Land Subsidence:

The Lowdown on the Drawdown

Michelle Sneed
California Water Science Center
U.S. Geological Survey
2016
Land Subsidence

- Land subsidence is a gradual settling or sudden sinking of the Earth’s surface owing to surface or subsurface movement of earth material.

- More than 80% of the identified 17,000 square miles of land affected by subsidence in the Nation is a consequence of our exploitation of groundwater (National Research Council, 1991).

- Most of the groundwater related subsidence is caused by the compaction of susceptible alluvial aquifer systems that typically accompanies overdraft of these systems.
Global Subsidence

Reported subsidence caused by groundwater withdrawal

Maximum Areas Affected: China, USA
Maximum Magnitudes: Mexico, USA, Japan
Reported subsidence caused by groundwater withdrawal

Maximum Areas Affected: California, Arizona
Maximum Magnitudes: California, Arizona, Texas, Nevada
CA Basins with Subsidence History

Reported subsidence caused by fluid (mostly water) withdrawal

<table>
<thead>
<tr>
<th>ID</th>
<th>Location Name</th>
<th>Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Antelope Valley</td>
<td>W</td>
</tr>
<tr>
<td>13</td>
<td>Antin-Bakersfield-Maricopa area (San Joaquin Valley)</td>
<td>W, O&amp;G</td>
</tr>
<tr>
<td>14</td>
<td>Chino Basin (and adjacent Claremont and Pomona basins)</td>
<td>W</td>
</tr>
<tr>
<td>15</td>
<td>Coachella Valley</td>
<td>W</td>
</tr>
<tr>
<td>16</td>
<td>Elsinore Trough (Elsinore, Temecula and Wolf valleys)</td>
<td>W</td>
</tr>
<tr>
<td>17</td>
<td>Fremont Valley</td>
<td>W</td>
</tr>
<tr>
<td>18</td>
<td>Los Banos-Kettleman City area (San Joaquin Valley)</td>
<td>W</td>
</tr>
<tr>
<td>19</td>
<td>Lost Hills-Belfridge (San Joaquin Valley)</td>
<td>O&amp;G</td>
</tr>
<tr>
<td>20</td>
<td>Lucerne Valley</td>
<td>W</td>
</tr>
<tr>
<td>21</td>
<td>Mojave River Basin</td>
<td>W</td>
</tr>
<tr>
<td>22</td>
<td>Paso Robles</td>
<td>W</td>
</tr>
<tr>
<td>23</td>
<td>Redondo Beach</td>
<td>O&amp;G</td>
</tr>
<tr>
<td>24</td>
<td>Sacramento Valley</td>
<td>W</td>
</tr>
<tr>
<td>25</td>
<td>San Bernardino</td>
<td>W</td>
</tr>
<tr>
<td>26</td>
<td>San Jacinto Basin</td>
<td>W</td>
</tr>
<tr>
<td>27</td>
<td>Santa Ana Basin</td>
<td>W</td>
</tr>
<tr>
<td>28</td>
<td>Santa Clara-Calleguas Basin (Oxnard Plain)</td>
<td>W, O&amp;G</td>
</tr>
<tr>
<td>29</td>
<td>Santa Clara Valley</td>
<td>W</td>
</tr>
<tr>
<td>30</td>
<td>Tulare-Wasco area (San Joaquin Valley)</td>
<td>W</td>
</tr>
<tr>
<td>31</td>
<td>Wilmington</td>
<td>O&amp;G</td>
</tr>
</tbody>
</table>

Maximum Areas Affected: San Joaquin, Antelope and Santa Clara Valleys
Maximum Magnitude: San Joaquin, Santa Clara and Antelope Valleys
Subsidence Processes

How are subsidence processes in the Delta different than processes in other parts of California (Central Valley, Santa Clara Valley, Coachella Valley)?
Land Subsidence in the Delta

A surficial process: Oxidation of Peat

Pre-reclamation land surface

Peat lost to primary subsidence from initial reclamation

Present land surface

Compacted and oxidized peat layer

Partially compacted but unoxidized

Uncompacted and unoxidized peat

Epiclastic sediment (clay, silt, and sand)

Peat lost to secondary subsidence

Mean sea level

Channel

Levee

Artificial water table

Compaction front

Not to scale

Courtesy of Judith Drexler, USGS
Land Subsidence in the San Joaquin Valley
A deep process: Aquifer-System Compaction

- Concentrated in the fine-grained deposits (aquitards)
- Inelastic (irreversible) compaction occurs when the preconsolidation stress is exceeded
- Preconsolidation stress $\approx$ previous lowest groundwater level
- Storage capacity is reduced

Galloway and others, 1999; USGS Circular 1182
Subsidence Damages Natural Resources and Infrastructure

► Flood Protection and Infrastructure
  - Damage to water conveyance systems and other infrastructure
    - Reduced conveyance capacity and freeboard, panel damage; water surface and liner misalignment; erosion/deposition in unlined channels
    - Roads, rails, bridges, pipelines, wells, etc.

► Natural resources
  - Reduces aquifer-system storage capacity
  - Impacts to wetland, riparian, and aquatic ecosystems
  - Restricted land uses
What is the Economic Impact?

► Vastly underestimated and under reported

Estimated Costs of Subsidence

<table>
<thead>
<tr>
<th>Site</th>
<th>Damages</th>
<th>Costs¹, M $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Santa Clara V.</td>
<td>Levees, wells, sewers, roadways</td>
<td>375</td>
</tr>
<tr>
<td>San Joaquin V.</td>
<td>Canals; design modifications</td>
<td>145</td>
</tr>
<tr>
<td>Long Beach</td>
<td>Flood; structural</td>
<td>600</td>
</tr>
</tbody>
</table>

Sources: Fowler, 1981; Freeze, 2000; NRC, 1991

 Courtesy of Devin Galloway, USGS
Measuring Subsidence

Bench Mark

InSAR

Spirit Leveling

GPS

Extensometer*

*measures part of land subsidence
Subsidence Measurement Methods

Classification by Spatial Density

- One to Several Points
  - Borehole Extensometry*

- Tens of Points
  - Spirit Leveling
  - GPS (RTK/static/continuous)

- Millions of Points
  - InSAR
  - Airborne LiDAR
  - Tripod LiDAR

* Measures aquifer-system compaction

Classification by Temporal Density

- <One-two measurement/year
  - Spirit Leveling
  - GPS (RTK, static)

- Several measurements/year
  - InSAR
  - Airborne/Tripod LiDAR

- 1000’s measurements/year
  - Borehole Extensometry*
  - GPS (continuous)
Combine Measurement Methods

► Guide terrestrial monitoring schemes
  ▪ InSAR’s spatial resolution can help target limited monitoring resources where most needed

► Groundtruth InSAR data
  ▪ Spirit leveling or GPS can validate/calibrate

► Improve spatial/temporal resolution of sparse data
  ▪ InSAR (spatial and temporal)
  ▪ CGPS (temporal)

► Determine coarse depth intervals of compaction
  ▪ GPS/InSAR/leveling data at an extensometer

► The list goes on…
Current and Recent Subsidence Studies in CA

► **Active subsidence studies**
  - Central Valley
  - Coachella Valley
  - Fort Irwin
  - Mojave River Valley
  - East Bay Plain
  - San Bernardino area
  - Santa Clara Valley

► **Recently active subsidence studies**
  - Antelope Valley
  - Cuyama Valley
  - San Diego
Central Valley Facts:

- 20,000 square miles
- Using about 1% of U.S. farmland, California’s Central Valley
  - Produces more than 250 different crops
  - Supplies 7% of the U.S. agricultural output (by value) — 1/4 of the Nation’s food, including about half of the Nation’s fruits, nuts, and vegetables
- Approximately 20% of the Nation’s groundwater is pumped from the Central Valley aquifer system.
Subsidence Summary

► 7,500 km² (2,900 mi²) subsided 50-540 mm (2-21 inches) during 2008-10; data indicate these rates have continued through 2016

► Adversely affecting water conveyances and other infrastructure
  ▶ Delta-Mendota Canal, San Joaquin River, Eastside Bypass system, Friant-Kern Canal, California Aqueduct, numerous local canals

► Subsidence occurred when groundwater levels declined as a result of pumping
  ▶ Water levels continue to decline; near or lower than historical lows

► Subsidence is largely permanent

► Long-term monitoring of water levels and subsidence is needed to detect and track groundwater conditions for decision support
Extensive withdrawal of groundwater caused widespread subsidence (1920s-1970)

Surface-water deliveries caused widespread recovery and slowing or cessation of subsidence, except when deliveries were curtailed and groundwater pumping increased to meet demand

Galloway and others, 1999; USGS Circular 1182
Recent Subsidence

► Renewed subsidence concern during 2007-09 drought, and now, the current drought
  ▪ Reduced surface water importation
  ▪ More reliance on the groundwater resources
  ▪ As it turns out...this is not just a problem during droughts for some areas without surface-water access

Drought

Subsidence (CGPS P307)

Groundwater Level

Previous lowest level (September, 1992)

CGPS data from UNAVCO; water level data from DWR, USGS, and Luhdorff and Scalmanini Consulting Engineers
Loss of capacity reported at Check Station 7 in April 2014, where flow was restricted because of subsidence upstream (Checks 2-6). The short-lived opportunity to fill San Luis Reservoir was impacted.
Delta-Mendota Canal Altitudes Simulated with CVHM

Graph showing the altitude simulation of Delta-Mendota Canal with and without deformable mesh, with points labeled ck1, ck6, ck11, ck16, and ck21.
InSAR Subsidence Measurements: Maximum Subsidence Area near El Nido, between Eastside Bypass and San Joaquin River

EXPLANATION
- Selected water conveyance features

Land Subsidence (2008-10)

- Inches
- 1. Estimated
- 1 - 2
- 2 - 4
- 4 - 6
- 6 - 11
- 11 - 16
- 16 - 21
- > 21

Preliminary and subject to revision
Subsidence: Eastside Bypass

A Preliminary and subject to revision

Rate increases during droughts

Rate increases during droughts

Subsidence only during droughts

Vertical deformation along bypass

USGS science for a changing world
Poland-Style 2.0

Eastside Bypass

Preliminary and subject to revision
Poland-Style 2.0

Eastside Bypass

H 1235 RESET

16 years: 2.3 ft

4 years: 0.6 ft

5 years: 1.9 ft

1988-2013 4.8 ft

Preliminary and subject to revision
Poland-Style 2.0

27 years: 1.2 ft
5 years: 2.2 ft
1981-2013 3.4 ft
Recent Subsidence: Pixley

Preliminary and subject to revision
GPS Measurements near Pixley

CGPS data from UNAVCO; subsidence contours are preliminary and subject to revision.
Groundwater-Level Declines and Geologic Setting are Causing High Subsidence Rates

Groundwater-level declines
- More than 180 ft since the late 1960s
- Some reached historical lows during 2007-10 and since 2013

Geologic setting – presence of compactable materials (clay)
- Sub-Corcoran fine-grained sediments
- Chowchilla, Fresno, Kaweah, Tule River Fans
Groundwater Levels Declined 2007-10 and since 2012

Water level data from USGS and Luhdorff and Scalmanini Consulting Engineers; Preliminary and subject to revision
Most Compaction Occurred Below the Corcoran Clay
8,500 Central Valley well logs
Central Valley Hydrologic Model
Sediment texture & Alluvial fans

- 50 ft thick
- 0-50 ft below land surface

EXPLANATION
Percent coarse-grained material—
> is greater than.

- 0 to 10
- >10 to 20
- >20 to 30
- >30 to 40
- >40 to 50
- >50 to 60
- >60 to 70
- >70 to 80
- >80 to 90
- >90 to 100

Modified from Faunt, 2009 and Weismann and others, 2005
Subsidence contours are preliminary and subject to revision.
Oro Loma

~3 inches of compaction in 2014 and 2015
2016 likely to be less

Preliminary and subject to revision
Panoche

~2 inches of compaction during 2014

almost none during 2015

2016 likely to be similar to 2014

Preliminary and subject to revision
DWR Yard

1-1.5 inches of compaction in 2014 and 2015, 2016 likely to be similar

Preliminary and subject to revision
Rasta

1 inch of compaction in 2014 and 2015, 2016 likely to be similar
Revised subsidence in historical areas

Largest new subsidence
  Adjacent to Sierras where surface-water deliveries for irrigation are less

Additional subsidence in growing urban areas

Nearly 200 million acre-ft from fine-grained sediments in 21st Century

Hanson and others, 2010
What Can Be Done About It?

► Focus on maintaining groundwater levels above the critical threshold
  - Reduction of groundwater withdrawal
    - Decreasing groundwater demand
    - Limiting/redistributing groundwater use
    - Increasing supplemental water supply
  - Enhanced groundwater recharge
    - Artificial recharge: direct well injection or surface infiltration
    - Natural recharge: source protection
Subsidence Summary

► 7,500 km\(^2\) (2,900 mi\(^2\)) subsided 50-540 mm (2-21 inches) during 2008-10; data indicate these rates have continued through 2016

► Adversely affecting water conveyances and other infrastructure

► Subsidence occurred when groundwater levels declined as a result of pumping

► Subsidence is largely permanent

► Long-term monitoring of water levels and subsidence is needed to detect and track groundwater conditions for decision support

Thanks!

For more information:
http://ca.water.usgs.gov/land_subsidince/
Nearly All Compaction Occurred Below the Corcoran Clay:
Oro Loma Extensometer Site (along Delta-Mendota Canal)

- Unconfined aquifer aquitards: >6%
- Corcoran Clay: <3%
- Confined aquifer aquitards: >90%
Historical Subsidence

Preliminary and subject to revision
GPS Subsidence Measurements

Rate increases during droughts

Subsidence only during droughts

CGPS Data from UNAVCO
Subsidence: Eastside Bypass
InSAR Subsidence Measurements:
Maximum Subsidence Area near El Nido, between Eastside Bypass and San Joaquin River

Max of at least 21 inches (2008-10)
DWR Basin Prioritization

► 127 high and medium
(96% of annual pumping; 88% of population)
- Many coincident with areas where subsidence has or is occurring
InSAR-Measured Subsidence

Preliminary and subject to revision