Workshop report—Earthquakes and High Water as Levee Hazards in the Sacramento-San Joaquin Delta

Delta Independent Science Board

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SUMMARY

Earthquakes and high water as hazards to Delta levees were reviewed in a seven-hour workshop organized by the Delta Independent Science Board and held at the campus of the University of California, Davis. Earthquake hazards in the Delta were described in terms of ground motions from Bay Area earthquakes, infrequent earthquake recurrence on faults beneath the Delta, and levee fills prone to earthquake-induced liquefaction. Large uncertainties attend all these seismic elements of levee hazard. Those uncertainties, according to presentations in the workshop, include whether the Delta ground motions previously computed for Bay Area earthquakes were too large. Hazards from high water were deemed greatest from the confluence of high river discharge, wind-driven surge and waves, and high tides. Major risk assessments have used available data on these hazards without mandates to advance the science. Research needs and opportunities identified in the workshop include expanded observations of Delta ground motions, improved estimates of geologically recent displacement on faults beneath the Delta, further identification of liquefiable materials and mechanisms beneath levees, continued airborne measurements of land-level change, updated mapping of the contracting area of remaining peat, and fuller documentation of past levee failures. Recurring assessments of earthquake hazards and climate change provide precedents for periodic reappraisal of Delta levee risk. The workshop brought together different parts of the diverse community of Delta levee specialists. Positive responses to the workshop suggest that it served levee specialists and outsiders alike.

INTRODUCTION

A public workshop on “Delta levee science” took place July 14, 2016 in Putah Creek Lodge on the campus of University of California, Davis[4]. The workshop was convened by Delta Independent Science Board (hereafter referred to as the Board).

This report describes the workshop scope, gives the Board’s understanding of highlights from presentations and discussions, and offers perspectives on Delta levee research. Illustrations locate places mentioned (Fig. 1), provide an index to workshop presentations (Fig. 2), and present timelines of levee failures and associated events (Fig. 3, App. 1).

WORKSHOP

Scope

The workshop focused on Delta levee hazards from earthquakes and high water. As used herein, hazards contribute to risk; levee risk is a broader concept that takes into account not just natural hazards to levees, but also the economic, environmental, and public-safety consequences of levee failures. The workshop considered little of the research into these consequences.

The workshop presenters highlighted findings that mostly postdate the risk assessments in the Delta Risk Management Strategy (DRMS) report. The hazards incorporated in these risk assessments were evaluated in 2007 and 2008, chiefly in reports on seismology[63], flood hazards[44], subsidence[26], and climate change[27]. A summary of levee science from that era is provided in a 2008 review[48], and earlier findings underpin levee plans reported in 1982[46].

In a 2009 summary of the first phase of DRMS[9], earthquakes were said to contribute more to Delta levee risk than does high water. A 2006 report gave roughly equal weight to the levee hazard from earthquakes and from high-water levels at 100-year recurrence intervals[49].

The workshop scope did not extend into hazard assessments for the Delta Levee Investment Strategy (DLIS). DLIS has its origins in the Sacramento-San Joaquin Delta Reform

Act of 2009, which tasked the Delta Stewardship Council with setting priorities for State of California spending on Delta levees[22]. The initial risk assessment methods used in DLIS were reviewed in 2015 by an expert panel[47]. DLIS products available before the workshop include reports on draft methods for assessing Delta levee risk (for example, ref [2]), preliminary maps of levee risk[21], and a review of wildlife habitats on, beside, and behind Delta levees[15]. Revised DLIS risk-assessment methods[30] were published soon after the workshop.

The Board convened the workshop and wrote this workshop report as part of its responsibility to review Delta science programs. The Sacramento-San Joaquin Delta Reform Act of 2009, in establishing the Delta Independent Science Board, directed it to “provide oversight of the scientific research, monitoring, and assessment programs that support adaptive management of the Delta through periodic reviews” (Water Code §85280(a)(3))[10]. Reviewing by theme, the Board has previously reported on habitat restoration[16], fish biology in relation to flows[19], and adaptive management[20]. The Board previously considered Delta levee risk in its mandated reviews of environmental documents of the Bay Delta Conservation Plan[17,18] and in a letter on modeling the hydrologic effects of salinity barriers and levee breaks[43]. This is the Board’s first review to be presented as a report on a meeting that focused on just part of a broad theme.

Structure

The workshop had two sessions—one on earthquakes, the other on high water. Each session contained a set of introductory talks, informal discussions at posters, and a panel discussion. The panel discussions enabled the session’s speakers and poster presenters to entertain rounds of questions from discussants, Board members, and other workshop participants. An abstract for each presentation was included in the workshop program, which along with other workshop materials was distributed on the premises and placed online[4].

Earthquake hazards received greater attention, with sixty or more participants, eight posters, and a panel discussion. The session on high water allowed for greater participation by a smaller afternoon audience.

Participants and affiliations

The participants included 30 audience members who voluntarily signed in, 16 lead presenters, two discussants, and all ten members of the Board.

The participants’ affiliations, listed alphabetically and excluding the primary affiliations of Board members, included:

Arcadis
Bachand & Associates
Bethel Island Municipal Improvement District
California Central Valley Flood Control Association
California Department of Fish and Wildlife
California Department of Water Resources
California Geological Survey
Central Delta Water Agency
Contra Costa Water District
Delta Independent Science Board
Delta Science Program
Delta Stewardship Council
HDR Engineering
Hultgren-Tillis Engineers
HydroFocus, Inc.

Infra Terra
Jet Propulsion Laboratory
Kueneman Consulting
Lettis Consultants International
MBK Engineers
Metropolitan Water District
Resource Management Associates
Sacramento Regional County Sanitation District
Shannon & Wilson
U.S. Army Corps of Engineers
U.S. Geological Survey
University of California, Davis
University of California, Los Angeles
University of California, San Diego
University of California, Santa Cruz

Two senior scientists from Delta levee studies served as discussants. Ivan Wong, discussant for the earthquake panel, had led the 2007 DRMS seismological study[63]. Larry Roth, discussant for the high-water panel, heads the consulting team that recently reassessed levee risk in support of the DLIS[30].

Highlights

This section of the report uses two-letter abbreviations, derived from the lead presenter's family name and explained in Figure 2, to cite particular presentations in the workshop. The citation Du, for instance, refers to two poster presentations by Joel Dudas.

Earthquakes

Earthquake hazards to Delta levees can be grouped by location of the earthquake source with respect to the levee. Seismic energy is radiated at a fault, passes through rocks of Earth's crust, and continues upward through unconsolidated materials, such as peat, into the levee (Fig. 2).

Discussion in the earthquake session focused largely on Bay Area earthquakes as sources of strong ground motions. Bay Area faults produce earthquake shaking in the Delta more often than faults beneath the Delta itself[33]. How strongly a Bay Area earthquake affects the Delta, however, depends on attenuation—on how abruptly the ground motions diminish as the seismic waves advance eastward from the Bay Area into the Delta[29]. A DRMS study a decade ago[63] used attenuation equations that were considered state of the art at the time. These equations have now been found to overestimate Bay Area transmission of ground motions by factors of two to four in the case of the 2014 South Napa earthquake of magnitude 6.0, and also for smaller Bay Area earthquakes [6,31] (presentations Bo and Er, Fig. 2). The earthquake panel discussed whether recordings from additional, larger earthquakes would be necessary to reappraise the attenuations that a DRMS report[63] used in estimating ground motions in the Delta.

The workshop also considered earthquake sources directly beneath the Delta. The Southern Midland Fault runs north-south beneath the western Delta (approximate fault location, Fig. 1)[42,58,61-63]. Movement on the Southern Midland Fault was reported to be consistent with infrequent earthquakes, at average intervals on the order of 10,000 years (Un). Faster movement was inferred for the West Tracy Fault (Hi), which projects beneath Clifton Court[59].

Whatever the earthquake source, the seismic response of Delta levee was shown to depend on materials through which the seismic waves travel. These materials include rocks between the fault and the Delta, rocks beneath the Delta[29] (Gr), and unconsolidated materials in the Delta that amplify ground motions by slowing seismic waves as they approach the ground surface[35] (Fl, Kn, Wi).

There was no dispute about liquefaction of levee fills as the most likely seismological cause of levee failure. Sand inside levees was described as capable of turning into quicksand if ground motions are sufficient (Ti). Participants considered how previous liquefaction assessments of Delta levees[52] might be improved by making new borings to clarify the extent of liquefiable sand. Also presented were laboratory findings on how levees may subside more quickly in the aftermath of an earthquake[54,55], and engineering approaches to estimating probabilities of levee failures (Br).

High water

Present-day Delta water levels were shown to rise with riverine floods, wind surge, and tides (Ru). Sea level has been rising at the Golden Gate (Fig. 3, monthly levels at San Francisco) and is predicted to rise more with time[11] (Ca). The hydraulic head beside Delta levees is also increasing from subsidence within central and western islands where decomposing peaty soils persist[25] (De). Datums for tides and flood levels are slated for reappraisal (Du). Floods and winds in the Delta are projected to become more severe with global warming[24,27]and these climate-change hazards were reiterated in the workshop. Radar interferometry[39] was described as a potential aid to levee inspections and as a potential guide to earthquake-related changes in land level (Jo).

Workshop participants made reference to water levels during Delta levee failures. Combinations of high tide, wind-driven surge, and high river discharge were deemed the greatest high-water threat in coming decades.

PERSPECTIVES

Existing data

The workshop exhibited a tension that often arises between scientific research and its practical application. While focused on research problems and opportunities, the workshop included reminders that Delta levees have received hundreds of millions of dollars spent for maintenance and upgrades in recent decades[22,23]. This engineering work is slated to continue[30], and it is unlikely to await solution of research problems.

Using existing data to assess levee risk was basic to the Delta Risk Management Strategy. The preamble for technical memoranda of DRMS states: “This study relied solely on available data. In other words, the effects of stressing events (changing future earthquake frequencies, future rates of subsidence given continued farming practices, the change in the magnitude and frequency of storm events, and the potential effects of global warming) on the Delta and Suisun Marsh levees were estimated using readily available engineering and scientific tools or based on a broad and current consensus among practitioners. Because of the limited time available to complete this work, no investigation or research was conducted to supplement the current state of knowledge.”[52]

Likewise, to assess levee risk for the Delta Levees Investment Strategy, “the project team gathered the best available existing data for levee hazards” (p. 47 of ref [30]). “Hazard data gaps” are described from Suisun Marsh only (p. 78 of ref [30]).

New measurements

The workshop elicited calls for new measurements of Delta levee hazards. The goals included:

Determining which parts of levees are most subject to earthquake-induced liquefaction. This type of information was seen as particularly important in a regional risk assessment like that of DLIS, in which islands are ranked by probability of levee failure, if the liquefaction of levee fills is the most likely seismological cause of Delta levee failure. It was suggested that previous risk assessments of Delta levees[52] could be improved by reducing the spacing between borings used to identify liquefiable sand in levee fills. The workshop discussions barely touched on geophysical methods for mapping potentially liquefiable sand beneath levees. At least a decade ago, geophysical techniques were found inadequate for assessing levee fragility[48]. A more optimistic view was recently presented at a levee meeting in Sacramento[32].

Clarifying attenuation of ground motions from Bay Area earthquakes. As noted above, it was shown that ground motions from certain Bay Area earthquakes diminished with distance more rapidly than had been expected[6,31]. It was proposed that more accelerometers be deployed to measure Delta ground motions before the next moderate or large earthquake on a Bay Area fault.

Gauging variability in site response. Also proposed at the workshop were ground-motion observations along profiles that begin in island interiors and cross levee crests. Building on previously findings in the southern Delta[35], the new observations would assess amplification of seismic waves in unconsolidated sedimentary deposits and levee fills through which seismic waves pass. The proposed deployment involved placing a dozen accelerometers across three levees, four instruments per profile.

Monitoring land-level changes. Participants were surprised by evidence, in the presented poster on radar interferometry, that land behind a Twitchell Island levee had subsided during a 16-day interval that included the 2014 South Napa earthquake. While the specific mechanism of the subsidence remains to be determined, the observation was seen at the workshop, and in a recent report for the California Seismic Safety Commission[40], as a benefit of repeated interferometric surveys.

Delineating today's extent of peat. Geologic maps on display depicted the extent of Delta peat as surveyed largely by soil scientists. The most extensive of the soil surveys used is three-quarters of a century old, having been published in 1941[14]. The maps also draw on interpretation of aerial photographs from the 1960s, and on spotty field work in the 1970s[5]. The current map of Delta peat draws on soil surveys from the late 1970s and the 1990s[25]. It was suggested in the workshop that the remaining peat should be delineated more accurately and sounded to clarify which parts of which islands and tracts remain subject to subsidence from peat decomposition.

Slip rates on the Southern Midland Fault

The workshop highlighted the Southern Midland Fault for two reasons. First, though buried, it lies directly beneath the western Delta (Fig. 1). Second, its importance as a source of Delta hazards increases if—as judged from Delta ground motions during the 2014 South Napa earthquake[6,31]—more distant Bay Area earthquakes pose less of a Delta hazard than was previously thought.

Previous hazard assessments of the Southern Midland Fault were founded on estimates of displacement on the fault, chiefly over the past few million years but also in the past few tens of thousands of years. Unless creeping, the fault is assumed to be locked except when slipping during earthquakes. The faster the long-term displacement, or average slip rate, the more often the fault can be expected to produce an earthquake.

Compared with slip rates on the San Andreas Fault, average slip rates on the Southern Midland Fault are less certain and are tens to hundreds of times slower. A 2007 DRMS report[63] gave the Southern Midland a range of weighted slip rates: 0.1 mm/yr (weight 0.3), 0.5 mm/yr (weight 0.4), and 1.0 mm/yr (weight 0.3). A workshop presentation, based on a new report[58], gave slip rates between 0.03 mm/yr and 0.13 mm/yr. By comparison, slip rates along the San Andreas in the Bay Area, are about 20 mm/yr (Table B1 in ref [33]).

Average slip rates on the Southern Midland have been estimated from present-day relief on buried surfaces[42,58,61-63]. It has been assumed that the surfaces started out flat enough for this present-day relief to represent warping above the tip of the fault. The maximum present-day relief is less than 300 m on a Miocene erosional surface, which is about 10 million years old[58,60]. This surface is known from gas-well logs and associated seismic-reflection profiles, most of them proprietary. Another surface, the base of tidal-wetland peat, has been identified mainly in levee borings. This younger surface has been traced across the crests of ice-age sand dunes at Webb Tract and vicinity[63]. The base of the peat descends east of this ancient dune field into a former San Joaquin River floodplain that coincides with the relatively downthrown side of the reactivated Southern Midland Fault[58].

Use of these surfaces as datum planes prompted sidebar discussions among earthquake geologists at the workshop. The topics included the original slope and flatness of the Miocene surface, the degree to which the base of peat in the western and central Delta drapes an uneven ice-age landscape, and whether erosion by tidal streams has further complicated the shape of the basal peat surface. Two additional surfaces were put forward for consideration as structural datums:

Floodplain is about 0.5 million years old. Traces of an ancient Sacramento River floodplain could be sought beneath the western Delta, between Hood and Bouldin Island, encountered volcanic ash layers a half-million years old that were deposited by water on a floodplain of the ancestral Sacramento River[45]. One of these volcanic ash layers was previously shown, in bridge-foundation cores, to continue to the vicinity of San Francisco[53,57].

Sea levels of the past 7,000 years. Former shorelines, identified and dated by means of tidal-wetland peat, have been used elsewhere to detect and measure uplift during an earthquake[41]. The uplift can also convert tidelands into uplands—a change that leaves geological signatures[7,51]. These approaches could be used to ask whether a meter or more of vertical displacement has occurred on the Southern Midland Fault since tidal wetlands began spreading into the Delta about 7,000 years ago.

Levee forensics

Even if “the past is no longer a guide to the future of the Delta"[48], there may be value in having a shared understanding of the history of Delta levee failures. The source documents could include reports on floods[56] and levees (metadata for ref [28]) that are currently unavailable or hard to find on the web. A virtual levee library could be curated under the auspices of one or more California state agencies, such as the Delta Protection Commission, the Central Valley Flood Protection Board, the Delta Stewardship Council, and/or the Department of Water Resources. Potential uses include:

Assessing the effectiveness of levee investments. How has human intervention affected the rates of levee failure in the Delta? The interventions include dams used in part for flood control and recent investments in levee maintenance and upgrades (examples, Fig. 3). A decade ago, levee failures were described as continuing at a rate undiminished by investments in levee maintenance and upgrades[36,48,52]. This finding has been contested[37] because it is based on failure rates in the Delta as a whole (lowest two timelines in Fig. 3), rather than on failure rates from high water at the peaty islands and tracts where most of the recent levee work has taken place (Fig. 3, third timeline from bottom). A shared understanding of the history of levee failures might help resolve this matter.

Evaluating effects of earthquakes. Earthquakes have caused documented damage in the Delta[34,64], but have they contributed to any of the Delta levee failures? A case in point is the flurry of levee failures and near failures in the southern Delta in June and July of 1906. These followed the 1906 San Francisco earthquake by less than three months. Articles in the *San Francisco Call* and *Los Angeles Herald* between June 21 and July 15, available online[12], show that the failures and associated flood fights, in which the flooding of some islands was prevented, coincided with unusually high discharge on rivers of the southern Sierra Nevada[37]. A flood from northern rivers the following March, 11 months after the earthquake, coincided with the record number of Delta levee failures, in 1907 (Fig. 3). It was reported at the workshop that an earthquake may trigger compaction of peat that would lower levees for years thereafter[54,55]. The potential role of this mechanism might be appraised for the April 1906 earthquake by comparing modeled amounts of subsidence with estimates of flood levels in June and July of 1906, and in March 1907 as well.

Evaluating effects of El Niños. Peaks in Delta levee failures coincided with major El Niños—notably in 1878 and 1983, and perhaps also in 1998—although the levee-failure maximum in 1907 did not (Fig. 3). On January 27, 1983, when Mildred Island flooded, West Coast sea levels were elevated by an El Niño and high tides reached record levels in San Diego and Seattle[13].

Calibrating models of levee failures. Documenting case histories of levee failures was recommended in a 2008 DRMS report[52]: “The Delta offers numerous case histories (although with incomplete details) for calibrating the levee flood-induced failure model. These case histories helped groundtruth the model used in the results. We observed that not all the details of historical flood events are recorded or available. It is recommended that failures in the Delta be fully documented in a formal and comprehensive way that covers the necessary details to reconstruct the events and verify them numerically. This documentation will provide increased validity to future modeling exercises."

Documenting causes of “sunny day” failures. In a workshop discussion, a senior levee engineer reviewed Delta levee failures that were not accompanied by unusually high water. Such “sunny day” failures were discussed in DRMS[52] and reassessed in a 2011 Ph.D. dissertation[37]. These events are important because they account for one-third of the failures since 1960 at peaty Delta islands outside floodways (Fig. 3). A 1982 levee report[46] contains the beginnings of a “sunny day” database.

Hazard updates

Many workshop participants were familiar with hazard assessments that incorporate new findings through periodic updates. Seismological examples include reappraisals of California faults[33] in support of the U.S. National Seismic Hazard Maps[50], and the updating of those national maps at six-year intervals for application to building codes. Similarly, successive assessments of climate change have been made by the Intergovernmental Panel on Climate Change (assessments completed in 1990, 1995, 2001, 2007, and 2014)[38] and by the California Climate Change Center (assessments completed in 2006, 2009, and 2012)[8].

The workshop discussion on earthquake hazards elicited a call to update the risk assessments that were made nearly ten years ago under DRMS. The risk assessment methods in DLIS, unavailable in their final form[30] at the time of the workshop, were not specifically discussed.

Networking

Scientists and engineers working on Delta levees, as a community, have been minimally represented in the biennial Bay-Delta Science Conference and in the annual Interagency Ecological Program Workshop. The 2016 Bay-Delta Science Conference includes a session on flood management, which is a logical venue for relating Delta levee hazards to assets that include terrestrial and aquatic habitats[15].

The July workshop overlapped slightly with a levee meeting three months prior to this one. That meeting was organized by local sections of the American Society of Civil Engineers and the Association of Engineering and Environmental Geologists[1]. The topics included levee standards in relation to levee risk, a California Department of Water Resources program for evaluation of urban and non-urban levees, a grants program under the Central Valley Flood Protection Plan, levee screening and risk assessment by the U.S. Army Corps of Engineers, certification and accreditation of levees by the Federal Emergency Management Agency, archaeological issues, levee guidance documents, geophysical methods, and construction practices.

Few who attended the July workshop brought first-hand experience with maintaining, patrolling, or living behind non-urban levees of the Delta. It was suggested that researchers reach out to these levee experts. Future workshops on Delta levee science could include field trips that would bring the parties together.

ACKNOWLEDGMENTS

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A few of the Board members received background on Delta levees through visits in 2015 to Jersey Island (January), Bouldin Island, Canal Ranch Tract, and Tyler Island (March), Staten Island and Twitchell Island (April), and Holland Tract and McDonald Island (August). The guides gratefully acknowledged, listed alphabetically, include:

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Nathan J. Hershey (MBK Engineers)
Steve Mello Tyler Island)

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A Board meeting in October 2015 included a levee outing at Jersey Island and a visit to the Dutra Museum of Dredging in Rio Vista[3]. Jenny Skrel (Ironhouse Sanitary District) and Jacob McQuirk (California Department of Water Resources) are thanked for providing context, as are Kevin Tillis and David DalPorto for a field briefing. Janet Bennett graciously opened the museum to the Board and guided visitors through the collection.

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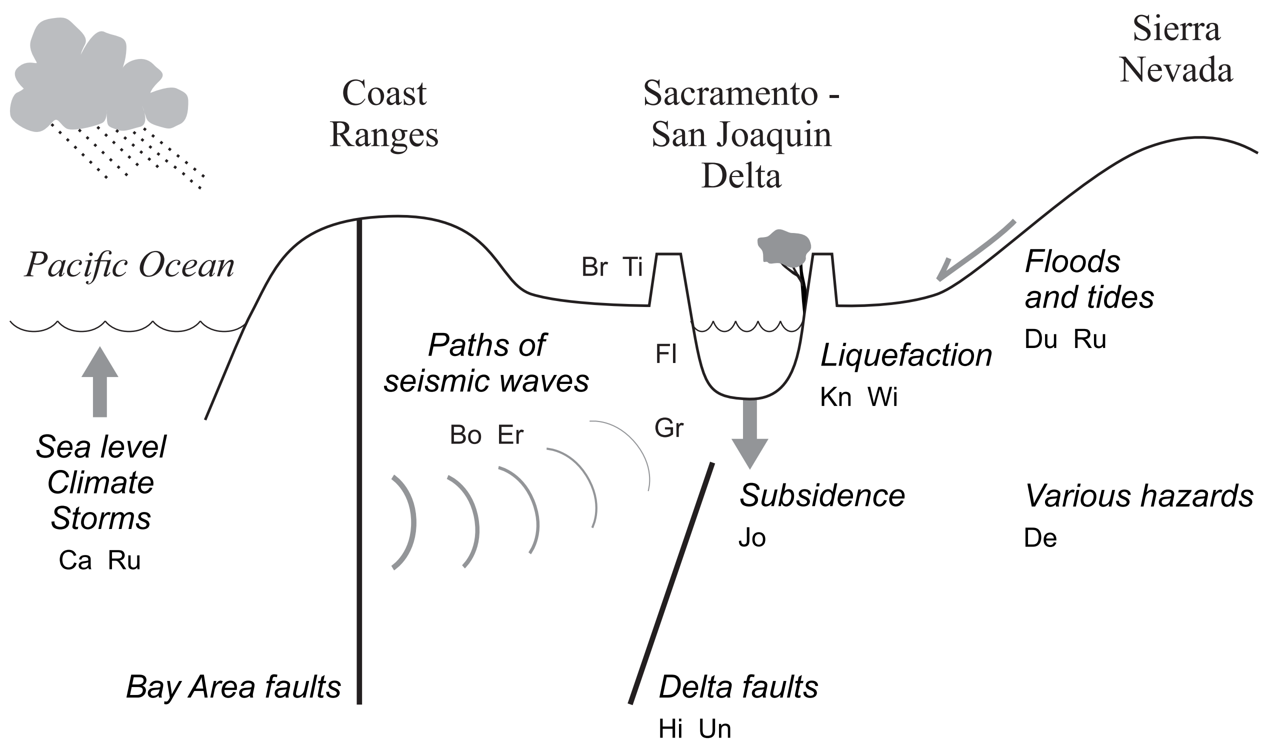
Figure 1. Index map including Delta place names used in the body of this report.



Presenter		Session	Topic	Program page
Bo	Boatwright, Jack	a.m.	Weakened shaking from Bay Area earthquakes	1
Br	Brandenberg, Scott	a.m.	Probabilities of levee failure from seismic shaking	
Br	Brandenberg, Scott	a.m.	Expected settlement of levees after seismic shaking	
Ca	Cayan, Dan	p.m.	Scenarios for sea level rise and climate change	2
De	Deverel, Steve	p.m.	Uncertainties about levee vulnerability	
Du	Dudas, Joel	p.m	100-year flood levels	
Du	Dudas, Joel	p.m.	Baseline conditions for tidal datums	
Er	Erdem, Jemile	a.m.	Weakened shaking from the South Napa earthquake	3
Fl	Fletcher, Joe	a.m.	Seismic shaking amplified in soft shallow soils	
Gr	Graymer, Russ	a.m.	Effects of deep geology on seismic waves	
Hi	Hitchcock, Chris	a.m.	Fold deformation above the West Tracy Fault	4
Jo	Jones, Cathleen	p.m.	Remote sensing of spatially variable subsidence	
Kn	Knudsen, Keith	a.m.	Liquefaction potential of natural deposits	
Ru	Russo, Mitch	p.m.	Water level forecasts	5
Ti	Tillis, Kevin	a.m.	Seismic concerns and levee engineering	
Un	Unruh, Jeff	a.m.	Reactivation of the Southern Midland Fault	
Wi	Wills, Chris	a.m.	Geologic maps as guides to seismic hazards	

Figure 2. Graphical index to presentations at the Delta levee workshop of 14 July 2016.

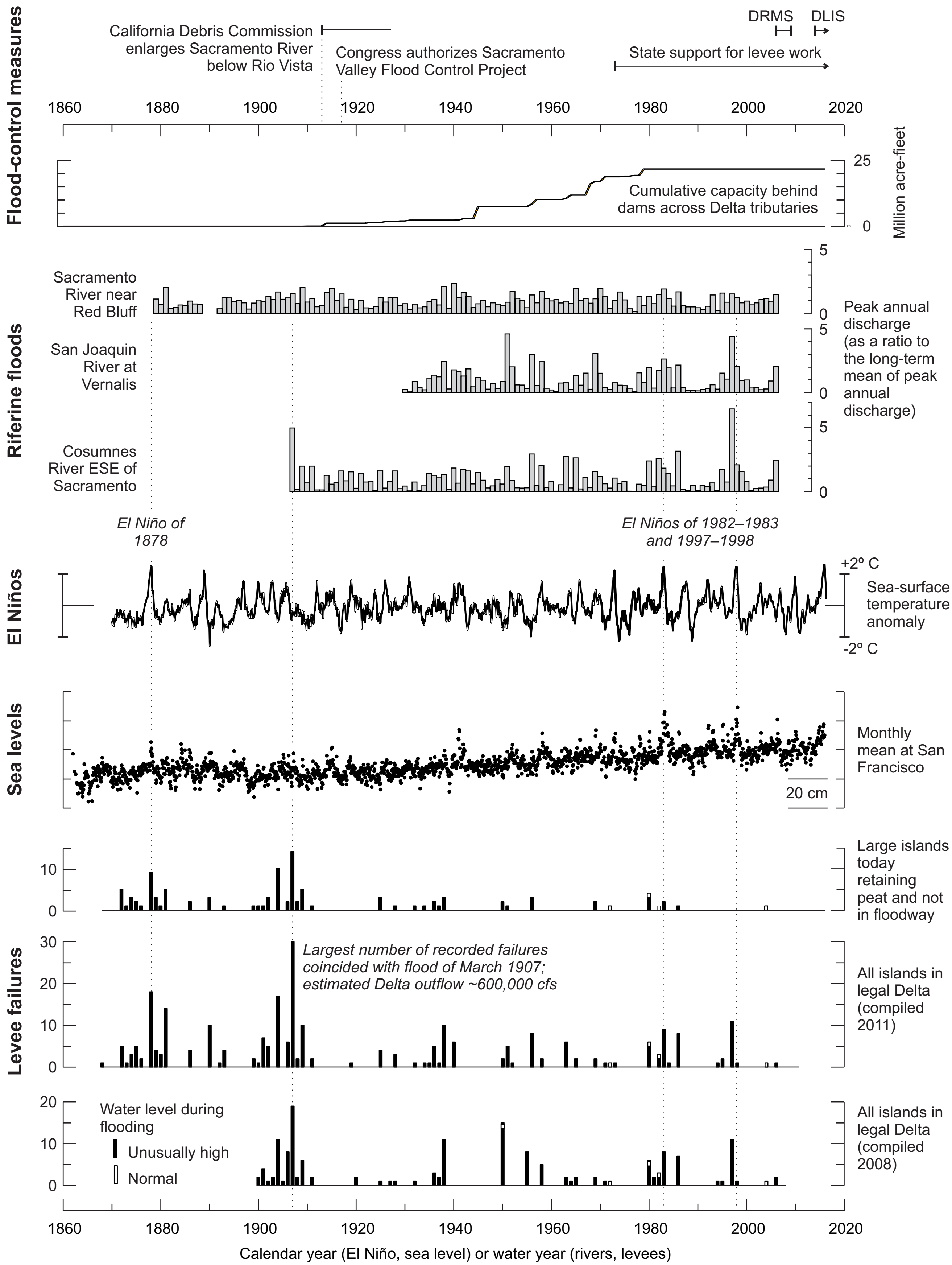


Figure 3. Timelines for levee failures, sea levels, El Niños, river floods, and flood-control projects.

APPENENDIX A: Sources for graphs in Figure 3

Headnotes

"[T]he major El Niño events of 1878, 1982/83, and 1997/98" were called out by Trenberth and Stepaniak (2001, p. 1698) in reference to their graph of the El Niño indicator cited below (Niño 3.4).

The second large Delta flood after the April 1906 earthquake took place in March 1907 (discharge cited below). A prior post-earthquake flood occurred in June and July 1906. Levees reportedly failed at Union Island (6/25); Venice Island, Twitchell Island, and Sherman Island (7/9); and Upper Jones Tract (7/11) (Hopf, 2011, p. 279-280, 367). In addition, flood fights were reported from Clifton Court (7/17), Fabian Tract (7/9) and from Lower Roberts Island, Victoria Island, Woodward Island, and Lower Jones Tract (7/10) (Hopf, 2011, p. 389). The central Sierra Nevada received above-average snowfall in the winter of 1906 (Central Sierra Snow Laboratory, 2015; Curry, 1969, p. 28).

On early 20th-century enlargement of the Sacramento River below Rio Vista and congressional authorization of comprehensive flood-control works, see Kelley (1989) and James and Singer (2008). The work below Rio Vista, including a dredged cut across Horseshoe Bend, was 80 percent complete in 1927 (Kelley, 1989, p. 300).

A recent review of Delta levee issues recounts the history of state support for Delta levee maintenance and upgrades (Delta Stewardship Council staff, 2015, p. 36-43). DRMS, Delta Risk Management Study (California Department of Water Resources, 2009; URS Corporation and Jack R. Benjamin & Associates Inc., 2011). DLIS, Delta Levee Investment Strategy.

Dams

The graph of reservoir capacity in the watershed of the Sacramento – San Joaquin Delta is based on Table 2-2 of MacDonald et al. (2008).

River floods

The dimensionless flood flows are redrawn from Florsheim and Dettinger (2007). The measurements were made at USGS gauges 11377100 (Sacramento River at Bend Bridge), 11303500 (San Joaquin River at Vernalis), and 11335000 (Cosumnes River at Michigan Bar). The discharge estimate for the 1907 flood is from Kelley (1989, p. 277, a secondary source).

El Niño

The graph shows Niño 3.4, a tropical sea-surface temperature anomaly averaged across the equatorial Pacific east of the International Date Line (Trenberth and Stepaniak, 2001). The data source is Working Group on Surface Pressure (2015). The compilation there includes historical data from Rayner et al. (2003), who provide "monthly globally complete fields of SST and sea ice concentration on a 1° latitude-longitude grid from 1871."

Sea level

Monthly data from National Oceanic and Atmospheric Administration (2016). The plot ignores an "apparent datum shift" in 1897.

Island flooding

The histograms of island flooding compare two compilations (bottom, middle) and show the further effects of limiting the history plotted to the large, mainly central Delta islands where peat is still present (upper). The term "island" here refers also to places called "tracts."

The *bottom histogram* is from the list of island flooding since 1900 in Salah-Mars et al. (2008, Tables 4-1 and 4-2). The graph shows all events listed except for some in Suisun Marsh that are outside the legal Delta.

The *middle histogram* show revisions by Hopf (2011). It depicts all the failures reported in his complete list of island flooding in the legal Delta (in his Appendix Q, p. 389-391).

The *upper histogram* may pertain more directly to hazards from peat that both underlies and adjoins Delta levees—a topic of several of the presentations at the July 14, 2016 meeting.

- The data source is the same as in the middle histogram, but the islands are limited to those meeting all four of these criteria:
    1. Remain subject to interior subsidence, as judged from peaty deposits mapped most recently about four decades ago (Atwater, 1982; Deverel and Leighton, 2010, Fig. 1);
    2. Are not completely fringed by mapped natural-levee deposits—a criterion that excludes Pierson Tract (southeast of Courtland);
    3. Cover about 150 hectares or more, thereby excluding Fay Island, Little Mandeville Island, and Little Franks Tract—all thought to contain "very little farmable area, particularly on a per mile of levee basis" (Hopf, 2011, p. 269)
    4. Are outside the floodways of Yolo Bypass and of the Mokelumne River and Cosumnes River, where levees are restricted in height according to Hopf (2011, p. 266-268). This criterion excludes Liberty Island, Prospect Island, and McCormack-Williamson Tract.
- Islands and tracts thus included: Andrus Island, Bacon Island, Bethel Island, Big Break, Bouldin Island, Brack Tract, Bradford Island, Brannan Island, Canal Tract, Donlon Island, Empire Tract, Frank's Tract, Grand Island, Holland Tract, Jersey Island, Lower Jones Tract, Lower Roberts Island, Mandeville Island, McDonald Island, Medford Island, Mildred Island, Palm Tract, Quimby Island, Rindge Tract, Sherman Island, Staten Island, Terminous Tract, Twitchell Island, Tyler Island, Upper Jones Tract, Venice Island, Victoria Island, Webb Tract, and Woodward Island.

Compiler

The diagram was compiled by Brian Atwater as a member of the Delta Independent Science Board.

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