAR in select locales for the past five to six years to determine the spatial extent, subsidence rates, and temporal history of several land subsidence features within the Phoenix and Tucson AMA's. With funding from NASA and technological help from Microsoft Vexcel Corporation and the Center for Space Research at the University of Texas at Austin, ADWR has developed an application using Synthetic Aperture Radar (SAR) data and InSAR processing techniques to conduct long-term

monitoring of land subsidence and improve water resource management. ADWR has established Inter-Governmental Agreements with both the Flood Control District of Maricopa County and the Pinal County Flood Control District to ensure funding is in place to monitor subsidence around each District's flood control structures. ADWR's InSAR program is expensive. As a result, ADWR is pursuing additional funding from other state and federal agencies to bolster their limited budget and continue this important monitoring program.

Satellite imagery is proving useful for tracking subsidence and aiding in delineating zones at risk of earth fissuring. Unfortunately, the state of the science is such that we can but broadly infer where new fissures might form. The earth fissure zone in east Scottsdale at the CAP Canal near Cactus Road was discovered in part by using InSAR imagery. In several cases, analytical and numerical models combined with InSAR data were used to successfully forecast continued subsidence and predict the possible future onset of fissuring. This type of analysis and the important results that it yields requires significant resources and a dedicated research team; engineers and geologists in private practice are unable to bring the necessary focus or resources to bear. Dedicated research work supported at the appropriate funding level is essential for developing robust models of where, when and how subsidence-related fissures will form next.

Mitigation

The combined efforts of the geoscience and engineering communities have led to successful mitigation practices for a plethora of geologic hazards. Swelling and collapsing soils, faults and earthquakes, and finding competent ground, for example, can be investigated, characterized, and delineated. Engineers, designers and builders have extensively studied the associated hazards and engineered solutions that for the most part successfully mitigate their impacts. Unfortunately, geologists and engineers lack adequate field tools or analytical methods to determine where a narrow earth fissure crack will present itself or when that fissure will erode and enlarge (perhaps overnight) into a dangerous chasm. It is difficult to mitigate and engineer a solution to a problem when the problem itself needs to be better understood.

The state of practice for fissure mitigation is restricted to a handful of designs by local engineers



Fig. 16 – Earth fissure mitigation effort on roadway in Pinal County, AZ (photo by Ken Euge)

and geologists using their experience and judgment to construct informal seat-of-the-pants solutions (Fig. 16). Generally accepted mitigation methods are lacking. Currently, mitigation is commonly a function of client budget and lacks the rigor of a formal cost-benefit, risk analysis approach. Moreover, studies of mitigation failure are wholly lacking, hampering our efforts to move forward with better and surer mitigation methods. In short, ALSG sees a strong need to develop the science of earth fissure mitigation.

Before the engineering and geoscience communities can develop sound evaluation and mitigation practices, we need to better understand the mechanisms that govern land subsidence and cause earth fissures to form. At present, mitigation strategies are predicated on knowing precisely where fissures occur so that developers can either strategically place structures to avoid existing fissures or redirect surface waters to impede capture by existing fissures. This is difficult, of course, where facilities already exist near or in existing fissure-prone zones, or for long baseline infrastructure (pipelines, roadways, canals, electric transmission lines, existing natural drainages etc.) that must extend through these zones. We need new and robust mitigation strategies for protecting facilities from damage; the experiences of the geoscience community in fissure-prone Las Vegas Valley may be of great help here (Table 2). Alternately, avoidance will be the most reasonable option, forcing restrictions on property development.

The ALGS recognizes three areas critically important to addressing subsidence and earth fissures in southeastern Arizona: (1) establishing a long-term monitoring program to track the occurrence and distribution of subsidence and fissuring, (2) supporting research into the processes that cause horizontal stresses, movement and fissuring, and, 3) instituting a formal evaluation of mitigation strategies using coherent step-by-step experimental and assessment procedures.

Table 2

Subsidence & Earth Fissure Mitigation Alternatives Recommended for the Las Vegas Valley ⁽¹⁾

- Reduce the net annual groundwater withdrawal to the level of net annual recharge (reduce dependence on groundwater, increase dependence on surface water, or increase artificial recharge).
- Continue defining potential hazard zones (based upon spatial distribution of faults, and fissures and required detailed geologic, geotechnical and structural engineering studies within zones). Definitions may include “high hazard” or “no-build” designations in areas of significant differential subsidence or fissuring. Developable subsidence zones may be defined on the basis of lower levels of potential hazard but may require that the area is buildable only with specialized construction.
- Place restrictions on the use of surface-applied water in already-built areas lying within high hazard zones to prevent the enlargement of fissures (may require implementation of strict water conservation – no watering or desert landscaping ordinances).
- Establish a “Subsidence District” as authorized by State legislation (similar to the Houston-Galveston area). The district would be responsible for setting water policy and priorities and for developing continued subsidence mitigation strategies.
- Establish long-term monitoring programs to track the occurrence and distribution of subsidence and fissuring (perform annual surveys of existing geodetic networks and surveillance of known fissure areas to detect changes in runoff and erosion patterns).
- Encourage continued research into the processes that cause horizontal movement, tension, cracks, and fissuring. Assess mitigation strategies using coherent step-by-step experimental and assessment procedures. Work in concert with research in other parts of the country that are similarly affected by damage due to fissures to avoid costly duplication of effort.

⁽¹⁾Results of a research project performed by Nevada Bureau of Mines and Geology, Desert Research Institute, USGS, University of Nevada-Reno Civil Engineering Dept., University of Nevada-Las Vegas Geoscience Dept., and Mifflin & Assoc. Sponsored by five local Las Vegas agencies, two Nevada state agencies and four federal agencies, with assistance from NDOT (Price, et al., 1992)

7 RECOMMENDATIONS

Mitigating hazards of subsidence and earth fissures requires diligent monitoring and the advent of new and effective models that incorporate historical and continuous observations in robust analytical techniques to foster new approaches to this problem. Pioneering engineering and geoscience studies are required to pinpoint data requirements and construct heuristic models to illuminate the underlying physical processes. Equally important is the need for a complementary and groundbreaking effort to identify and test engineered structures that promote human health and safety. There exists, too, a compelling need to obtain, warehouse, and disseminate relevant data to the community at large.

Recommendation 1: Encourage research centers to embrace concentrated research on subsidence and earth fissures in Arizona.

What are desperately needed are research centers or groups dedicated to furthering studies into subsidence-related phenomenon and associated hazards. The National Science Foundation, the National Institute of Health, individual States, and philanthropic foundations and businesses have provided initial funding to research centers undertaking cutting-edge and focused research. As an example, the University of Arizona has obtained several of these centers over the past decade and has operated them successfully (e.g., Water Resources Research Center, Water Quality Center). In Arizona, the public universities are particularly well suited to host and nurture research centers for subsidence and earth fissures because of the variety and quality of their current research facilities, faculty, staff and students. Dr. Muniram Budhu's Arizona Geohazards Research Center at the University of Arizona is a model of a university-based research center that may be capable of meeting the identified needs.

Dedicated research centers will fill a dire need that can not otherwise be met by operations within state agencies or by private entities. Centers would partner with state agencies (e.g. the Arizona Geological Survey, the Arizona Department of Water Resources) and the private sector to bring high quality research information to the community at large. In addition to collaborating with local, state and federal agencies, and utilities and private companies, research centers are magnets for attracting external funding, highly-trained personnel, and the kinds of cross-disciplinary synergy required to address complex problems that extend across scientific fields. Fortunately, the expertise required can be found in the many departments that comprise a university, such as geosciences, hydrology and water resources, environmental science, civil engineering, law, and public planning and administration. The resources and expertise available at Arizona's universities are not to be found (or cobbled together) from state agencies or private consulting firms.

The mission of a subsidence and earth fissure research center, as perceived by ALSG, is to conduct research on associated geohazards and their impacts on engineered and non-engineered facilities, to disseminate center studies, and to educate technical professionals, citizens and officials in Arizona. An early goal is to quantify the magnitude of subsidence and the proliferation of earth fissures as a function of groundwater withdrawal.

Through research into patterns of groundwater decline, land subsidence, subsurface stratigraphy, and geomechanics of aquifer materials, a research center can build models to predict the real extent and magnitude of subsidence, and explore physical thresholds on earth fissure formation. This, of course, requires a multidisciplinary approach beyond what any single state agency could provide. Moreover, the collaborative environment native to research centers bolsters efficacious information distribution and idea sharing via conferences and symposia.

Dedicated research centers (such as those noted earlier at the University of Arizona) have a long history of sustainable operations via grants and contracts from Federal and private sources. Initial funding for subsidence and earth fissure research would be most readily available from both public and private stakeholders.

Recommendation 2: Establish a long-term commitment to obtain subsidence data

Funds provided last year via HB2639 authorized monies to the AZGS solely for mapping existing earth fissures. This is a good start, but does nothing to assist geologists and engineers in their efforts to monitor subsidence, or develop models to predict future earth fissure development. What is required is collecting more new data and integrating that with historic data to document earth fissure formation and to monitor subsiding alluvial basins. At present, data gathering is fragmented and lacks the long-term commitments essential for success.

Agencies with statutory requirements are better served by gathering and storing available data. Such institutionalized data bases tend to remain intact, viable and available when held by government entities, rather than in the private sector. Unfortunately, the rigid funding climate of state agencies sometimes precludes effective treatment of problems that are not fully addressed by legislation.

In the case of basin subsidence, the ADWR is trying to supplement their existing resources by pursuing extra-agency agreements to fund continuous monitoring. The result is a fragmented effort that survives solely through the efforts of several dedicated individuals who have the vision and drive to perceive the long-term benefits. A long-term commitment is needed to fund widespread satellite InSAR coverage of Arizona's subsiding basins – at the very least those with histories of subsidence -- and create a dedicated monitoring program with adequate personnel to process the data. Long-term commitments are also needed to ferret out and collate historic ground surveys as well as GPS and subsurface data that reside with various agencies and private companies. Only by compiling and analyzing large volumes of high-quality data can hazard zones be established, physical models developed, and prevention and mitigation measures reliably engineered.

Recommendation 3: Create a distributed network that can integrate inter-operable online sources for geohazard data.

ALSG strongly recommends constructing an integrated, inter-operable online data library for use by the geoscience research community. Currently, information about land subsidence and earth fissures in Arizona is widely scattered among county, state and federal agencies, educational institutions, and numerous private consulting companies. For example, InSAR data for the Phoenix, Tucson and Pinal AMAs are collected and processed by ADWR; CAP maintains a wealth of deep geophysical data from years of service that is not readily available for public use; ADWR, ADEQ, and numerous water districts maintain ground surface and groundwater data for much of Arizona. And new earth fissure maps of AZGS will soon be available through the Arizona Department of Real Estate and the Arizona Department of State Lands.

Any related organization wanting to share data could allow users access by providing a link through the online library. This eliminates the problems inherent with large-scale database management and longevity, as each contributing organization would be responsible for its own data. An effort to gather and link data sources should greatly improve dissemination of this knowledge by allowing users access to all the information stored in many locations. The University of Arizona's Geotechnical, Rock and Water Resource Library (GROW) is a marvelous

template for a robust, inter-operable, online library; GROW is part of the National Science Digital Library (NSDL) funded by the National Science Foundation.

Recommendation 4: Partner with neighboring states who are experiencing similar problems

Arizona's public and private stakeholders should work with neighboring states to jointly seek federal and other financial support and to collaborate on research efforts. State and local agencies in Nevada have made progress in establishing mitigation strategies (see discussion on page 15) and should be able to provide valuable insight for Arizona.

Land subsidence and earth fissure issues are not restricted to Arizona. Several states, including Nevada, California, Utah and Texas have similar problems with subsidence and earth fissures. Moreover, land subsidence and earth fissures are important geological hazards in other countries where groundwater mining is prolific, including Mexico, China, and Saudi Arabia. International research is a hodgepodge affair where individual researchers or groups of researchers tackle local issues and lack a clear, larger mission. Also, the information generated is sometimes controversial and is scattered in journals and reports, some of which are proprietary. Partnering with others should significantly reduce duplication of efforts in research work.

Recommendation 5: Integrate new knowledge into Earth Fissure and Land Subsidence publications and mapping products.

A risk analysis approach needs to be incorporated into publications and mapping products as research and data acquisition techniques advance. New and existing data documented by a distributed network along with models and mitigation methods developed at research centers should be applied by state agencies to map products that showcase fissure locations (in accordance with the 2006 A.R.S Arizona Revised Statute 27-152.01). Where feasible, earth fissure hazard maps, with differentiated high, intermediate, and low risk zones, should be constructed to assist local authorities and other stakeholders in their decision-making process. Such zones initially may be quite broad, but would be expected to be refined as further research develops better information.

8 BENEFITS TO THE CITIZENS AND STAKEHOLDERS OF ARIZONA

Through orchestrated, multidisciplinary research of patterns of groundwater decline, land subsidence, subsurface stratigraphy, and geomechanics of aquifer materials, the Arizona geoscience community can markedly improve our knowledge of subsidence and earth fissures. This strategic approach of centralized and orchestrated research was pioneered in the U.S. by the California geoscience community as they struggled with that state's major geological hazard, earthquakes. Not long after the *Great 1906 San Francisco Earthquake* reduced San Francisco to rubble, a small group of scientists and engineers, working with governmental agencies, developed the scientific foundation and political infrastructure required to reduce risk associated with earthquake hazards; their efforts are the basis for the modern science of seismology. Today, California's educational institutions, governmental agencies and private consultants are among the world's leading experts on earthquake monitoring, modeling and mitigation

Centralized research centers provide forums for data collection, analysis, discourse and dissemination that could lead to wholly new ways of examining subsidence and earth fissures. This in turn would stimulate new ideas and physical models that could be used to draw insights into effective mitigation strategies and methods. Such a capability requires resources and multidisciplinary research beyond the scope of any single state agency or private consulting firm. Arizona would measurably benefit by such a centralized, coordinated effort.

One of the ultimate aims of centralized research is to provide state-of-the-art information about how to mitigate the impact of subsidence and fissures. Currently, state, county, and city agencies and local consultants are clamoring for advice about what specific methods are available to mitigate subsidence and earth fissures once these are identified.

Right now, experts generally recommend that developers steer clear of earth fissures. Our entire approach is reactive and designed to avoid earth fissure whenever possible. This, of



course, is of little help to home owners whose lands are bisected by gullies that grow larger and more dangerous with every rainstorm (Fig. 17). Concentrated research and data gathering offer the best hopes for optimal land utilization while providing a rational way to protect facilities and property owned by Arizonans.

Fig. 17 – Earth fissure gully that reopened August 2005 near residences south of Queen Creek, Arizona – led to the enactment of HB2639 (photo by Mike Schaffer)

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