Title:
Water Availability and Subsidence in California's Central Valley

Journal Issue:
San Francisco Estuary and Watershed Science, 13(3)

Author:
Faunt, Claudia C., California Water Science Center, U.S. Geological Survey, San Diego
Sneed, Michelle, California Water Science Center, U.S. Geological Survey, Sacramento

Publication Date:
2015

Permalink:
http://escholarship.org/uc/item/6qn2711x

Keywords:
water supply, groundwater, Central Valley Hydrologic Model, Interferometric Synthetic Aperture Radar, land subsidence, drought

Local Identifier:
jmie_sfews_28790

Abstract:
doi: http://dx.doi.org/10.15447/sfews.v13iss3art4

<Abstracts are not associated with Essays. -The Editors of SFEWS.>

SEPTEMBER 2015

SAN FRANCISCO ESTUARY & WATERSHED SCIENCE

Sponsored by the Delta Science Program and the UC Davis John Muir Institute of the Environment

ESSAY

Water Availability and Subsidence in California's Central Valley

Claudia C. Faunt *[1] and Michelle Sneed[2]

Volume 13, Issue 3 | Article 4

doi: *http://dx.doi.org/10.15447/sfews.v13iss3art4*

* Corresponding author: *ccfaunt@usgs.gov*

1 U.S. Geological Survey
California Water Science Center
4165 Spruance Road, Suite 200
San Diego, CA 92101 USA

2 U.S. Geological Survey
California Water Science Center
6000 J Street, Placer Hall
Sacramento, CA 95819 USA

California's Central Valley covers about 52,000 square kilometers (km^2) and is one of the most productive agricultural regions in the world. More than 250 different crops are grown in the broad alluvial filled structural trough, with an estimated value exceeding $20 billion per year (Faunt 2009) (Figure 1). Central Valley agriculture depends on state and federal water systems that divert surface water, predominantly originating from Sierra Nevada snowmelt, to agricultural fields. Because the valley is semi-arid and the availability of surface water varies substantially from year to year, season to season, and from north to south, agriculture, as it grew, developed a reliance on groundwater for irrigation.

The extensive withdrawal of groundwater caused water levels to decline on the west side of the southern two-thirds of the Central Valley, also known as the San Joaquin Valley. Long-term groundwater-level declines resulted in a one-time release of "water of compaction" from compacting fine-grained deposits, which caused land subsidence (Galloway et al. 1999). More than half of the thickness of the Central Valley aquifer system is composed of fine-grained sediments, including clays, silts, and sandy or silty clays (Williamson et al. 1989; Faunt 2009), that are susceptible to compaction if depressurized by groundwater pumping. Land subsidence in the Central Valley from groundwater pumping began in the mid-1920s, and by 1970 about half of the San Joaquin Valley, or about 13,500 km^2, had subsided more than 0.3 meters (m) (Poland et al. 1975). Locally, magnitudes reached 9 m by the early 1980s (Ireland 1986).

Partially in response to these groundwater-level declines and associated subsidence, an extensive surface-water delivery system was developed to redistribute some of the water from north to south and east to west. Surface-water imports from the Delta–Mendota Canal (DMC) since the early 1950s and the California Aqueduct since the early 1970s resulted in decreased groundwater pumping in

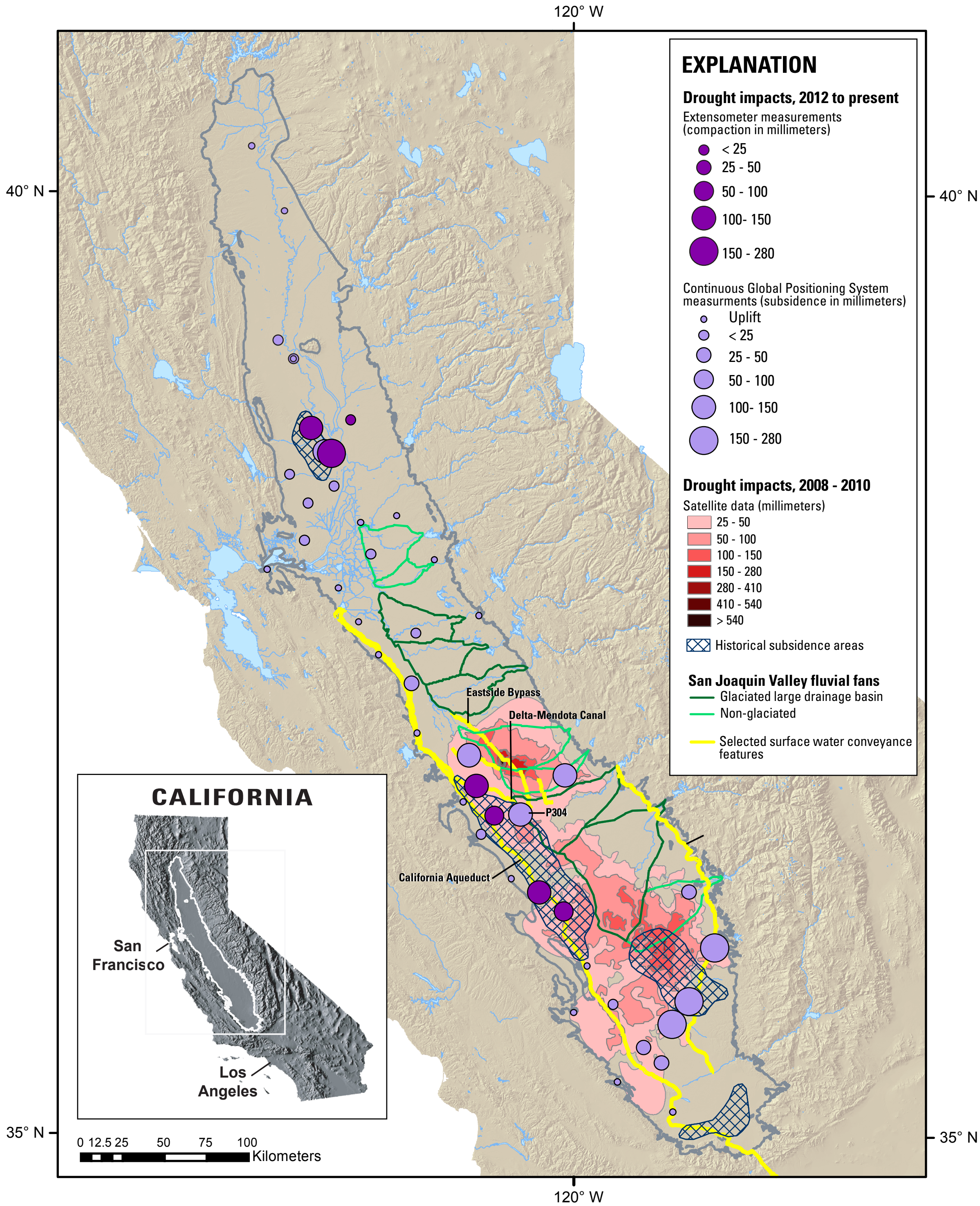

Figure 1 Map showing compaction and land subsidence measurements during current drought (2012–2015) from extensometers and continuous global positioning system, respectively, estimated subsidence derived from InSAR interferograms for 2008–2010 from previous drought, and historical subsidence (before 1980). In addition, locations of major surface water conveyance features and glaciated and non-glaciated alluvial fan extents are shown (modified from Weissmann et al. 2005).

some parts of the valley, which was accompanied by a steady recovery of water levels and a reduced rate of compaction (Ireland 1986).

This essay describes more recent changes in water availability and competition for water in the Central Valley and evaluates the influence that climate variability and human action has on subsidence, particularly during the most recent drought periods. The hydrology of the present-day Central Valley is driven by surface-water deliveries and associated groundwater pumpage, which in turn reflect the spatial and temporal variability in climate, water availability, and land use. Climate variability has had profound effects on the Central Valley hydrologic system. During droughts, surface water is less available, and groundwater pumpage increases. For example, the diminished availability of surface water during the droughts of 1976–1977 and 1987–1992, reversed the overall trend of groundwater-level recovery and re-initiated land subsidence in the San Joaquin Valley. Following each of these droughts, recovery to pre-drought water levels was rapid and compaction virtually ceased (Swanson 1998; Galloway et al. 1999).

Since the early 1990s, the availability of surface water has also decreased because of operational changes of the federal Central Valley Project and the California State Water Project. Although irrigation has become more efficient, since 2000, land use in the Central Valley has trended toward the planting of permanent crops (vineyards and orchards), replacing non-permanent land uses such as rangeland, field crops, or row crops. This has the effect of "demand hardening," which refers to the need for stable water supplies to irrigate crops that cannot be fallowed.

During the more recent droughts of 2007–2010 and 2012–present, groundwater pumping has again increased. This results from a combination of factors including less surface water availability—especially during droughts—and land-use changes. The increased pumping has re-initiated subsidence. The spatially variable subsidence has changed the land-surface slope and caused operational, maintenance, and construction-design problems for water-delivery and flood-control canals (Sneed et al. 2013) as well as other infrastructure (LSCE et al. 2014).

To help explain the variability in location and magnitude of land subsidence, we examined water-level measurements retrieved from U.S. Geological Survey (USGS) and California Department of Water Resources (CDWR) databases. According to the CDWR databases, groundwater levels in 55% of the long-term wells (1,718 of 3,124) in the San Joaquin Valley and 36% of the long-term wells (216 of 599) in the Sacramento Valley are at or below the historical spring low levels in 2015 (CDWR 2015). The San Joaquin Valley has many areas where recent groundwater levels are more than 100 feet (ft) below previous historical lows. These correspond to areas of recent subsidence. Figure 2 shows an example of the correlation between groundwater levels and land subsidence.

http://dx.doi.org/10.15447/sfews.2015v13iss3art4

In addition to varying with groundwater levels, the magnitude and rate of subsidence also varies based on geologic materials and consolidation history. We compared the extent of land subsidence with the extent of fluvial fans from the Sierra Nevada (Weissmann et al. 2005) (Figure 1). In general, the sediments from the Coast Ranges and the non-glaciated fluvial fans from the Sierra Nevada are fine-grained and easily compacted, resulting in high rates of subsidence. Conversely, the upper reaches of the Central Valley's large drainage area are dominated by more coarsely grained glaciated fluvial fans, and have much lower rates of subsidence (Figure 1).

To determine the location, extent, and magnitude of land subsidence during the last 3 years of the 2007–2010 drought, we used Interferometric Synthetic Aperture Radar (InSAR), continuous Global Positioning System (CGPS), and extensometer (an instrument for measuring the deformation) data to estimate subsidence. Subsidence maps based on analysis of InSAR images from the European Space Agency's ENVISAT satellite and the Japan Aerospace Exploration Agency's ALOS satellite acquired between 2008 and 2010 indicated 50 to 540 millimeters (mm) of subsidence in two large agriculturally dominated areas in the San Joaquin Valley (Figure 1). One area is centred near the town of El Nido (2,100 km^2) and the other near the town of Pixley (5,500 km^2; Figure 1). InSAR, extensometer, and CGPS data collected during 2007–2015 were used to generate land subsidence time series. CGPS confirmed the InSAR-derived rates and generally indicated that these rates continued or accelerated through summer 2015 (Figures 1 and 2). It is important to note that large areas of recent subsidence in the San Joaquin Valley (LSCE et al. 2014) do not have continuous GPS or extensometers in the areas of maximum subsidence found during 2008–2010 (Figure 1). The period 2008–2010 is shown in Figure 1 because suitable InSAR data were not available for 2010–2014. However, Farr et al. (2015) used InSAR and estimated about 0.35 m (about 0.5 m per year) of subsidence between May 2014 and January 2015, in the third year of California's ongoing severe drought.

Comparisons of historical (Williamson et al. 1989) with recent subsidence patterns reveal that while subsidence has decreased in some areas, it has continued or increased in others (Figure 1). First, subsidence along the western San Joaquin Valley has decreased in size and magnitude. Second, subsidence around Pixley has continued. In this area, groundwater levels declined to near or below historical lows during 2007–2010 and 2012–2015. Third, subsidence has strongly increased in the El Nido area. This area had the largest subsidence magnitude in the San Joaquin Valley during 2007–2015, and, similar to the Pixley area, groundwater levels declined to near or below historical lows during 2007–2010 and 2012–2015. The Pixley area is more extensive than the El Nido subsidence area, but subsided at a slower rate during 2007–2015. Unfortunately, the most northern and southern historical subsidence areas were not analysed with InSAR (Figure 1). Recent extensometer and CGPS data in the northern area in the Sacramento Valley indicate

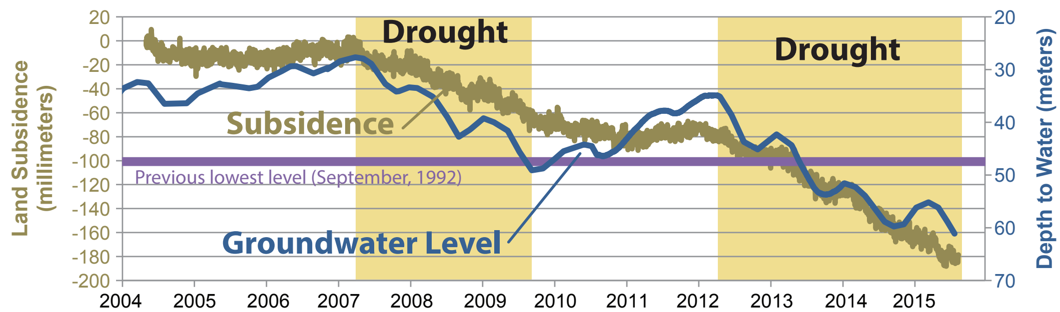

Figure 2 Graph showing vertical displacement at a selected GPS station and depth to water in a nearby well for 2004–2015 (see Figure 1 for location)

that this area has experienced recent subsidence. In the southernmost part of the Central Valley, no data available to indicate whether or not this area has recently subsided.

The comprehensive spatial coverage provided by the InSAR data allows for the delineation of the location and extent of areas of maximum subsidence: continuous CGPS and extensometer measurements at specific locations show monthly, seasonal, and inter-annual variations in subsidence rates: both types of data are needed to understand the mechanisms that underlie the spatial subsidence patterns and model subsidence under different water-management scenarios. For example, vertical displacement at CGPS station P304 (Figure 1) near El Nido indicates that most subsidence occurred during drought periods, and very little occurred between drought periods (Figure 2). This area received surface water when it was available between drought periods. In contrast, vertical displacement at two other CGPS stations, where limited surface water was available, indicated subsidence at fairly consistent rates during and between drought periods (not shown). In general, high rates of subsidence are associated with the increased groundwater extraction needed to support more water-intensive land uses in areas where surface water supplies are limited. This includes planting of permanent crops that require year-round irrigation during dry and wet seasons and years (USDA 2000–2013).

To provide information to stakeholders addressing these issues, the USGS developed the Central Valley Hydrologic Model (CVHM) that accounts for integrated, variable water supply and demand, and simulates surface-water and groundwater flow across the entire Central Valley (Faunt 2009). Specifically, the CVHM simulates the integrated hydrologic system, irrigated agriculture, land subsidence, and other key processes on a monthly basis. CVHM was developed at scales relevant to water management decisions for the entire Central Valley aquifer system. Recently, this model was extended through 2013. In part, it was extended to simulate the effect on subsidence of surface-water delivery and land-use changes, managed aquifer recharge, and the recent droughts.

http://dx.doi.org/10.15447/sfews.2015v13iss3art4

Since the majority of the surface water delivery system has been in place, the CVHM simulates that on average about 40% of the water supply of the Central Valley has come from groundwater (ranging from about 30% during wet years to 70% during dry years). During the recent drought (2012–present), more wells have been drilled, and groundwater is used to meet about 70% of the water demand. The groundwater proportion would be expected to increase if less surface water is available in future years, particularly given the increase in permanent crops.

Over time, the extra pumping has stressed the aquifer, which for decades has had an overall loss in storage. The Central Valley has been depleted by about 1.85 km^3 per year on average since 1960 (Faunt et al. 2009), and has been depleted about twice this rate during the current drought (Figure 3). If dry conditions persist, this rate is likely to increase. However, under legislation passed in 2014, the California Sustainable Groundwater Management Act (SGMA) requires basins to reach sustainable yield. The SGMA recognizes that groundwater is best managed at the local or regional level because of local geographic, geologic, and hydrologic differences. The goal of this legislation is reliable groundwater management, which is defined as "the management and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results" (CDWR 2015). To meet these requirements, dramatic changes will need to be made.

Water agencies are already working on some new projects to increase the water in storage. Projects that have been used for a number of years, but are expanding in popularity, are managed aquifer recharge. Most of the surface-water impound-

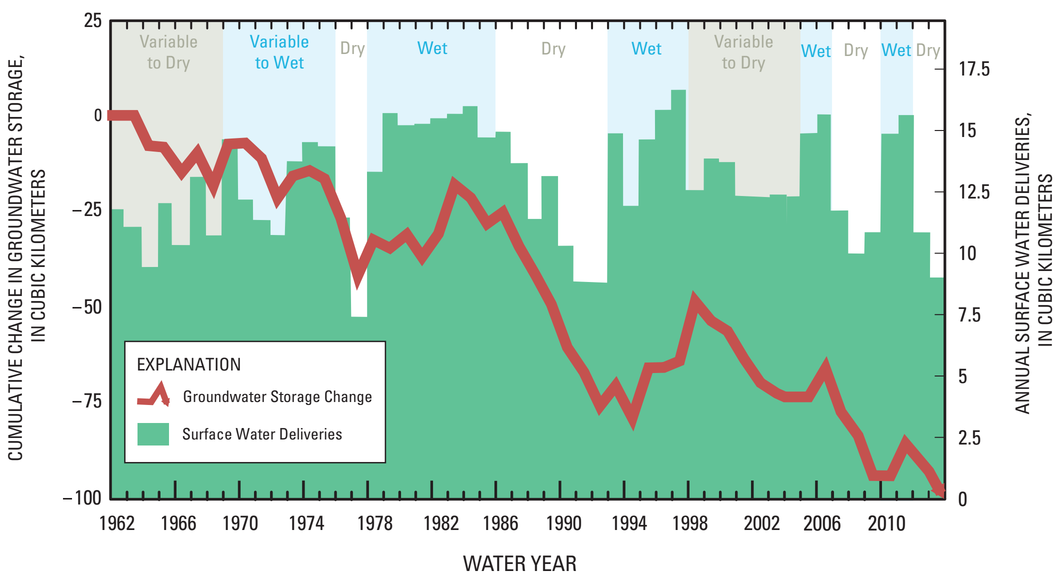

Figure 3 Graph showing surface water deliveries and cumulative storage changes simulated by the Central Valley Hydrologic Model. One cubic kilometer is about 811,000 acre-feet.

ments are located on alluvial fans of the glaciated portions of the Sierra Nevada. These fans consist of sandy sediments that are highly permeable and, therefore, are well suited for surficial recharge (spreading) and later recovery (withdrawal) by high-capacity wells. In general, recharge and recovery data corresponded with climatic wet and dry periods. Although these projects are putting large amounts of water in storage, other projects may be needed to either increase recharge or decrease use to meet SGMA.

Planning for the effects of continued land subsidence in the area will be important for water agencies. As land use, managed aquifer recharge, and surface-water availability continue to vary, long-term groundwater-level and land-subsidence monitoring and modelling are critical to understanding the dynamics of the integrated system. Modeling tools, such as the CVHM, can be used to evaluate management strategies to mitigate adverse effects from subsidence while also optimizing water availability.

REFERENCES

[CDWR] California Department of Water Resources. 2014. Summary of recent, historical, and estimated potential for future land subsidence in California [Internet]. [cited 2015 Sep 02]. Available from: *http://www.water.ca.gov/groundwater/docs/Summary_of_Recent_Historical_Potential_Subsidence_in_CA_Final_with_Appendix.pdf*

[CDWR] California Department of Water Resources. 2015. California sustainable groundwater management act [Internet]. [cited 2015 Sep 02]. Available from: *http://www.water.ca.gov/cagroundwater/moresgma.cfm*

Farr TG, Jones C, Liu Z. 2015. Progress report: subsidence in the Central Valley, California [Internet]. Sacramento (CA): California Department of Water Resources. [cited 2015 Sep 10]. Available from: *http://water.ca.gov/groundwater/docs/NASA_REPORT.pdf*

Faunt CC, editor. 2009. Groundwater availability of the Central Valley aquifer, California. Reston (VA): U.S. Geological Survey. U.S. Geological Survey Professional Paper 1766. [cited 2015 Sep 14]; 225 p. Available from: *http://pubs.usgs.gov/pp/1766/*

Galloway DL, Jones DR, Ingebritsen SE. 1999. Land subsidence in the United States. U.S. Geological Survey Circular 1182. Reston (VA): U.S. Geological Survey. [cited 2015 Sep 14]; 175 p. Available from: *http://pubs.usgs.gov/circ/circ1182*.

Ireland RL. 1986. Land subsidence in the San Joaquin Valley, California, as of 1983. Reston (VA): U.S. Geological Survey. U.S. Geological Survey Water-Resources Investigations Report 85–4196. [cited 2015 Sep 14]; 50 p. Available from: *http://pubs.er.usgs.gov/publication/wri854196*

http://dx.doi.org/10.15447/sfews.2015v13iss3art4

[LSCE et al.] Luhdorff & Scalmanini Consulting Engineers, Borchers JW, Grabert VK, Carpenter M, Dalgish B, Cannon D. 2014. Land subsidence from groundwater use in California. Report prepared by LSCE with support by the California Water Foundation. [cited 2015 Sep 10]. Available from: *http://www.californiawaterfoundation.org/uploads/1397858208-SUBSIDENCEFULLREPORT_FINAL.pdf*.

Poland JF, Lofgren BE, Ireland RL, Pugh AG. 1975. Land subsidence in the San Joaquin Valley, California, as of 1972. Reston (VA): U.S. Geological Survey. U.S. Geological Survey Professional Paper 437-H. [cited 2015 Sep 14]; 78 p. Available from: *http://pubs.usgs.gov/pp/0437h/report.pdf*

Sneed M, Brandt J, Solt M. 2013. Land subsidence along the Delta–Mendota Canal in the northern part of the San Joaquin Valley, California, 2003–10. Reston (VA): U.S. Geological Survey. U.S. Geological Survey Scientific Investigations Report 2013–5142. [cited 2015 Sep 10]; 87 p. doi: *http://dx.doi.org/10.3133/sir20135142*.

Swanson AA. 1998. Land subsidence in the San Joaquin Valley, updated to 1995. In: Borchers JW, editor. Land subsidence case studies and current research. Proceedings of the Dr. Joseph F. Poland symposium on land subsidence; 1995 Oct 4–5; Sacramento. Association of Engineering Geologists, Spec Publ No. 8. Belmont (CA). p. 75–79.

[USDA] United States Department of Agriculture, National Agricultural Statistics Service. 2000–2013. Summary of National Agricultural Statistics Service County Agricultural Commission reports [Internet]. [cited 2015 Sep 10]. Available from: *http://www.nass.usda.gov/Statistics_by_State/California/Publications/AgComm/Summary/index.asp*.

Weissmann GS, Bennett G, Lansdale AL. 2005. Factors controlling sequence development on Quaternary fluvial fans, San Joaquin Basin, California, USA. In: Harvey A, Mather A, Stokes M, editors. Alluvial fans: geomorphology, sedimentology, dynamics. Geol Soc Lond Spec Publ 251. p. 169–186. doi: *http://dx.doi.org/10.1144/GSL.SP.2005.251.01.12*

Williamson AK, Prudic DE, Swain LA. 1989. Ground-water flow in the Central Valley, California. Reston (VA): U.S. Geological Survey. U.S. Geological Survey Professional Paper 1401-D. [cited 2015 Sep 10]; 127 p. Available from: *http://pubs.usgs.gov/pp/1401d/report.pdf*.