

Arizona Department of Water Resources Land Subsidence Monitoring Program

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Abstract

Land subsidence due to groundwater overdraft has been an ongoing problem in south-central and southern Arizona since the 1940s. The first earth fissure attributed to excessive groundwater withdrawal was discovered in the early 1950s near Picacho, Arizona. In some areas of the State, groundwater level declines of more than 120 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, Arizona. The Arizona Department of Water Resources (ADWR) has been monitoring land subsidence throughout Arizona since 1998 using Interferometric Synthetic Aperture Radar (InSAR) Data and Global Navigation Satellite System (GNSS) Data. The ADWR InSAR program has proven to be a critical resource for monitoring land subsidence throughout Arizona and has resulted in the identification of more than 26 individual land subsidence features that cover an area of more than 7300 km². 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. The declining groundwater levels in Arizona are both a challenge for future groundwater availability and for mitigating land subsidence. ADWR's InSAR program will continue to be a critical tool for monitoring land subsidence due to excessive groundwater withdrawal.

Keywords

Subsidence • InSAR • Earth fissures • Arizona (USA)
Groundwater management

1 Introduction

Land subsidence due to excessive groundwater overdraft has been an ongoing problem in south-central and southern Arizona. 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 120 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 273 km of earth fissures have been identified and mapped by the Arizona Geological Survey (AZGS 2017). Land subsidence will continue to pose a problem across Arizona as long as groundwater demands exceed natural and/or artificial 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.

2 Interferometric Synthetic Aperture Radar (InSAR) Data

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

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Since 2002, ADWR has collected more than 140,000 km² of InSAR data throughout Arizona, identifying more than 26 individual land subsidence features that cover an area greater than 7500 km². ADWR has compiled an extensive historical InSAR dataset for the active land subsidence areas in Arizona. Most data sets cover time periods between 1992 to 2000, 2004 to 2010, 2006 to 2011, and 2010 to present, which reflect the time-series for each satellite sensor. ADWR has utilized SAR data from the ERS-1, ERS-2, Envisat, Radarsat-1, Radarsat-2, ALOS-1, ALOS-2, TerraSAR-X, and Sentinel-1 satellites (Fig. 1). ADWR has used the InSAR data to produce more than 400 land subsidence maps that can be accessed and downloaded at this link: <http://www.azwater.gov/AzDWR/Hydrology/Geophysics/LandSubsidenceInArizona.htm>.

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 not only for monitoring land subsidence but also seasonal deformation (uplift and

subsidence), natural and artificial recharge events, as a tool for geological mapping and investigations, locating earth fissures, identifying areas where conditions may exist for future earth fissure formation, for dam mitigation and land subsidence modeling, and for monitoring floodplains and changing drainage patterns due to land subsidence. 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 their own research, monitoring, modeling, mitigation, planning and design projects.

3 Land Subsidence

Groundwater pumping in south-central and southern Arizona has been occurring since the early 1900s. Groundwater has been a primary source of water for the municipal, agricultural, industrial, and mining sectors. 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

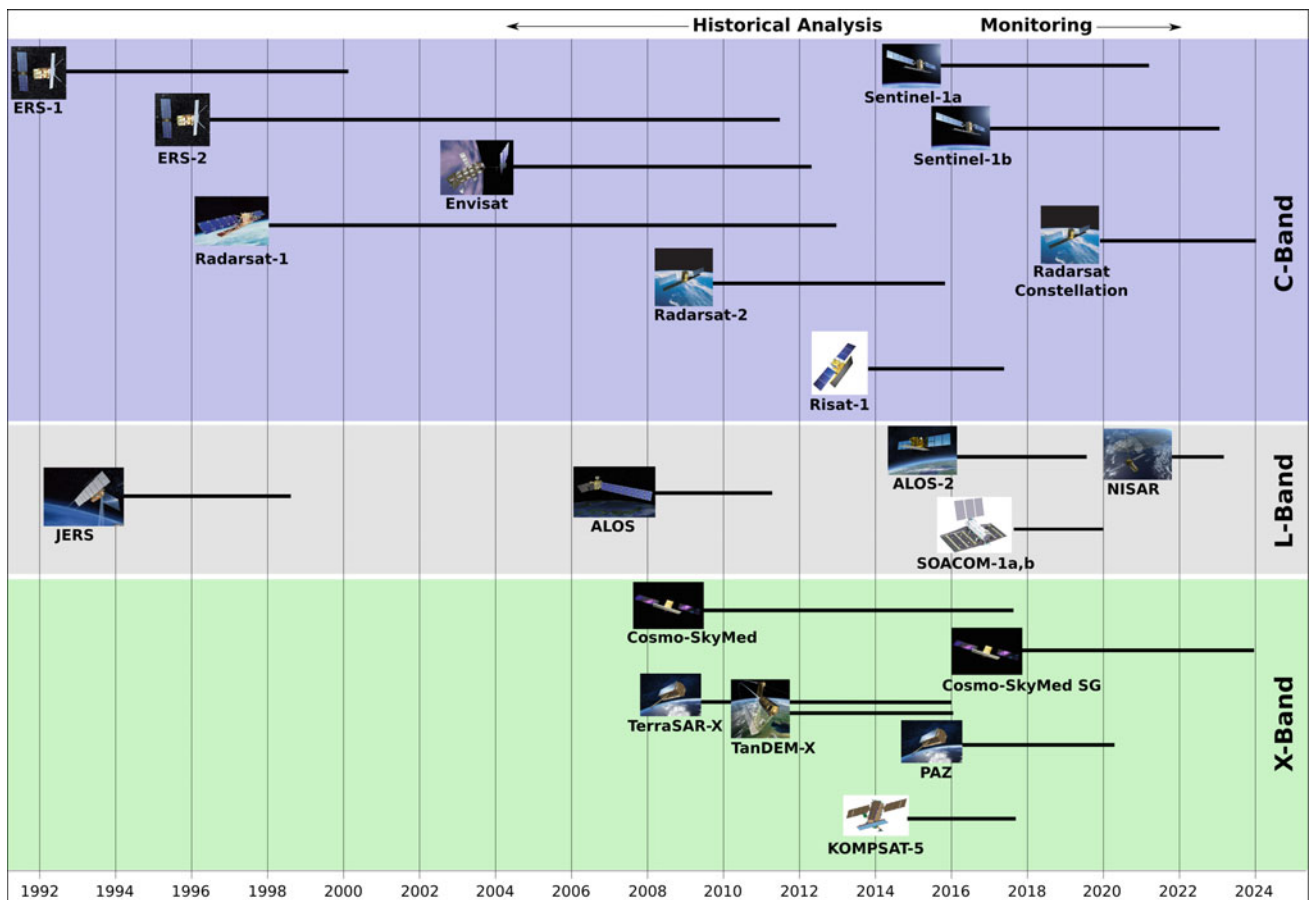


Fig. 1 Chart of past, present, and projected SAR satellite missions Image courtesy UNAVCO

120 m of groundwater decline (ADWR 2017b). These groundwater declines have resulted in regional land subsidence (Fig. 2) 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 (Schumann and O'Day 1995) and near the town of Eloy (Schumann and Genualdi 1986).

The construction and completion of the Central Arizona Project canal in the mid-1980s began delivering Colorado

River water to water-users in the Phoenix and Tucson metropolitan areas as well as water to agricultural users in Pinal County (located between Phoenix and Tucson). These surface water deliveries have reduced groundwater demands, resulting in groundwater recovery in many areas. The groundwater recoveries have slowed land subsidence rates in these areas where surface water is being used to replace or supplement groundwater, but residual land subsidence continues to exist. Climate change, drought, and/or a decrease in

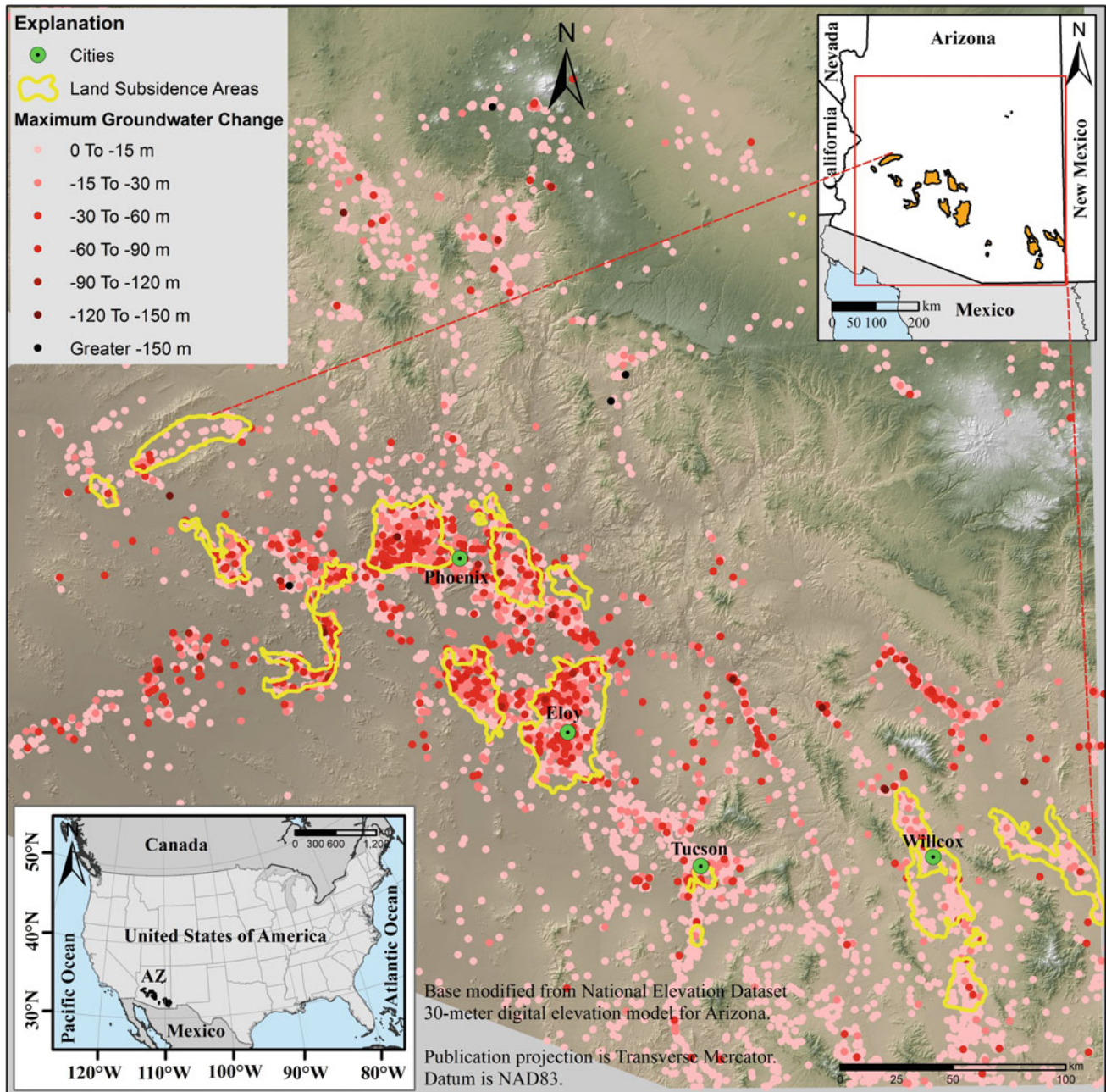


Fig. 2 Land subsidence features in Arizona based on InSAR data and maximum groundwater change from ADWR groundwater sites inventory database (ADWR 2017a, b)

surface water deliveries could cause an increase in groundwater pumping, resulting in renewed land subsidence rates that were present during the pre-1980s era.

Hazards associated with land subsidence include the potential to change natural drainage patterns and floodplains, which has occurred in the McMullen Valley basin and the Eloy sub-basin of central Arizona, and elsewhere (ADWR 2013). Land subsidence causes earth fissures in areas that experience differential compaction. Land subsidence may also affect the hydraulic properties of the aquifer. As the pores become more compressed, it becomes more difficult for water to move through the aquifer, which may reduce transmissivity. Also, compaction of the aquifer results in a loss of storage because pore volume decreases.

4 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 sub-surface. 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 meters (Fig. 3). The Arizona Geological Survey (AZGS) started mapping earth fissures in 2007 and has since mapped more than 273 km of earth fissures throughout Arizona (AZGS 2017). The AZGS has published 26 earth fissure study area maps that display all the earth fissures mapped in each study area. These maps, as well as an online earth fissure viewer and GIS earth fissure shapefiles, can be accessed at this link: <http://www.azgs.gov/efmaps.shtml>. Several of these earth fissures have impacted and damaged pipelines, highways, roads, railways, flood control structures and homes.

5 Land Subsidence in Active Management Areas

The 1980 Arizona Groundwater Act recognized the need to aggressively manage the state's finite groundwater resources to support its growing economy. Areas with heavy reliance on mined groundwater were identified and designated as Active Management Areas (AMAs). The five AMAs (Prescott, Phoenix, Pinal, Tucson and Santa Cruz) are subject to regulation pursuant to the Groundwater Code. Each AMA carries out its programs in a manner consistent with these



Fig. 3 Earth fissure in Pinal County, Arizona that opened in 2016

goals, while considering and incorporating the unique character of each AMA and its water users.

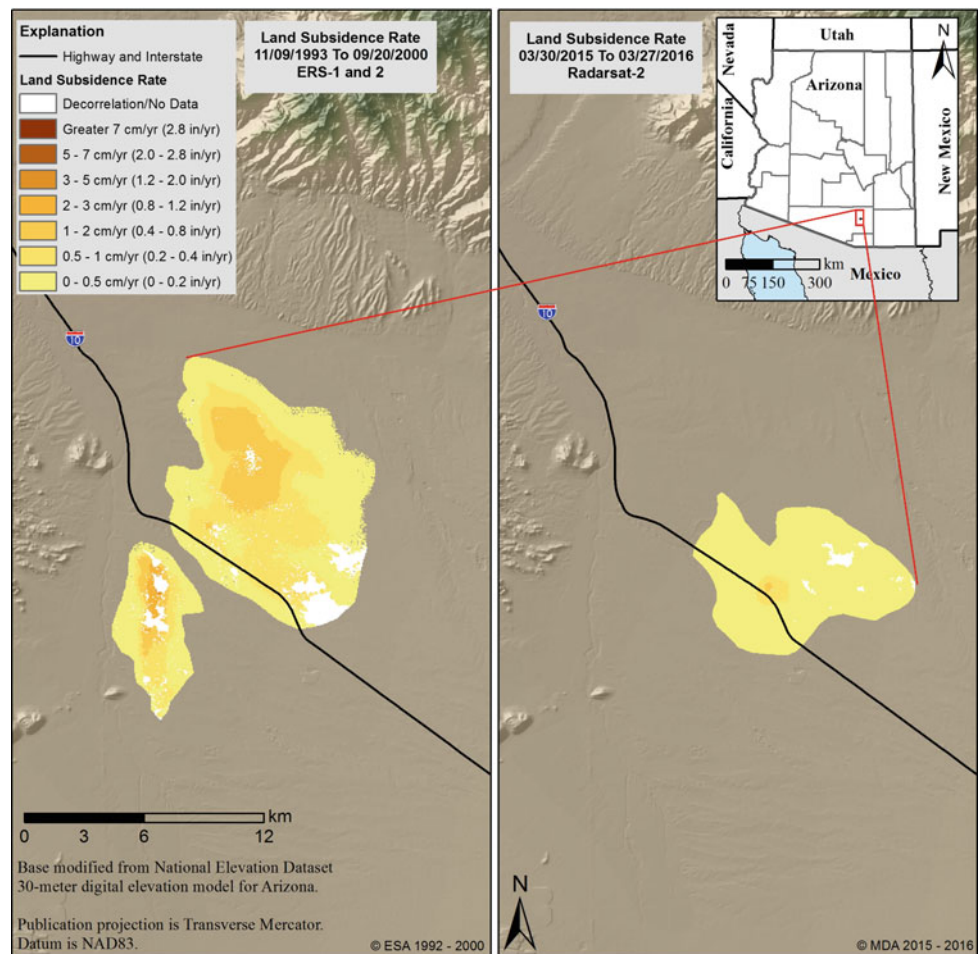
In the Phoenix, Prescott and Tucson AMAs, the primary management goal is safe-yield by the year 2025. Safe-yield is accomplished when no more groundwater is being withdrawn than is being annually replaced.

In the Pinal AMA, where the economy is primarily agricultural, the management goal is to preserve that economy for as long as feasible, while considering the need to preserve groundwater for future non-irrigation uses.

In the Santa Cruz AMA the management goal is to maintain a safe-yield condition in the active management area and to prevent local water tables from experiencing long term declines.

Groundwater levels in the Phoenix, Pinal and Tucson AMAs have been recovering since the early 1990s. This is due to a number of reasons: increase in water-use efficiency; artificial groundwater recharge; using renewable surface water; decrease in agricultural acreage; mandatory conservation programs; 100-year assured water-supply requirements for all new developments; and, groundwater management. The Tucson AMA has seen a significant decrease of almost 90% in land subsidence when comparing the InSAR rates between the 1990s and 2015–2016 (Fig. 4).

Fig. 4 Land subsidence rate comparison between 1993–2000 and 2015–2016 in Tucson AMA (ADWR 2017e, f)



Groundwater pumping in and around these land subsidence features had been reduced and replaced by using recharged surface water, resulting in recovering groundwater levels. The Phoenix AMA has seen decreases between 25 and 50% in land subsidence when comparing InSAR rates between the 1990s and 2015–2016.

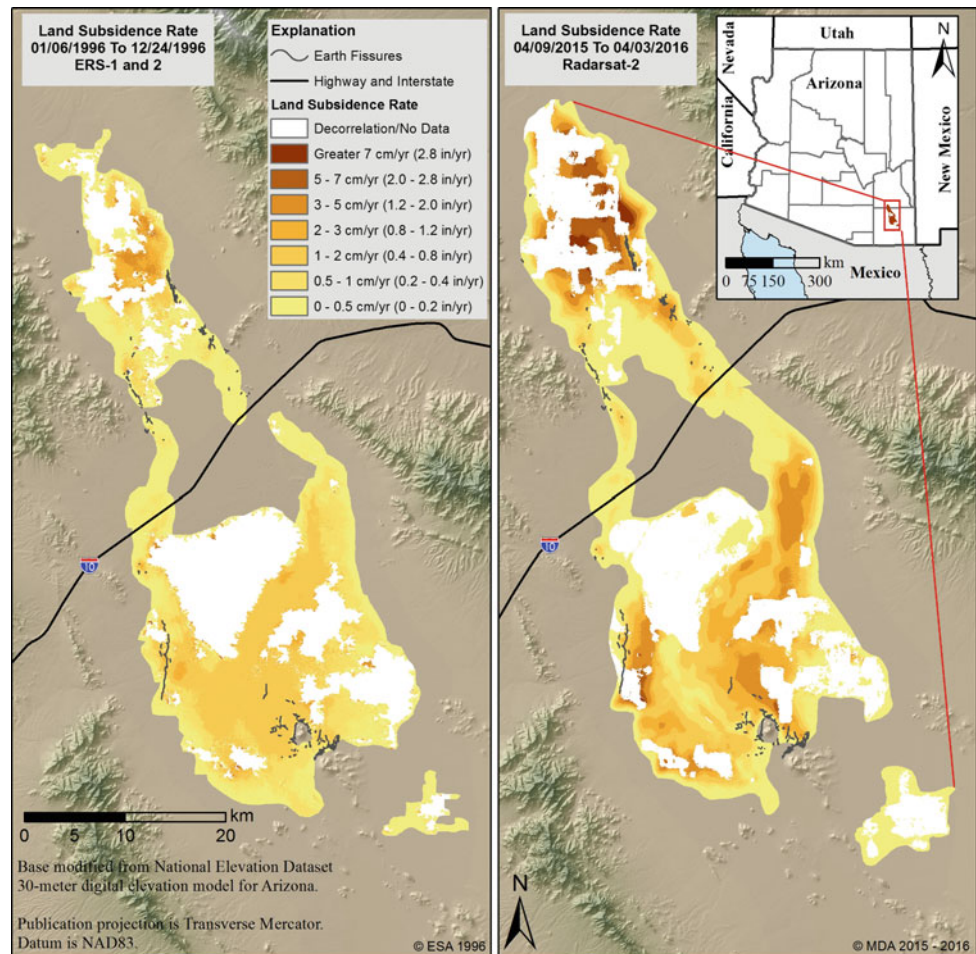
6 Land Subsidence Outside Active Management Areas

The majority of land subsidence areas outside AMAs do not have access to renewable surface water supplies and are not subject to mandatory conservation programs and groundwater management. Two of the land subsidence areas are within two separate Irrigation Non-Expansion Areas (INA):

the Harquahala INA and Douglas INA. INAs have restrictions on increasing the number of irrigated acres.

All the land subsidence areas outside the AMAs have seen an increase in land subsidence when comparing older InSAR data to the more recent InSAR data. The Willcox Groundwater Basin located in southeastern Arizona (and outside an AMA) is a closed groundwater basin. Water-users there currently do not have access to any renewable surface water supplies. The Willcox Basin has seen an increase in agricultural acreage since the 1950s. Groundwater levels have declined as much as 100 m since the 1950s, resulting in land subsidence of more than 1.5 m. There has been a significant increase in land subsidence when comparing the InSAR rates between the 1990s and 2015–2016 (Fig. 5.); rates have increased between 200 and 400%.

Fig. 5 Land subsidence rate comparing between 1996 and 2015–2016 in the Willcox Basin (ADWR 2017c, d)



7 Conclusions

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

There are several factors that could affect groundwater conditions and land subsidence in a groundwater basin. A few of these are climate change, drought, or even wet periods. Wet periods have resulted in groundwater recoveries and even uplift in some areas in 2005 and 2010. The

ongoing drought in Arizona has resulted in some basins receiving decreased surface water deliveries and thereby causing increased groundwater pumping in those particular areas. As a result, land subsidence started to occur in the area where groundwater pumping had increased (to offset decreased surface water supplies) and groundwater levels had declined. This type of situation could repeat itself for those entities that use Colorado River water if a shortage is declared for the Lower Colorado River system at Lake Mead. That would cause Arizona to lose 325,000 acre-feet of water per year of its Colorado River allotment. Groundwater would be used to replace the cuts in the Colorado River water deliveries, and would result in increased pumping and the possible increase in land subsidence or the possible development of new land subsidence features.

All these factors and many others that could affect groundwater conditions and land subsidence are why it is critical to monitor both land subsidence and groundwater conditions throughout Arizona. These data allow

water-planners, hydrologists, policy makers, etc. to research a problem, or develop a water management plan, or make informed decisions because they are using the most recent and comprehensive data that are available.

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