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PAPER

Land subsidence and earth fissures in south-central and southern Arizona, USA

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Abstract Land subsidence due to groundwater overdraft has been an ongoing problem in south-central and southern Arizona (USA) since the 1940s. The first earth fissure attributed to excessive groundwater withdrawal was discovered in the early 1950s near Picacho. In some areas of the state, groundwater-level declines of more than 150 m have resulted in extensive land subsidence and earth fissuring. Land subsidence in excess of 5.7 m has been documented in both western metropolitan Phoenix and Eloy. The Arizona Department of Water Resources (ADWR) has been monitoring land subsidence since 2002 using interferometric synthetic aperture radar (InSAR) and since 1998 using a global navigation satellite system (GNSS). The ADWR InSAR program has identified more than 25 individual land subsidence features that cover an area of more than 7,300 km^2. Using InSAR data in conjunction with groundwater-level datasets, ADWR is able to monitor land subsidence areas as well as identify areas that may require additional monitoring. One area of particular concern is the Willcox groundwater basin in southeastern Arizona, which is the focus of this paper. The area is experiencing rapid groundwater declines, as much as 32.1 m during 2005–2014 (the largest land subsidence rate in Arizona State—up to 12 cm/year), and a large number of earth fissures. The declining groundwater levels in Arizona are a challenge for both future groundwater availability and mitigating land subsidence associated with these declines. ADWR's InSAR program will continue to be a critical tool for monitoring land subsidence due to excessive groundwater withdrawal.

Keywords Subsidence · Geohazards · InSAR · Earth fissures · USA

Introduction

Land subsidence due to excessive groundwater overdraft has been an ongoing problem in south-central and southern Arizona, USA. The first documented case of land subsidence was from repeat leveling in 1948 in the Eloy area (Robinson and Peterson 1962). Historical groundwater declines vary by groundwater basin, but in some of the alluvial groundwater basins of south-central and southern Arizona, groundwater declines have exceeded 150 m. The potential problems of land subsidence prompted the Arizona Department of Water Resources (ADWR) to start a land subsidence monitoring program in 1998.

Land subsidence has resulted in extensive earth fissuring, with the first earth fissure attributed to groundwater withdrawal being discovered in the early 1950s near Picacho, Arizona (Carpenter 1999). More than 250 km of earth fissures have been identified and mapped by the Arizona Geological Survey (AZGS 2015). The Willcox groundwater basin located in southeastern Arizona is an area of particular concern for land subsidence and earth fissures because of the high magnitudes of groundwater level declines. Land subsidence will continue to pose a problem across Arizona as long as groundwater demands exceed natural recharge, or until groundwater levels recover to refill the open pore-spaces in the aquifer, or until the dewatered and open pore-spaces completely compact, resulting in permanent loss of aquifer storage. Permanent

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loss of storage due to inelastic compaction could pose a problem for future groundwater availability even if groundwater pumping is reduced (Carruth et al. 2007).

Land subsidence

Groundwater pumping in south-central and southern Arizona has been occurring since the early 1900s. This groundwater pumping has exceeded the natural recharge for more than half a century, resulting in declining groundwater levels; some groundwater basins have experienced more than 150 m of groundwater decline (ADWR 2015a, b). The groundwater declines have resulted in regional land subsidence (Fig. 1) with some areas experiencing land subsidence in excess of 5.7 m in the western portion of the Phoenix metropolitan near Luke Air Force Base between 1957 and 1991 (Schumann and O'Day 1995) and near the town of Eloy between 1948 and 1985 (Schumann and Genualdi 1986).

The Central Arizona Project canal, completed in the early-1990s, began delivering Colorado River water to municipal water-users in the Phoenix and Tucson metropolitan areas and to agricultural users in Pinal County (located between Phoenix and Tucson). These imported surface-water deliveries have reduced demand for groundwater, resulting in groundwater recovery in many areas. The groundwater-level recoveries have slowed land subsidence rates by 25–50 % in these areas where imported surface-water supplies replace or supplement groundwater supplies, but residual land subsidence continues to occur in many areas. (Miller and Shirzaei 2015).

Hazards associated with land subsidence include the potential to change natural drainage patterns and floodplains (which has occurred in the McMullen Valley basin of central Arizona and elsewhere). Land subsidence can cause earth fissures in areas that experience differential compaction. Land subsidence can also affect the hydraulic properties of the aquifer by reducing hydraulic conductivity as the pores become more compressed, making it more difficult for water to move through the aquifer. Also, compaction of the aquifer can result in a permanent loss of groundwater storage because pore volume decreases.

Wet periods have resulted in groundwater-level recoveries and even uplift in some areas in 2005 and 2010. More recently, drought in Arizona has resulted in decreased surface-water deliveries, increased groundwater pumping, and renewed land subsidence. This has implications for those municipalities that use Colorado River water. If a

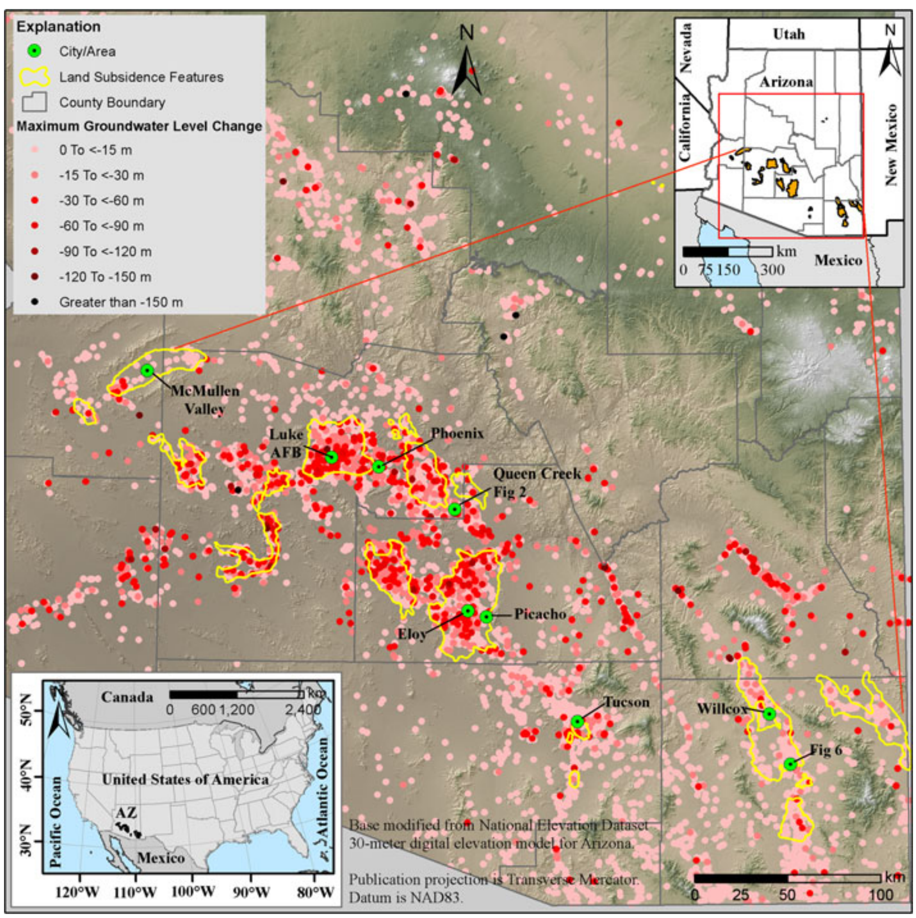

Fig. 1 Land subsidence features in Arizona (*AZ*) based on interferometric synthetic aperture radar (InSAR) data between 1992 and present, and the maximum groundwater-level change for the historical record from the ADWR Groundwater Sites Inventory database (ADWR 2015a, b)

shortage is declared for the Lower Colorado River system at Lake Mead, that would cause Arizona to lose 320,000 acre-feet (39,471 hectare-meter) of water per year of its Colorado River allotment. Local groundwater would be used to offset reduced imported surface-water supplies and possibly result in increased land subsidence and associated land subsidence features, like earth fissures.

Earth fissures

Regional land subsidence has resulted in a large number of earth fissures. Earth fissures are tension cracks that are formed from differential land subsidence occurring near the basin fringes or near shallow bedrock. Earth fissures develop as small hairline cracks in the subsurface. Some cracks may reach the surface and others may lie hidden just below the surface. Earth fissures are usually identified after large rain events when the hairline crack intercepts surface runoff, causing erosion. The earth fissure opens up creating what is called a fissure gulley. An earth fissure gulley can be more than 3 m wide and have depths of 10 or more m (Fig. 2). The Arizona Geological Survey (AZGS) started mapping earth fissures in 2007 and has since mapped more than 251 km of earth fissures throughout Arizona (AZGS 2015). The AZGS has published a series of 25 maps, an online viewer, and GIS shapefiles that map these earth fissures in detail (AZGS 2015). Several of these earth fissures have damaged pipelines, highways, roads, railways, flood control structures and homes.

Interferometric synthetic aperture radar (InSAR) data

ADWR began using survey-grade global navigation satellite system (GNSS) equipment at the onset of its land subsidence monitoring program in 1998. In 2001, ADWR tested a pilot program using interferometric synthetic aperture radar (InSAR) methods. After deeming the pilot InSAR program a success and a proven method in monitoring regional land subsidence, ADWR fully implemented its own in-house InSAR program in 2002 after being awarded a NASA Earth Sciences grant.

Synthetic aperture radar (SAR) is a side-looking, radar-imaging system that transmits a pulsed microwave signal towards the earth and records both the amplitude and phase of the back-scattered signal that returns to the antenna. InSAR is a technique that utilizes interferometric processing that compares the amplitude and phase signals received during successive passes of the SAR platform over a specific geographic area at different times. Phase is proportional to the line of site distance from the SAR platform to the target area, and amplitude is the measure of radar signal strength returned to the antenna. InSAR techniques, using satellite-based SAR data, can be used to produce land-surface deformation products with cm-scale vertical resolution (Bawden et al. 2003). Changes in land elevation are detected through the change in phase of the radar signal. InSAR is used to detect surface motion not only in alluvial basins, but also along active faults, on volcanoes, landslides, sinkholes, and other geologic hazards (Galloway and Hoffmann 2007). ADWR has processed InSAR data from the European Space Agency's ERS-1, ERS-2, and Envisat satellites, Japanese Aerospace Exploration Agency's ALOS-1 satellite, and MacDonald, Dettwiler and Associates' Radarsat-2 satellite.

Since fully implementing its InSAR monitoring program in 2002, ADWR has identified more than 25 individual land subsidence features throughout Arizona, which collectively cover more than 7,300 km^2 (Conway 2014). ADWR has compiled an extensive InSAR dataset for the active land subsidence areas in Arizona. Most data sets cover time periods 1992–2000, 2004–2010, 2006–2011, and 2010 to present, which reflect the available time-series for each satellite sensor. ADWR has used the InSAR data to produce more than 240 land subsidence maps that can be publicly accessed (ADWR

Fig. 2 Earth fissure in Queen Creek, Arizona, which reopened after a large rain event in August 2005

2015a, b). The land subsidence maps cover various periods of time for each land subsidence feature and are updated each year. ADWR has also developed an interactive land subsidence map that can be used to view the extent of each land subsidence feature.

ADWR has used InSAR: for monitoring land subsidence, seasonal deformation (uplift and subsidence), and the aquifer response to natural and artificial recharge; as a mapping tool for locating earth fissures and identifying areas susceptible to future earth fissure formation; for helping to identify and mitigate damage to flood-control structures due to land subsidence; and for land subsidence modeling. ADWR's InSAR program has produced valuable results and end products that are used not only by ADWR but also other state, county, and local agencies, universities, and private companies for research, monitoring, modeling, mitigation, planning and design projects.

Willcox groundwater basin

The Willcox groundwater basin is located in southeastern Arizona in Cochise and Graham counties and is approximately 4, 950 km^2 in size (Fig. 3). The basin is internally drained, with the majority of the surface water flowing into the Willcox Playa. The playa is located in the center of the basin and covers approximately 129 km^2. Groundwater is the primary source of water in the Willcox basin and irrigation agriculture is the largest groundwater use. There are no external sources of surface water currently being delivered or planned for the Willcox basin that could supplement groundwater use to decrease the reliance on groundwater and help mitigate land subsidence-related problems. Groundwater level declines of more than 60 m occurred by 1975, with some recovery during a challenging economic period of the late 1970s that forced some farms to cease operations (Oram II 1990). The groundwater recovery was short-lived as farming and groundwater pumping resumed in the 1980s, resulting in renewed groundwater level declines.

In December 2014, groundwater levels in more than 530 wells were measured by ADWR in the Willcox basin. There were 390 well sites that had measurements collected in both 2005 and 2014. The largest groundwater level decline during the 9-year period was 32.1 m at one well site and the average decline was 7.7 m (Fig. 3). The rapid groundwater level declines have affected domestic well owners in several areas of the basin, causing their wells to go dry. This prompted discussions between

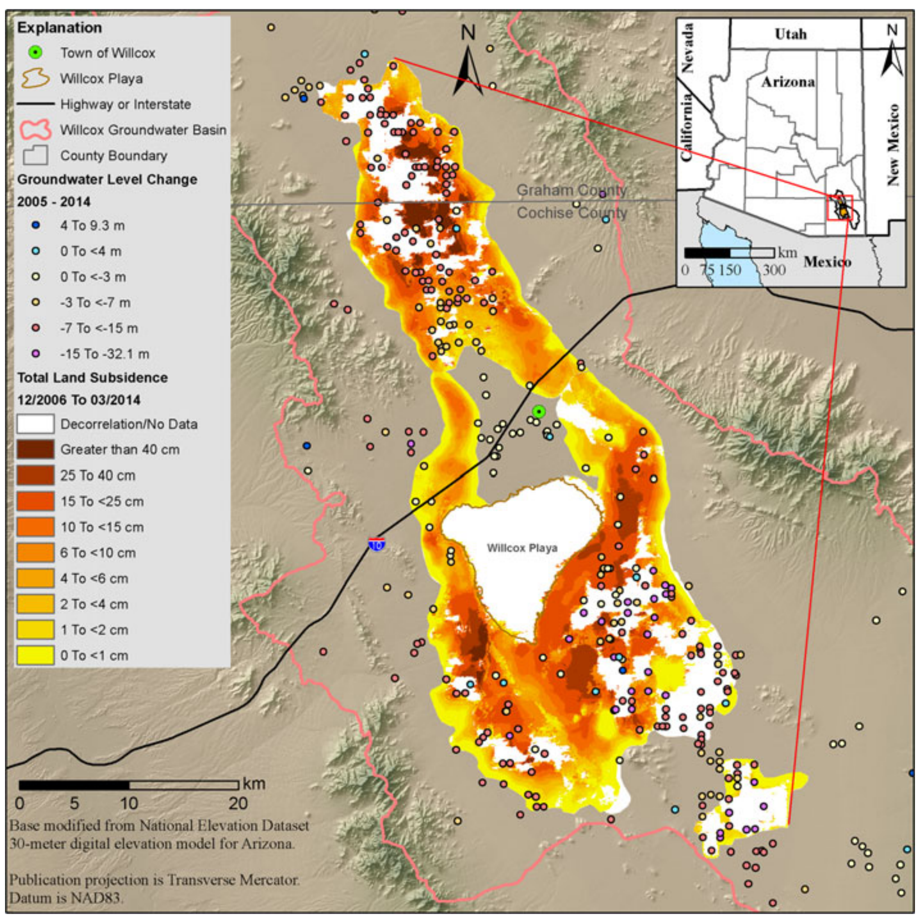

Fig. 3 Change in groundwater levels between 2005 and 2014 and land subsidence between 2006 and 2014 for the Willcox groundwater basin (ADWR 2015a, b)

groundwater users in the Willcox basin and ADWR on the best course of action for managing the groundwater supplies for future use.

Land subsidence and earth fissures in the Willcox groundwater basin

The central portion of the Willcox basin was a Pleistocene lake known as Lake Cochise, which deposited extensive lacustrine and other fine-grained clays throughout the area. (Waters 1989) Declining groundwater levels and subsequent drainage and compaction of these clay deposits has led to widespread land subsidence (Fig. 3). Land subsidence was first documented in this area in the 1970s. Land subsidence of 1.63 m was measured 13.2 km northwest of the town of Willcox between 1937 and 1974 (Holzer 1980). ADWR collected GNSS survey data at ten survey monuments in late 2014 and compared the results to previous survey data from 1945, 1991, 2005, and 2008. The survey results showed land subsidence as much as 1.32 m since 1945 and 0.37 m since 2008 (Fig. 4). ADWR plans on re-surveying these monuments every 1–2 years for monitoring the land subsidence and for ground-truthing and comparison with ongoing InSAR data collection.

InSAR data show that land subsidence rates have tripled from 1996 to 2014. ERS-1 and ERS-2 data from 01/1996 to 12/1996 measure land subsidence rates as high as 4 cm/year (ADWR 2015b), Envisat data from 01/2009 to 01/2010 measure land subsidence rates as high as 11 cm/year (ADWR 2015b), and Radarsat-2 data from 03/2013 to 03/2014 measure land subsidence rates (Fig. 5) as high as 12 cm/year (ADWR 2015b).

Earth fissures were observed in the Willcox basin using aerial photography from 1978 and confirmed with subsequent field checks (Holzer 1980). The Arizona Geological Survey began mapping earth fissures in the Willcox basin in 2009 and has since mapped 61.5 km of earth fissures (AZGS, 2015). Earth fissure activity is ongoing in the basin due to large land subsidence rates of 12 cm/year and differential land subsidence near the areas of shallow bedrock (Fig. 5). Several earth fissures have impacted roads, a power generating facility, and a gas pipeline (Fig. 6). The AZGS and ADWR work together to monitor land subsidence and earth fissures in the basin and to identify areas of differential land subsidence that could lead to potential earth fissuring using InSAR data.

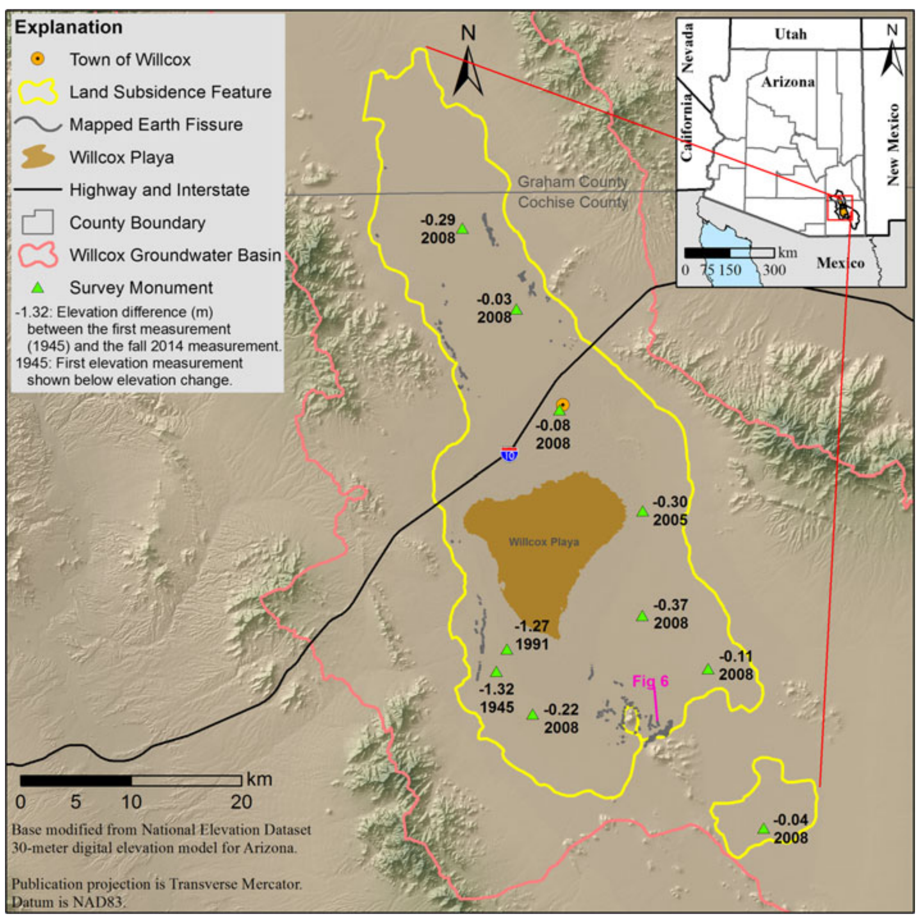

Fig. 4 Land subsidence in the Willcox groundwater basin based on historical and 2014 survey data and mapped earth fissures

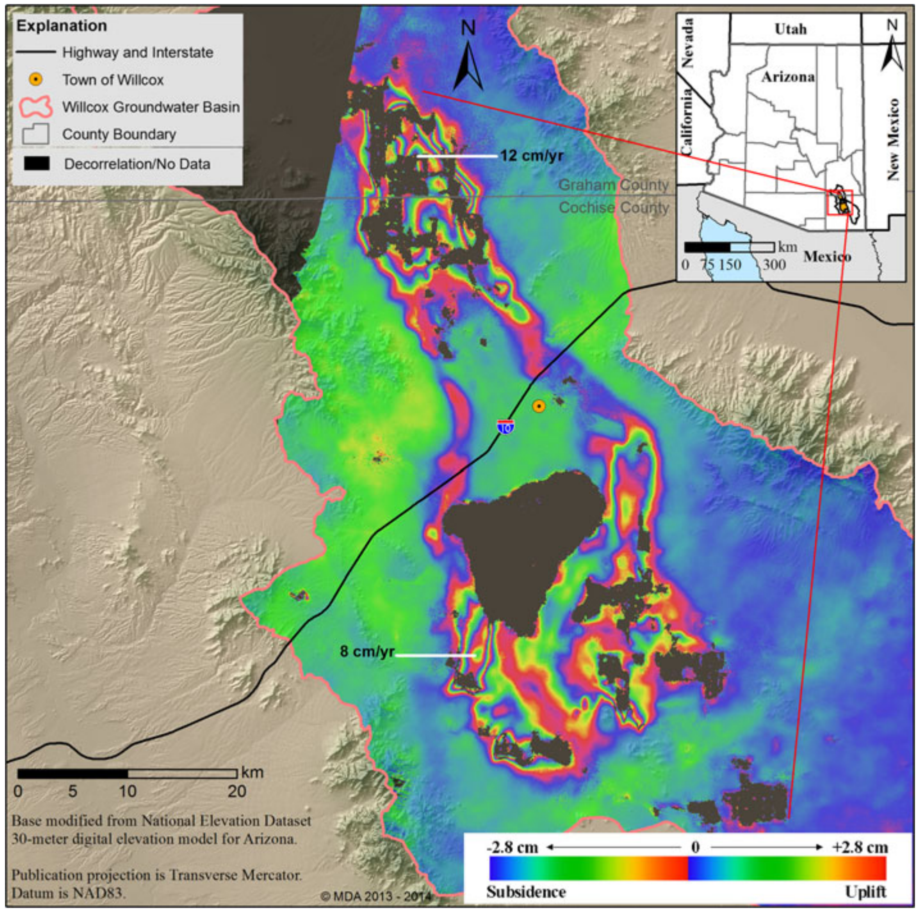

Fig. 5 Radarst-2 unwrapped interferogram 03/26/2013 to 03/21/2014 for the Willcox groundwater basin

Conclusions

Land subsidence and earth fissures have been a problem in south-central and southern Arizona for more than 50 years and will likely continue to be a problem into the future. Even though groundwater levels are recovering in many areas where imported surface-water supplies are being used to supplement water supplies and thereby reduce groundwater demand, residual land subsidence continues to occur. Many of the rural groundwater basins that do not have access to imported surface water are experiencing greater groundwater declines and land subsidence rates than those basins that do have access to surface-water supplies.

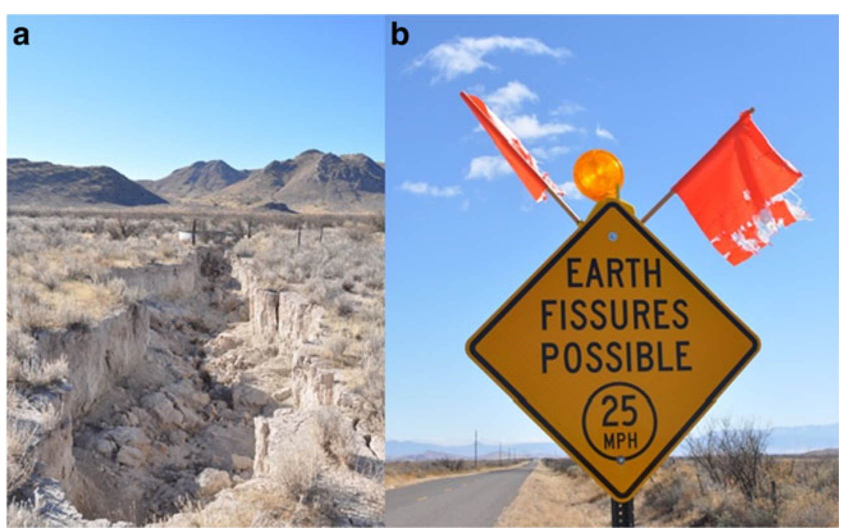

Fig. 6 **a** Earth fissure in the Willcox Basin, Arizona, which opened after a large rain event in July 2011 and **b** a Cochise County earth fissure-warning sign posted along the road where the earth fissure crosses and damaged the road

Several factors that could affect groundwater conditions and land subsidence in a groundwater basin are climate change, drought, or even wet periods. Because these factors (and many others) affect groundwater conditions and land subsidence, it is critical to monitor both land subsidence and groundwater conditions in all of the susceptible groundwater basins in Arizona. This will allow water-planners, hydrologists, policy makers, and other stakeholders to develop water management plans, and make informed decisions based on the most recent and comprehensive data.

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