LAND SUBSIDENCE AND EARTH FISSURES FROM GROUNDWATER WITHDRAWAL – A GROWING WORLDWIDE PROBLEM

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We

- Former graduate students
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  - Dylan Moriarty, BS.

AGENDA

- What are land subsidence/uplift and earth fissures?
- How do we measure them?
- How do they affect infrastructures?
- What is our understanding about them?
- What can we do to mitigate negative effects of land subsidence/uplift and earth fissures?

What are land subsidence/uplift and earth fissures?

How do we measure them?

How do they affect infrastructures?

DEFINITIONS

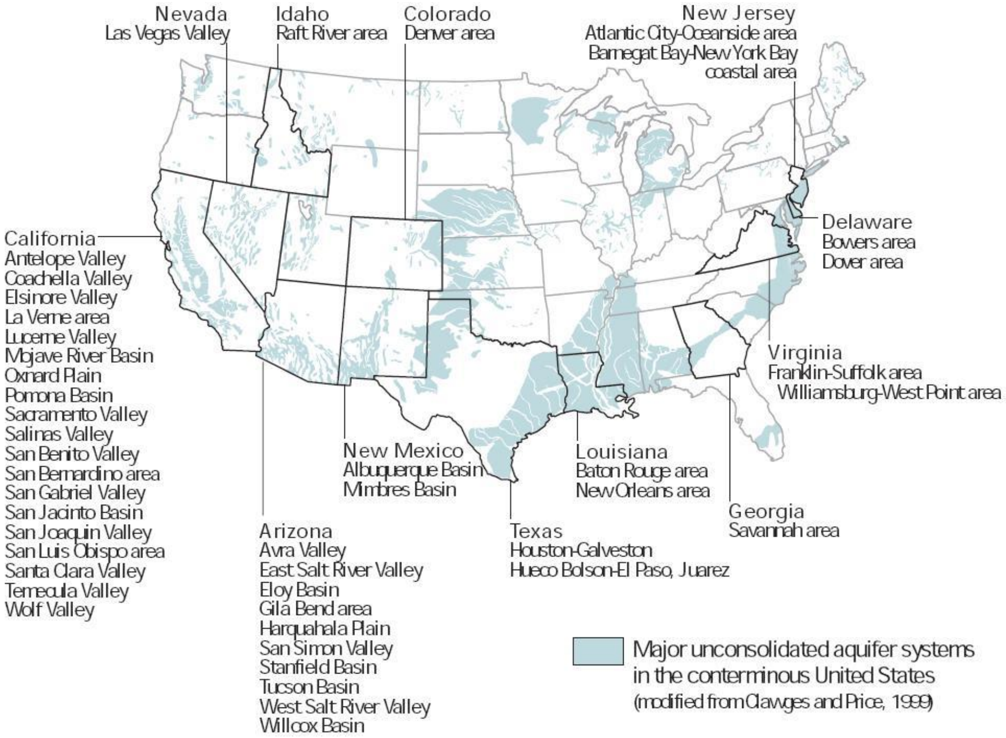
- Land Subsidence
  - sinking of the ground
  - ground settlement
  - Compaction (Geologists, hydrologists, hydro-geologists)
  - Consolidation (geotechnical Engineers)
- Uplift
  - rising of the ground
  - ground uplift

- Earth fissures
  - Long, deep cracks in the ground (depths extend to groundwater elevation ??)

LAND SUBSIDENCE FROM GROUNDWATER WITHDRAWAL IN US

About 80% of land subsidence in the US is due to groundwater withdrawal
[Hoffman et al. 2003]

Land subsidence is a worldwide problem (Philippines, China, Iran, India and many others)



States where subsidence has been attributed to pumping of groundwater.
[USGS, 2000]

MAIN ISSUE

- Groundwater withdrawal exceeds natural recharge

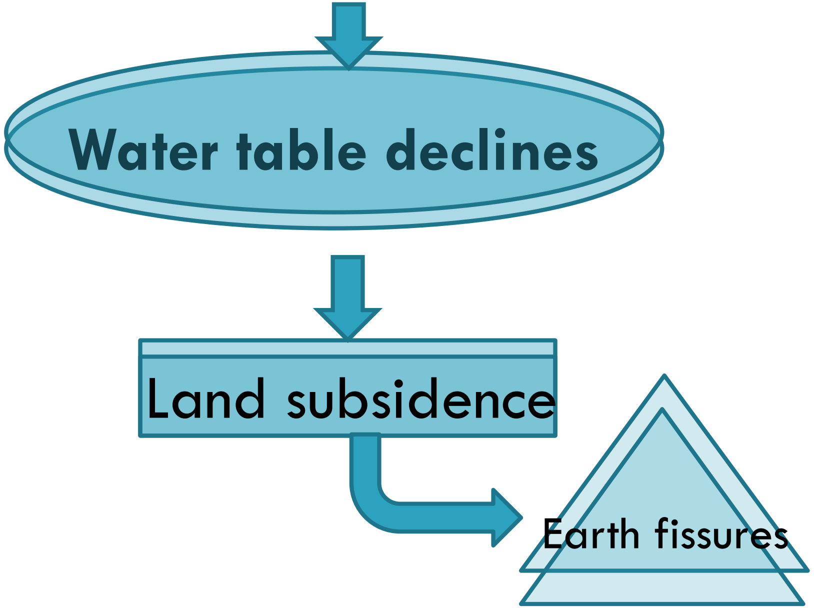
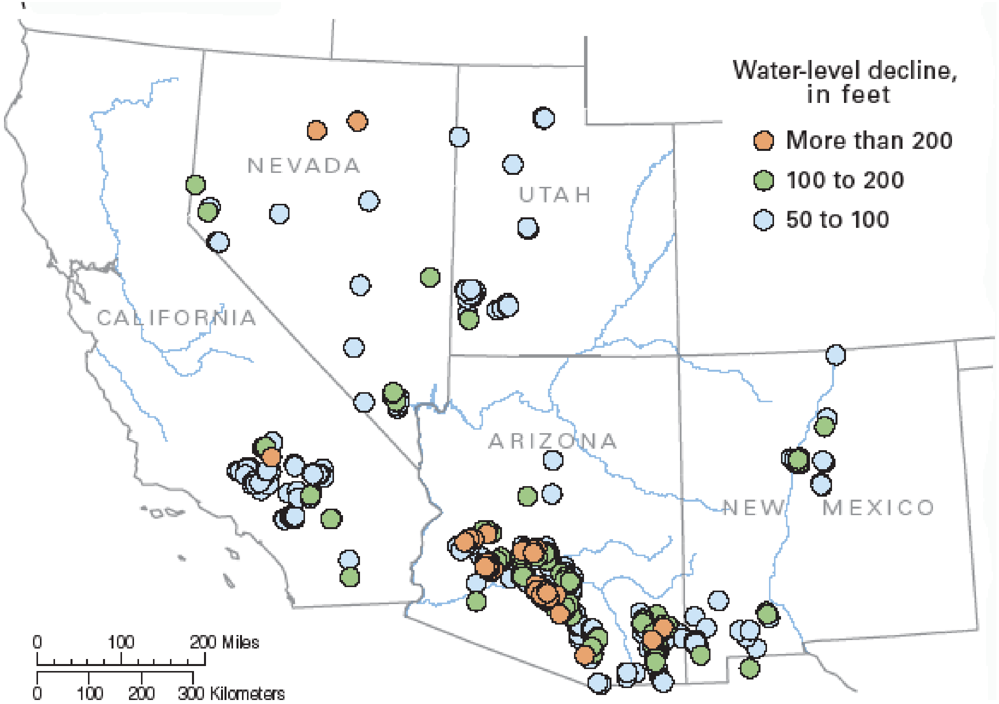


Image. Courtesy Ralph Weeks

GROUNDWATER LEVEL DECLINES IN 5 WESTERN STATES



Water levels have recovered in some area from reduction in pumping and increased groundwater recharge (Leake and others, 2000).

SUBSIDENCE FOR SELECTED LOCATIONS IN SOUTHWEST US.

State	Location	Subsidence		Years	Reference
Arizona	Eloy	12.5 ft	381 cm	1969	Schumann and Poland, 1969
		>15 ft	457 cm	1952-1985	Arizona Bureau of Geology and Mineral Technology, 1987
	Stanfield	11.8 ft	360 cm	1977*	Laney et al., 1978
	Queen Creek	3 ft	91 cm	1977*	ALGS**, 2007
	Northeast Phoenix	5 ft	152 cm	1962-1982	ALGS, 2007
	Bowie	6 ft	183 cm	1952-1982	Strange, 1983
	Tucson	<1 ft	<30 cm	1997*	Leake, 1997
		0.5 ft	15 cm	1952-1980	Schumann and Anderson, 1988
		4.3 ft	131 cm	1989-2005	Carruth, 2007
	Luke Air Force Base	18 ft	549 cm	1992*	Carpenter, 1999
	Northwest Avra Valley	1 ft	30 cm	1948-1980	Schumann and Anderson, 1988
		1.7 ft	52 cm	1989-2005	Carruth, 2007
Nevada	Las Vegas	6 ft	183 cm	1997*	Leake, 1997
New Mexico	Albuquerque	< 1 ft	<30 cm	1997*	Leake, 1997
	Mimbres Basin	2 ft	61 cm	1997*	Leake, 1997
California	Lancaster	6 ft	183 cm	1997*	Leake, 1997
	Southwest of Mendota	29 ft	884 cm	1997*	Leake, 1997
	Davis	4 ft	122 cm	1997*	Leake, 1997
	Santa Clara Valley	12 ft	366 cm	1997*	Leake, 1997
	Ventura	2 ft	61 cm	1997*	Leake, 1997
Texas	El Paso	1 ft	30 cm	1997*	Leake, 1997
	Houston	9 ft	274 cm	1997*	Leake, 1997

* This is the year in which the amount of subsidence was reported in the literature.

**Arizona Land Subsidence Group.

EXAMPLES OF LAND SUBSIDENCE

San Joaquin Valley southwest of Mendota, California.

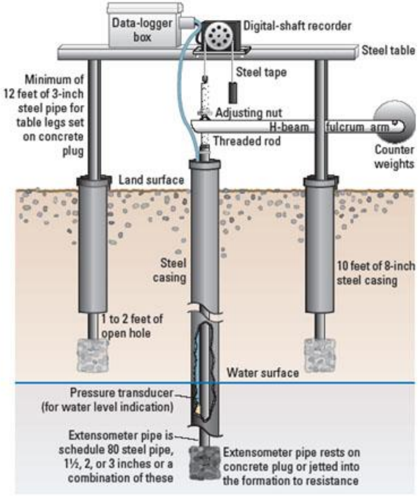
South of Eloy, Arizona. Subsided more than 15 feet between 1952 – 1985

[Arizona Bureau of Geology and Mineral Technology, 1987]

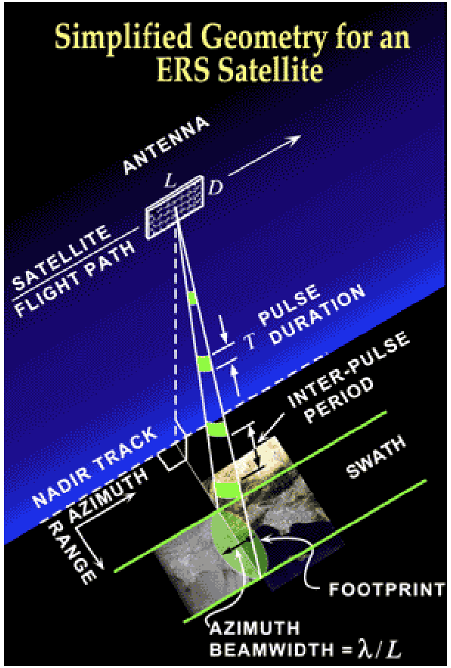
MONITORING LAND SUBSIDENCE

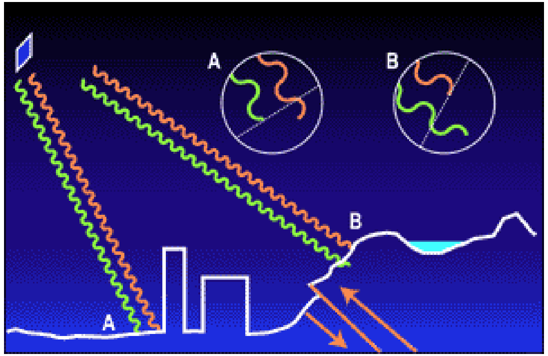
- Land surveys
- Aerial surveys
- Lidar
- GPS

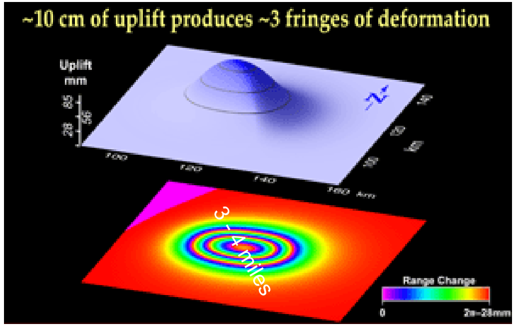
- Compaction recorder



INTERFEROMETRIC SYNTHETIC APERTURE RADAR (InSAR)

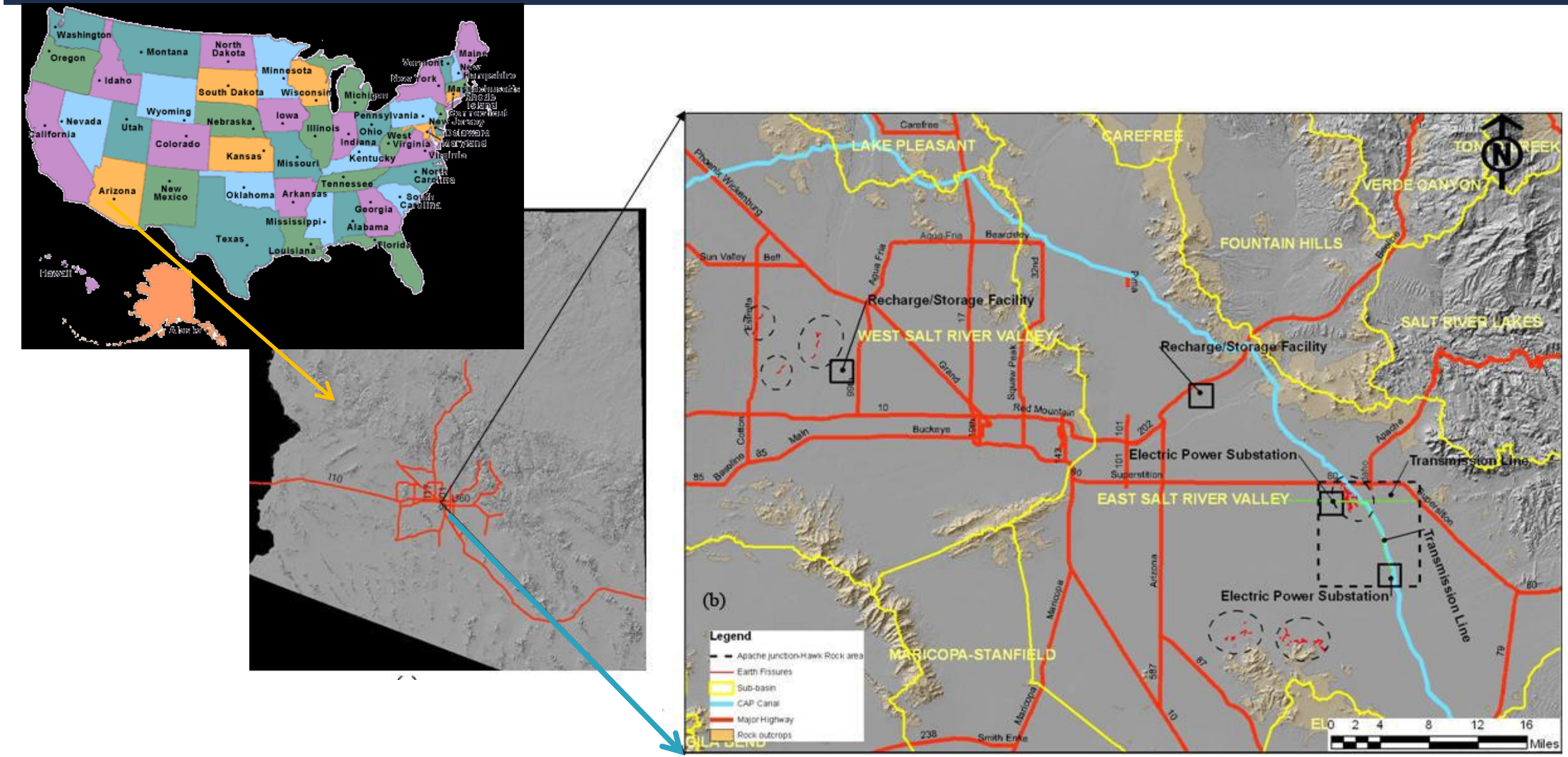




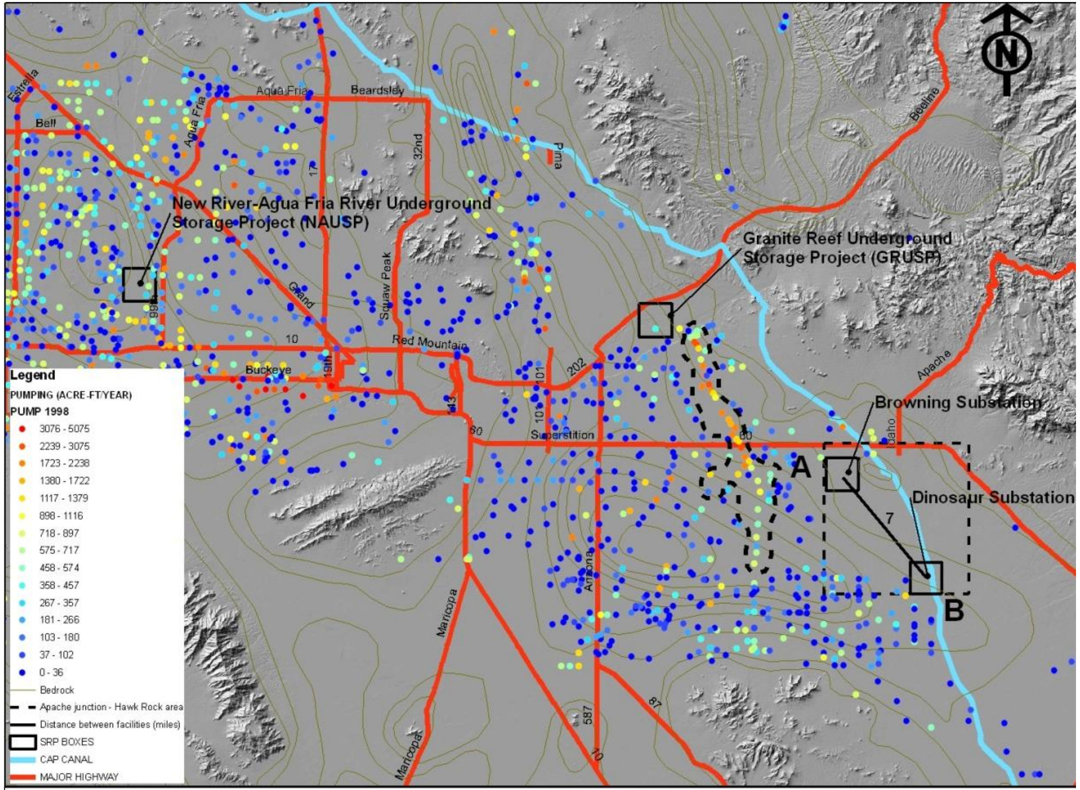


http://www.esa.int/

SALT RIVER VALLEY



WELLS IN PART OF SALT RIVER VALLEY

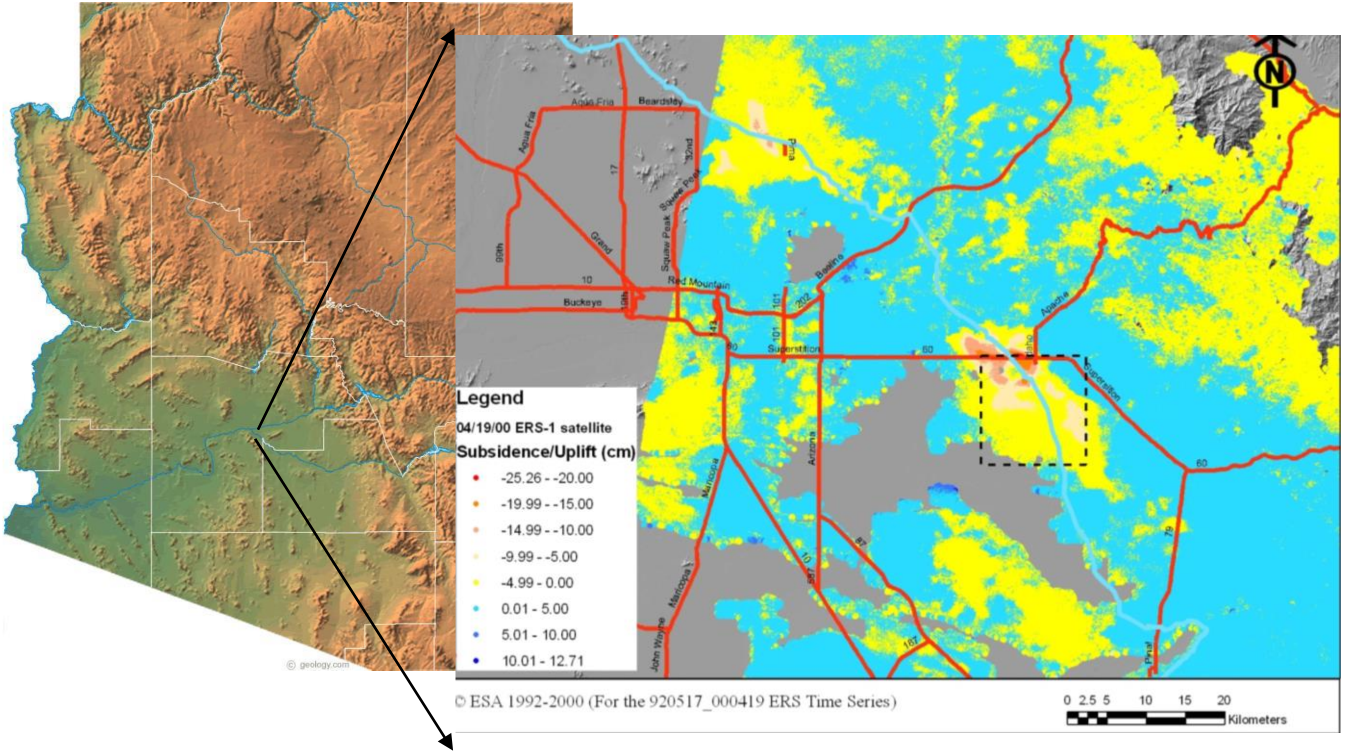


Locations of Wells and Volume Pumped in 1998

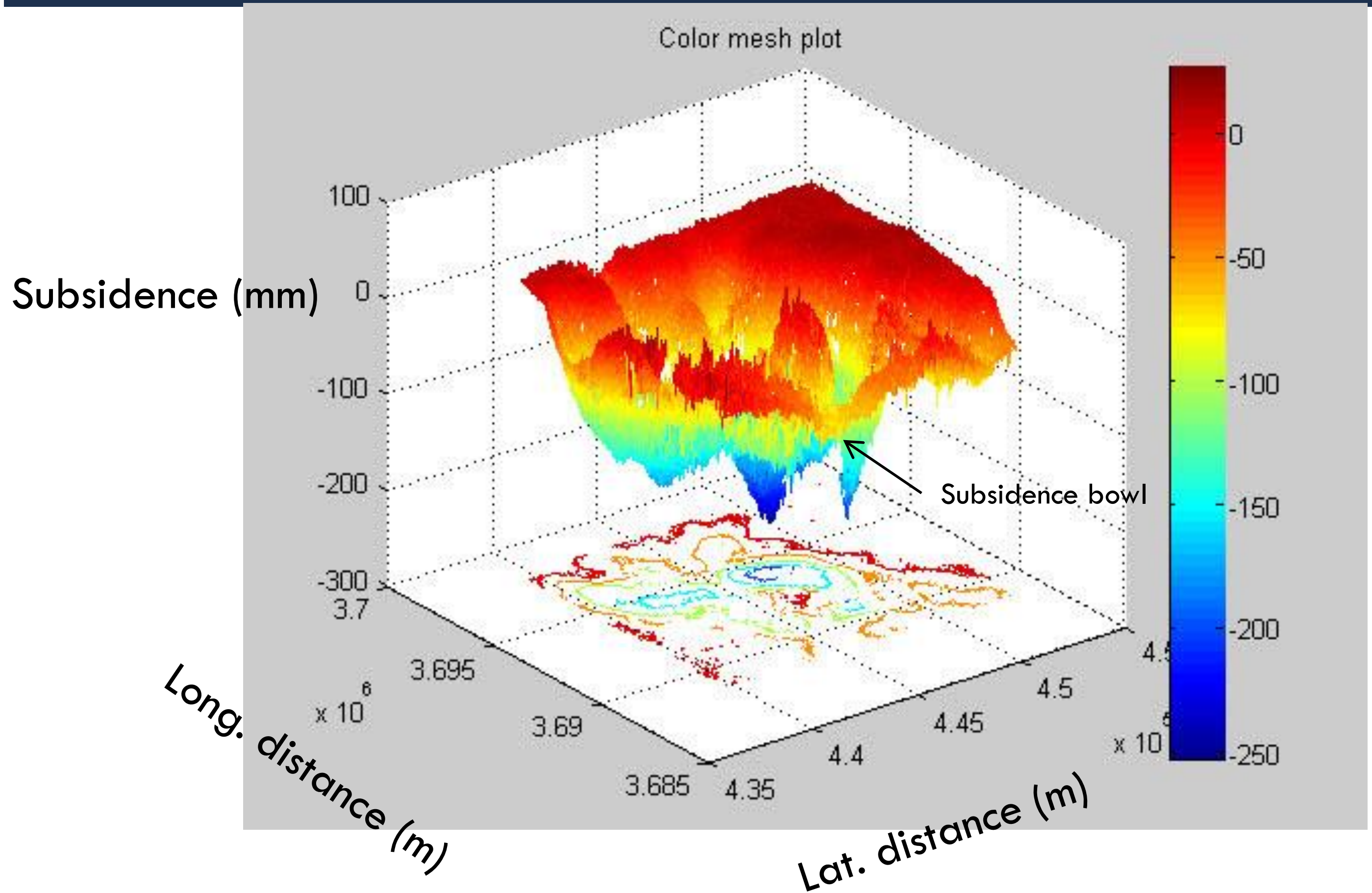
0 1 2 4 6 8 Miles

Data from ADWR

LAND SUBSIDENCE IN PART OF SALT RIVER VALLEY FROM InSAR



MEASURED SUBSIDENCE USING InSAR NEAR BROWNING SUBSTATION



IMPACTS OF LAND SUBSIDENCE

- Enhanced Flooding
- Damage to infrastructure
- Damages to utilities
  - Electric transmission lines, gas and water pipes, cables
  - Reversal of flow in canals and irrigation systems
  - Damage to well-casings
- Land use
- Earth fissures

Flooding of Happy Road, Queen Creek, Arizona

Image: Courtesy Ray Harris

EARTH FISSURES

Earth fissure in an open range.

Image: Courtesy, Ray Harris

Earth fissure winding its way through farm/residential land.

Image: Courtesy, Ken Fibelkorn

Earth fissure identified during trenching near an earth dam.

Image: Courtesy. Mike Rucker, AMEC.

THREATS TO TRANSPORTATION , LIFE LINE SYSTEMS AND ENVIRONMENT

Image: Larry Fellows

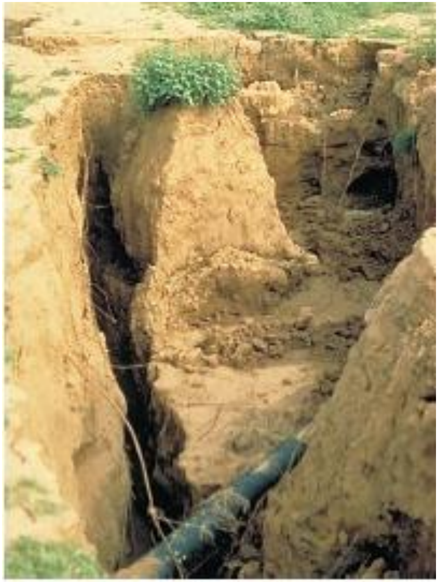


Image: USGS

Image: Ken Fibelkorn

Image: Larry Fellows

LAND USE

Image. Boggan, 2008

S.R. Anderson/U.S. Geological Survey

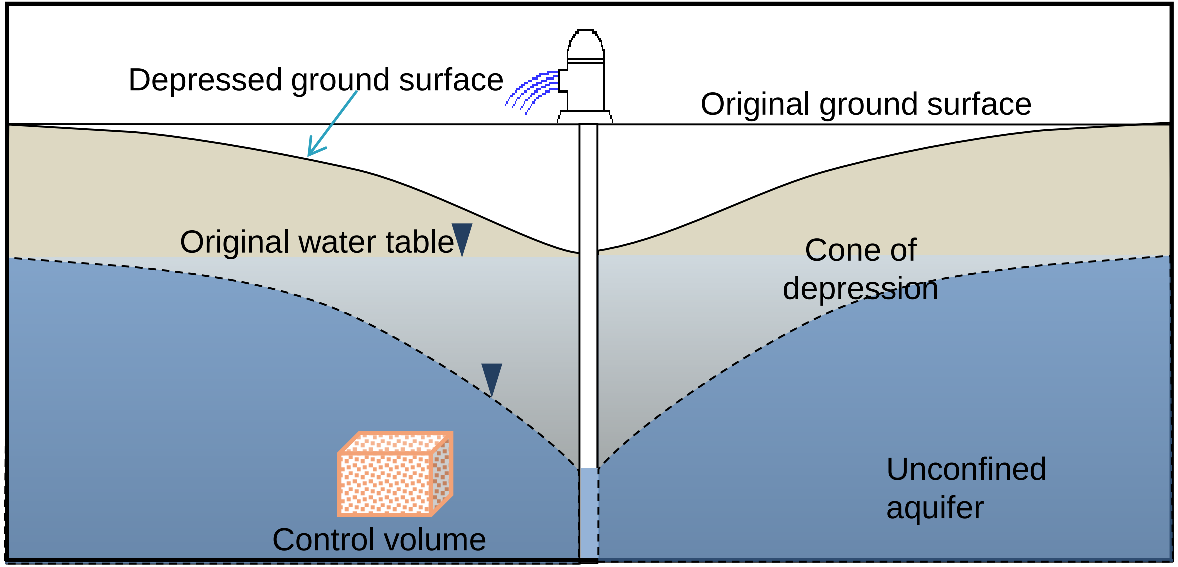
Sign warning motorists of subsidence hazard was erected after an earth fissure damaged Snyder Hill Road in Pima County, Arizona, 1981.

OPENING OF AN EARTH FISSURE FROM EROSION

Images Courtesy, Ken Fibelkorn

What is our understanding on land subsidence and earth fissures?

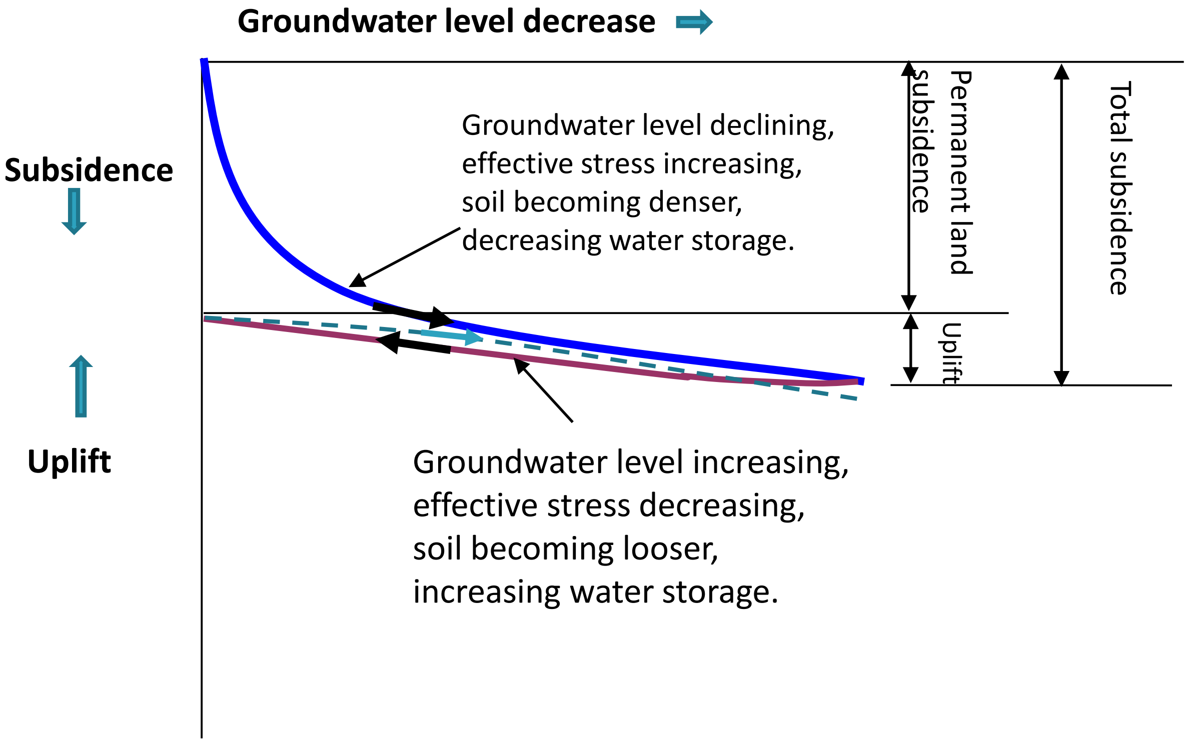
GROUNDWATER AND GROUND SURFACE CHANGES FROM PUMPING



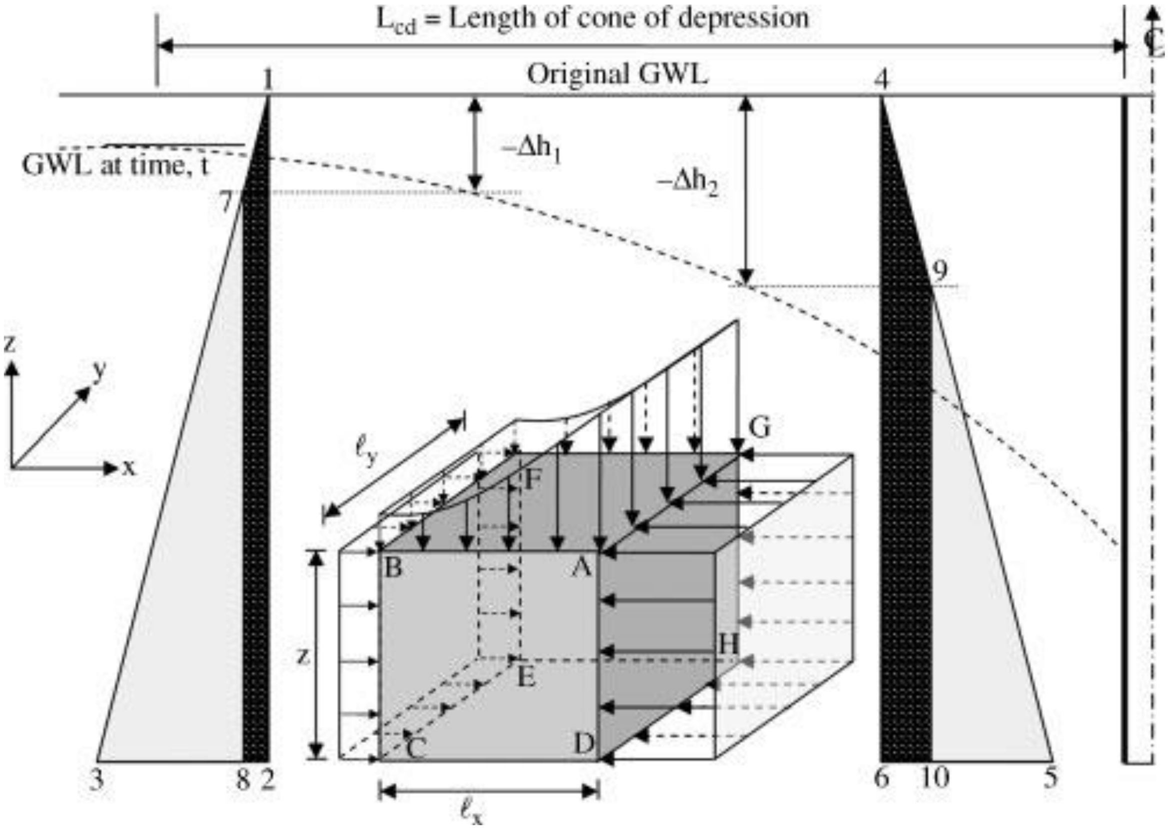
Groundwater level decreases

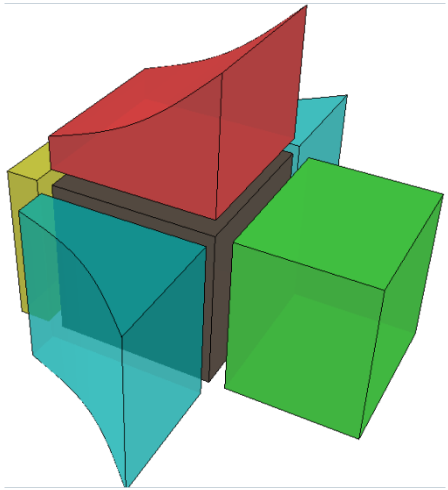
Equivalent stress changes transferred to the soil particles → Soil settles

GROUNDWATER EXTRACTION/RECHARGE ON GROUND DISPLACEMENT AND WATER STORAGE CAPACITY



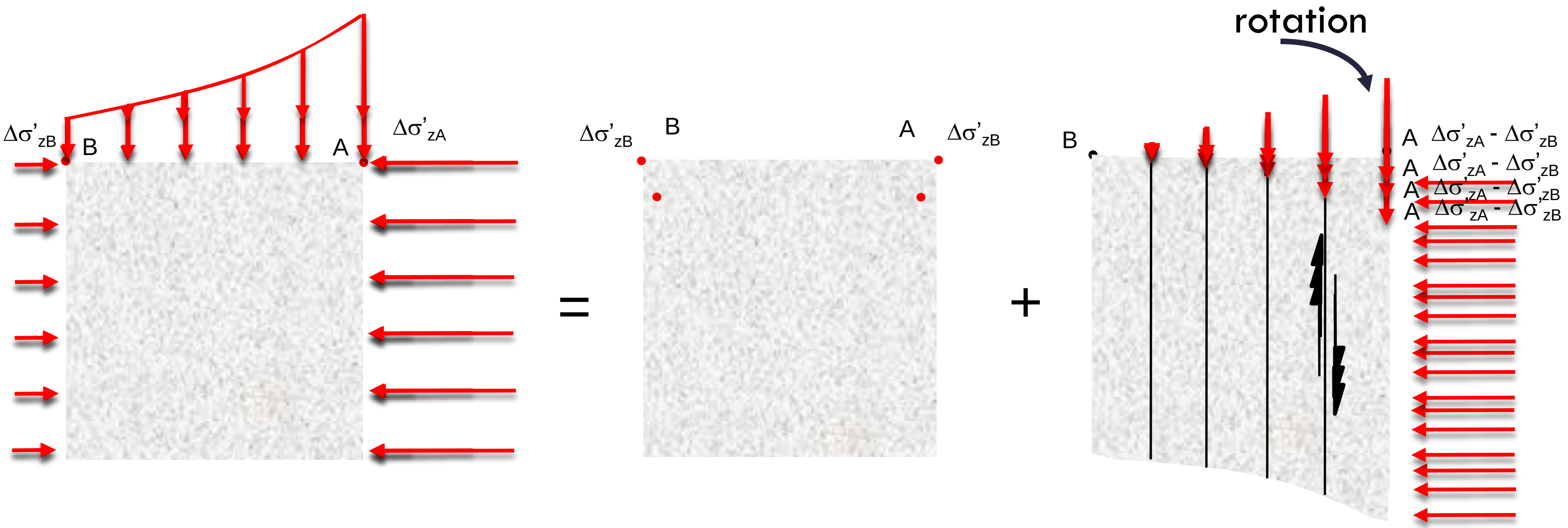
STRESSES FROM GROUNDWATER DECLINE





Budhu, M. and Adiyaman, I. 'Mechanics of Land Subsidence due to Groundwater Pumping,' International Journal for Numerical and Analytical Methods in Geomechanics, Vol. 34, No. 14, 2010, pp. 1459-1478.

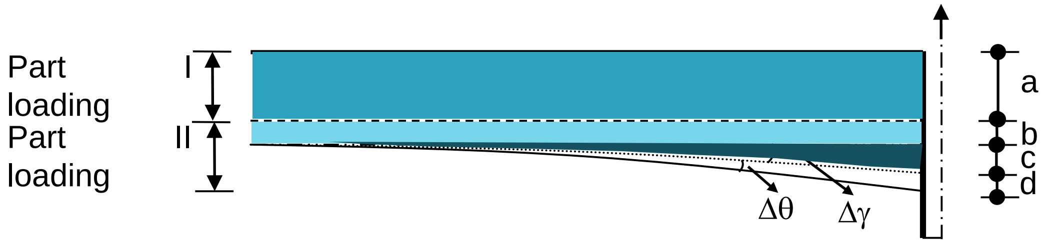
SOIL DEFORMATION FROM GROUNDWATER DECLINE



Isotropic consolidation

Simple shear on vertical planes

RESULTS: COMPONENTS OF LAND SUBSIDENCE

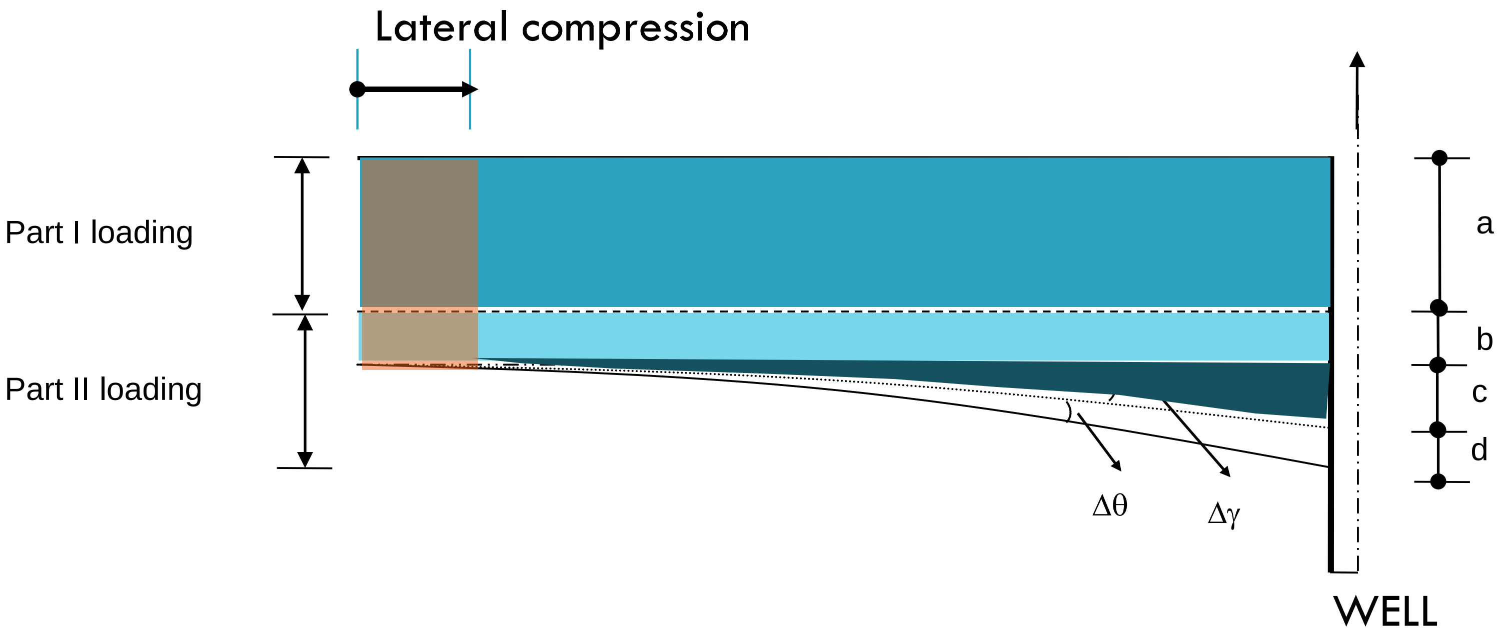


Components of land subsidence from groundwater pumping.

a = subsidence due to hydrostatic consolidation (compression, compaction)
b = subsidence due to consolidation settlement from simple shearing
c = subsidence due to simple shear on vertical plane
d = subsidence due rotation (when micro-rotation = macro-rotation)
$\Delta\theta$ = change in rotation
$\Delta\gamma$ = change in simple shear strain

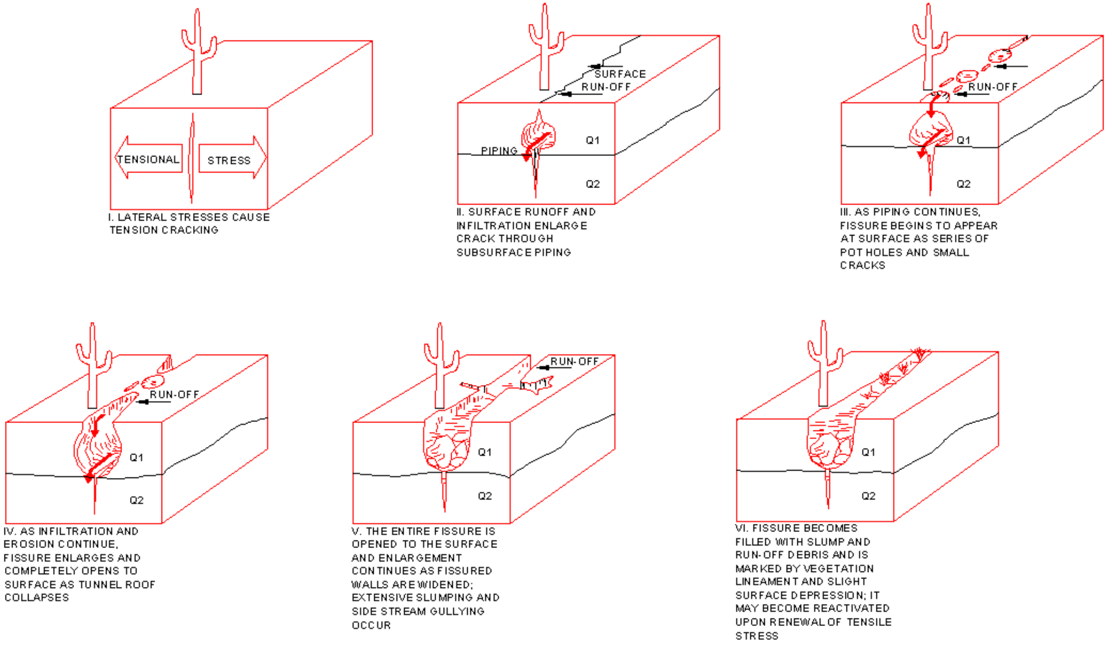
Budhu, M. and Adiyaman, I. "Mechanics of land subsidence due to groundwater pumping." International Journal for Numerical and Analytical Methods in Geomechanics, Vol 34 (14), 2010, pp.: 1459-1478.

RESULTS: LATERAL COMPRESSION



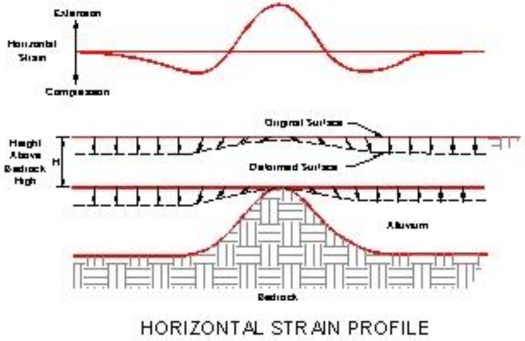
Budhu, M. and Adiyaman, I. “Mechanics of land subsidence due to groundwater pumping.” International Journal for Numerical and Analytical Methods in Geomechanics, Vol 34 (14), 2010, pp.: 1459-1478.

THE MECHANICS DO NOT SHOW THESE TENSILE STRESSES



After Bell, 1981

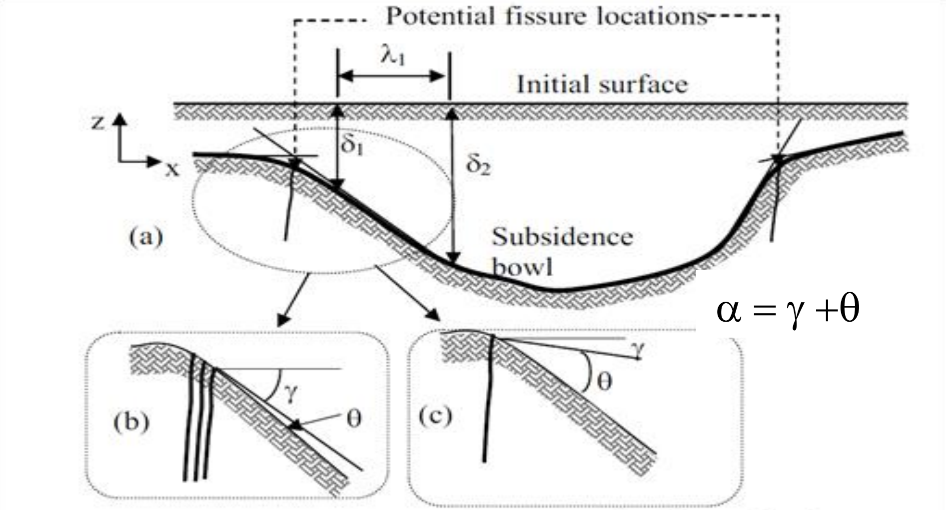
Bending Beam Model



After Jachens and Holzer (1979 and 1982)

RESULTS: PREDICTION OF THE FORMATION OF EARTH FISSURES

- Slope of subsidence bowl is a good indication of the possible initiation of earth fissures.
- Slope must be calculated over a distance of about √2 times aquifer thickness or thickness of top cemented layer.
- EF location can be predicted by the intersection of the slopes of the subsidence bowl slope and the upper curve.

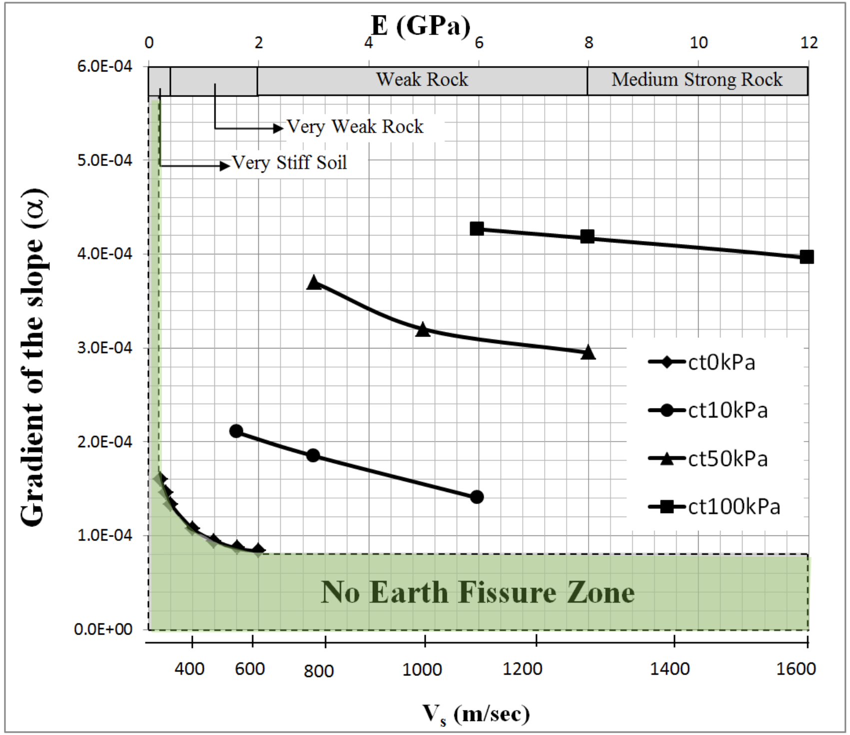


Large shear strain, γ, small rotation, θ → multiple, parallel earth fissures

Large rotation, θ, small shear strain, γ → single earth fissure

Budhu, M. "Earth Fissure Formation from the Mechanics of Groundwater Pumping." International Journal of Geomechanics, Vol. 11(1), 2011, pp.1-11.

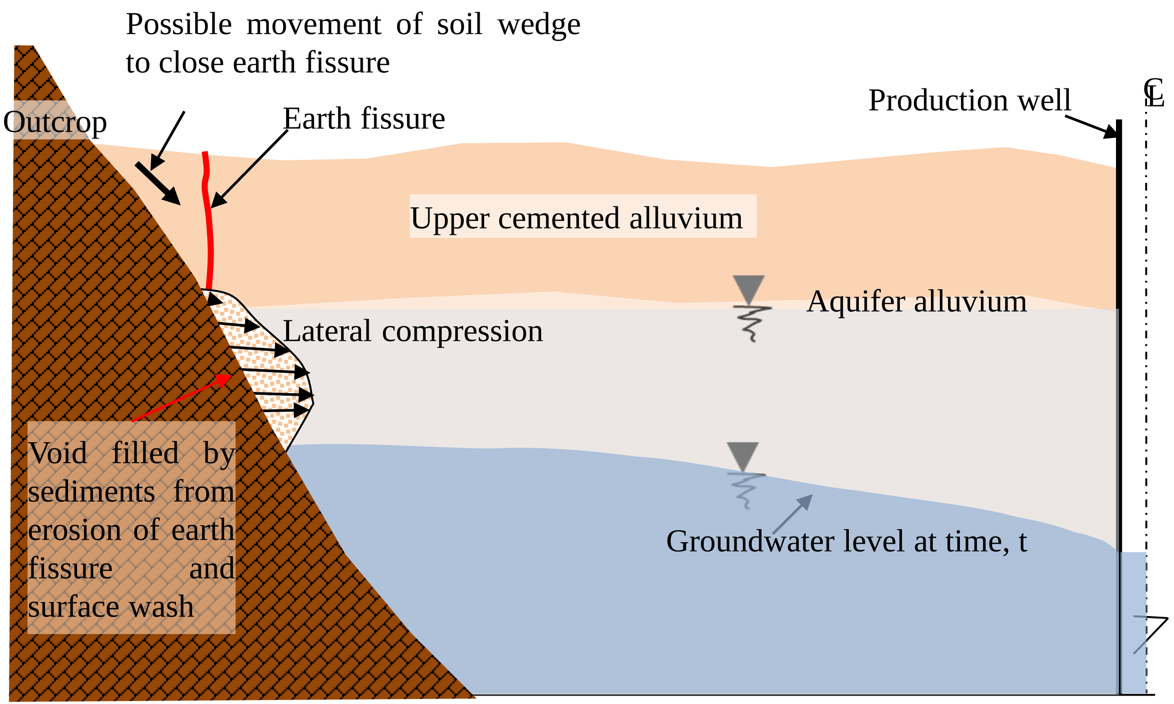
RESULTS: SLOPES FOR INITIATION OF EARTH FISSURES: TOP CEMENTED SOIL



- Important finding for groundwater management
  - Earth fissures will not form if the slope of the "subsidence bowl" is less than 8 x 10^{-5} (0.008%) regardless of soil type, pumping rate and volume pumped.

Budhu, M. and Adiyaman, I. 'Earth Fissure Formation from Groundwater Pumping and the Influence of a Stiff Upper Cemented Layer,' Quarterly Geology and Hydrogeology, vol. 25, 2012, pp. 197-205.

RESULTS: WHAT HAPPENS WHEN AN OUTCROP IS ENCOUNTERED?



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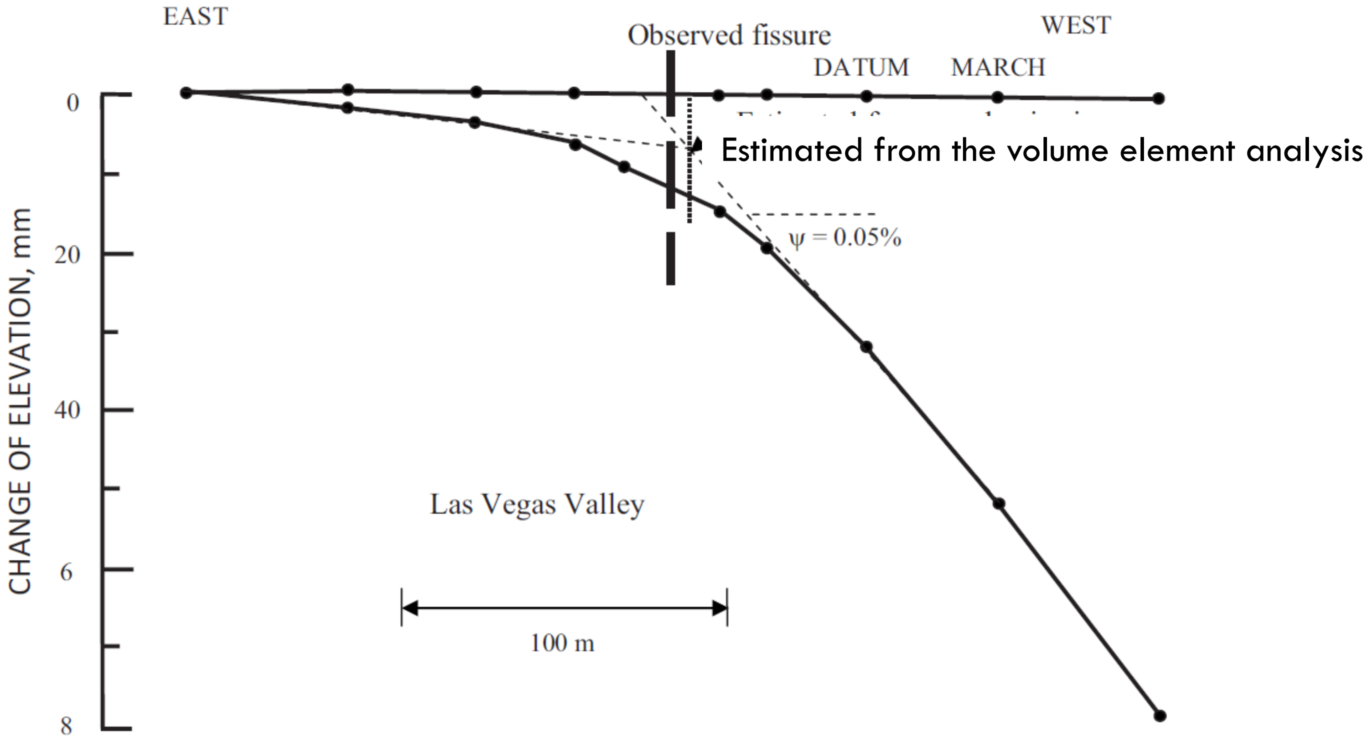
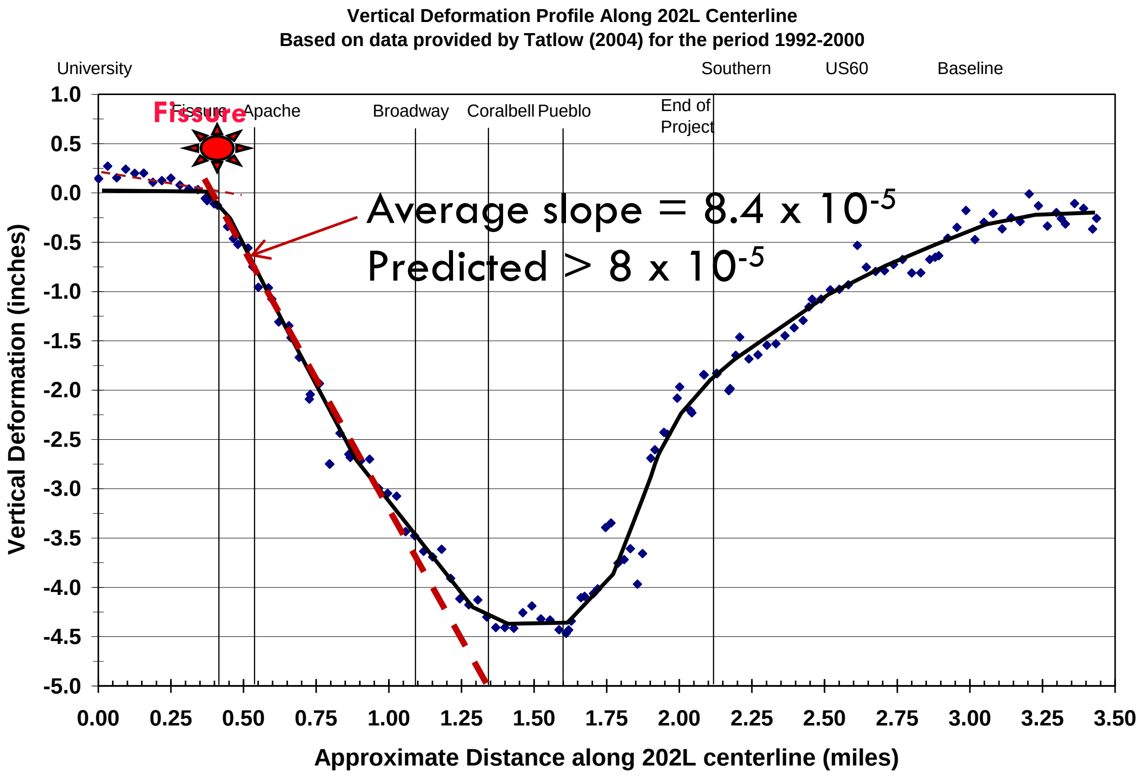
PRACTICAL APPLICATION OF RESULTS: EARTH FISSURE INITIATION AND LOCATION



EF location at a site in Las Vegas Valley, Nevada. Data and observations made by Holzer 1984

Budhu, M. "Earth Fissure Formation from the Mechanics of Groundwater Pumping." International Journal of Geomechanics, Vol. 11(1), 2011, pp.1-11.

PRACTICAL APPLICATION OF RESULTS: EARTH FISSURE INITIATION AND LOCATION



Graph: Courtesy Dr. Samtani, NCS Consultants, LLC

What can we do to mitigate negative effects of land subsidence and earth fissures?

SOME POSSIBLE SOLUTIONS

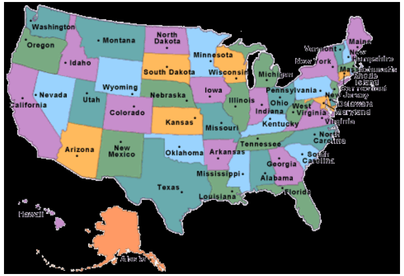
- Stop pumping groundwater
- Aquifer recharge

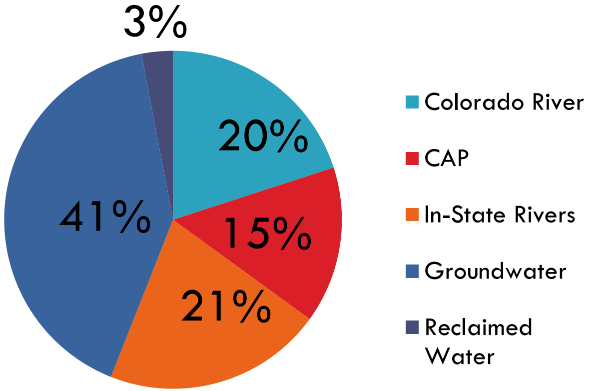
  Muniram Budhu, Rashidatu Ossai, and Ibrahim Adiyaman (2014). "Ground Movements from Aquifer Recharge and Recovery." *J. Hydrol. Eng.*, 19(4), 790–799.

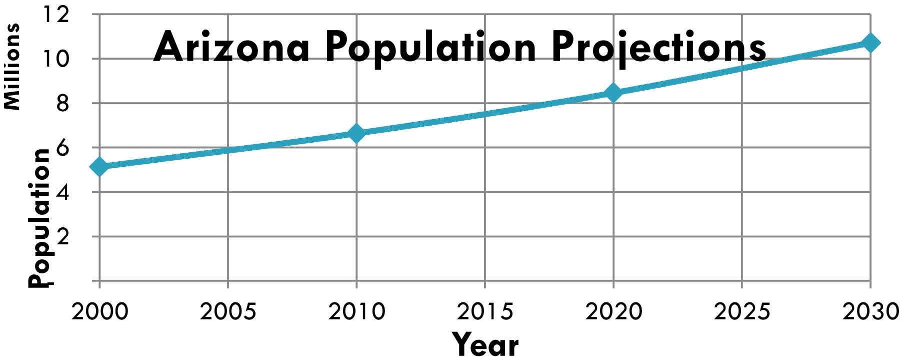
- Manage groundwater extraction and aquifer recharge
  - reduce negative effects of subsidence and reduce the potential for earth fissure initiation.

WATER FOR THE FUTURE

Water use

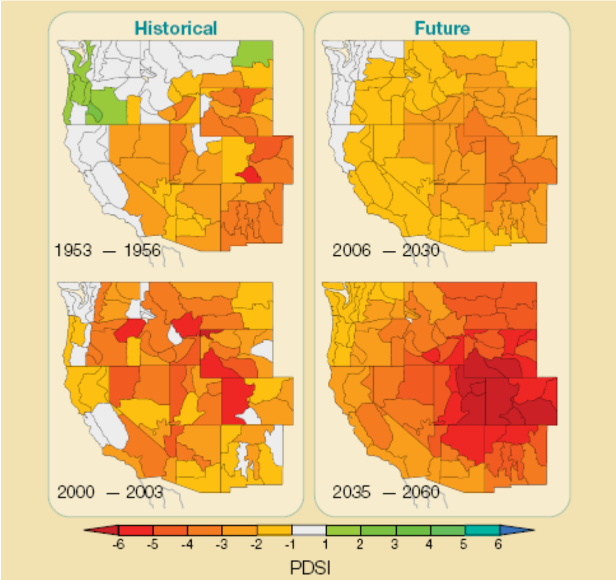






[US Population Projections from the US Census Bureau]

Climate change

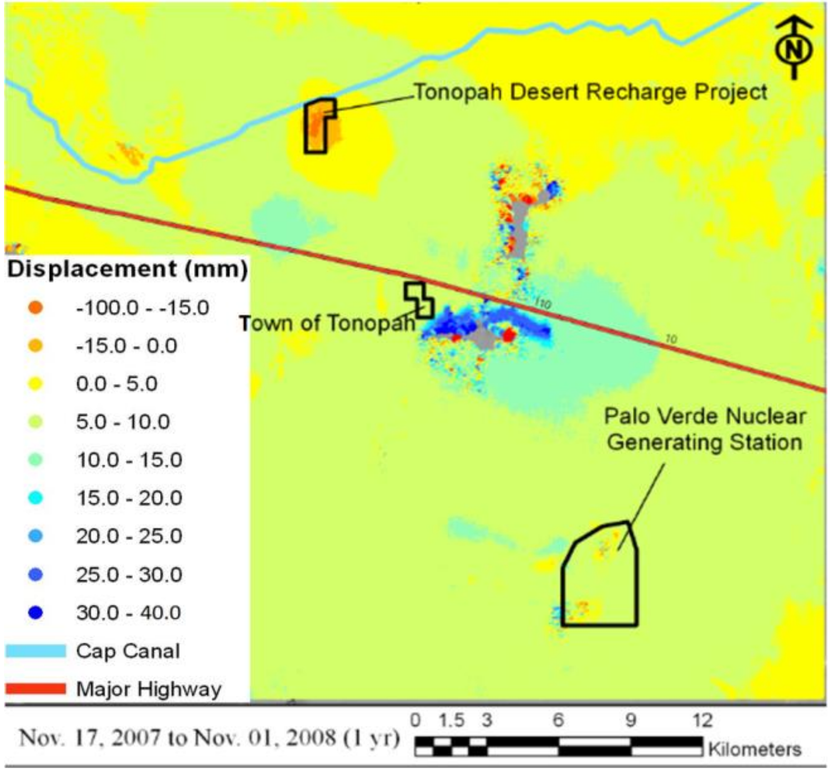


Palmer Drought Severity Index (PDSI). Values less than -3 denote severe drought conditions. Left panels illustrate the 4-year average drought conditions experienced during the 1950s drought and the recent drought. Right panels are future projections of the PDSI based on 42 simulations conducted to support the Fourth Assessment Report of the IPCC. By about 2050, average moisture balance conditions will mimic conditions experienced only rarely at the height of the most severe historical droughts.

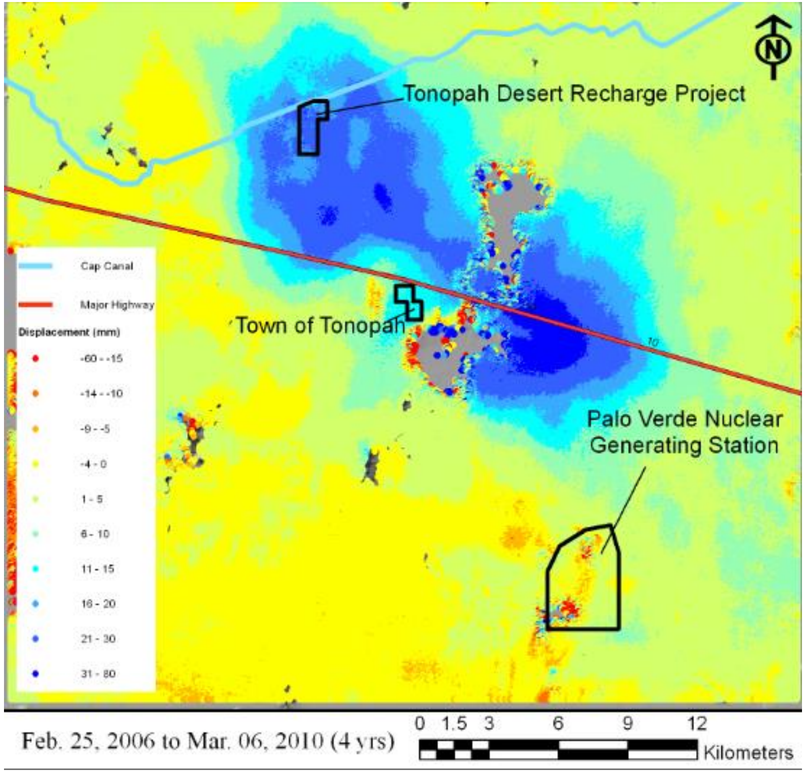
Hoerling, M., 2007, Past Peak: Water in the Southwest, Southwest Hydrology, Volume 6, Number 1, January/February.

GROUND MOVEMENTS FROM TDRP

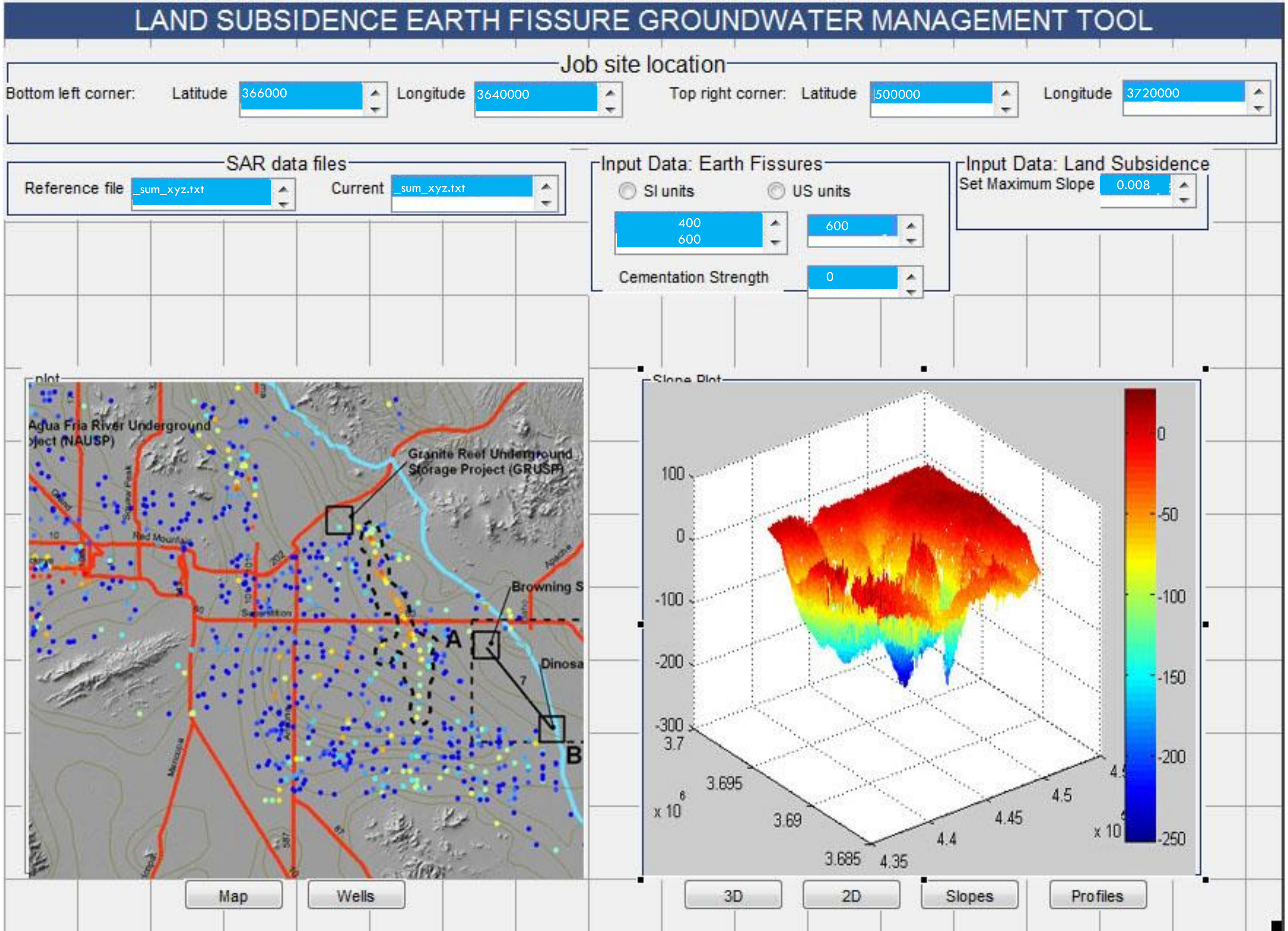
OUTAGE



AFTER 4 YEARS OF OPERATION



HOW CAN OUR ANALYSIS OF LS AND EF FORMATION BE USED FOR SUSTAINABLE GROUNDWATER MANAGEMENT?


LAND SUBSIDENCE EARTH FISSURE GROUNDWATER MANAGEMENT TOOL
Job site location
Bottom left corner:
Latitude
366000
Longitude
3640000
Top right corner:
Latitude
500000
Longitude
3720000
SAR data files
Reference file
_sum_xyz.txt
Current
_sum_xyz.txt
Input Data: Earth Fissures
SI units
US units
400
600
600
Cementation Strength
0
Input Data: Land Subsidence
Set Maximum Slope
0.008
Agua Fria River Underground
Granite Reef Underground Storage Project (GRUSP)
Browning S
Dinosa
A
B
100
0
-100
-200
-300
3.7
3.695
3.69
3.685
4.35
4.4
4.45
4.5
0
-50
-100
-150
-200
-250
Map
Wells
3D
2D
Slopes
Profiles

CONCLUSIONS

- Land subsidence comprises settlement from (a) hydrostatic consolidation and (b) simple shearing and rotation.

- Earth fissures will not initiate in any soil or from any pumping regime if the slope of the subsidence bowl is less than 0.008%.

CONCLUSIONS

- Low hydraulic conductive geo-materials
  - Responsible for large ground movements
  - "Delayed" ground movements
  - Harmonic (wavy) ground movements
  - Affect flow patterns

CONCLUSIONS

- Ground slope is the key to managing groundwater considering land morphology.
- Remote sensing using InSAR is an excellent tool to collect the monitoring data for use with the model results.