Hydrologic Extremes and Water Management in a Warmer World – California Perspectives

Draft Report

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Workshop Overview and Goals

The purpose of the workshop was to identify applied science activities that can facilitate climate change adaptation to extreme events and severe weather and to develop a road map for implementing those activities. The focus was on flood management and California.

California has been a leader in climate change adaptation, and California state agencies involved in the water sector are making progress on adaptation related to water management and sea level rise. However, planning for flood-related adaptation is complicated by hydrologic non-stationarity induced by climate change, a concept that suggests past statistical descriptions of climate and hydrological events do not adequately characterize future statistics. This notion challenges traditional standards of practice in hydrologic analysis and engineering design that have been in place for decades.

Recently, workshops involving California state and federal water agencies and the broader research community have identified a variety of issues associated with climate change non-stationarity. This workshop built on past efforts and sought to develop strategies that advance research and practice that support adaptation by state and local resource management agencies. This workshop was the first of two planned events.

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Agenda

Session I: Workshop background

Time	**Description**	**Presenter**
11:00 a.m.	Welcome & Introductions	
11:15 a.m.	Purpose of Workshop	J. Jones and J. Overpeck
11:30 a.m.	Viewpoints from Practitioners	J. Jones and M. Anderson
12:10 p.m.	Status of RISA/SWA Planning and Activities	J. Overpeck
12:30 p.m.	Report from WSWC San Diego Workshop	J. Jones

Session II: State of the Science for Climate Extremes in California

Time	**Description**	**Presenter**
2:00 p.m.	Constraining Flood Probabilities with Hydroclimateological and Paleohydrological Information	K. Hirschboeck
3:00 p.m.	Observed Changes in California: What has Happened and Why, Emphasizing Extremes	K. Redmond
Break:.		
4:00 p.m.	Extremes in the Coastal Environments	D. Cayan
5:00 p.m.	Special Challenges to Models and Analyses that Arise from Growing Focus on Extreme Events	J. Barsugli

Session III: Scientific knowledge and tools needed to support water managers

Time	**Topics**	**Presenter**
9:00 a.m. – 12:00 p.m.	Observations and Monitoring	K. Redmond
	Modeling	M. Dettinger
	Forecast-based Management	M. Ralph
	Water Manager Needs	J. Jones

Session IV: Next steps

Time	**Description**	**Presenter**
1:00 – 3:00 p.m.	Next steps	All

Synthesized Notes

The following notes were recorded at the workshop during presentations and attendant discussions. They relate to five themes: unanswered questions on extreme events, perspectives on extreme events, how water managers manage, challenges and constraints climate extremes present to water managers, and next steps and opportunities.

Unanswered Questions on Extreme Events

Water Managers' perspectives

- What does "extreme events become more extreme" mean, and how quickly do they become more extreme?
- What are the important gaps in observational and monitoring capabilities?
- What kinds of observations will be needed in 50 years?
- How might the observed flood frequency distributions shift in the future?
- How will intensity-duration-frequency (IDF) characteristics of precipitation and floods change?
- Has there been and will there be a change in the frequency of winter storms including storms classified as atmospheric rivers?
- Can factors affecting coastal inundation be modeled, including increased wave height and run-up during storms?
- What additional damages will be associated with storm surges when sea level is approximately one meter higher than its current level?
- Which areas will be inundated from sea level rise, river flooding, and/or a combination of both?
    - For example, many roads are near coasts. It will be crucial to designate which segments will be inundated, and what conditions cause the inundation.

Scientists' perspectives

- What is the scientific capability of tracking extremes?
    - Is there capacity to identify and diagnose extremes in near real-time and/or **r**etrospectively?
- How accurate do models characterize the entire probability distributions?
    - More information is known for about means and medians than extremes.
- What is the nuanced connection between the Madden Julian Oscillation (MJO) and climate of the West Coast?
- How does temperature by itself influence extreme events?
- Are probabilistic concepts, which are used often to communicate climate science, well understood?
- What are the impacts of topographic orientation, height, and gaps on precipitation and floods?

- When do significant changes in extreme events start to occur in future scenarios and when did they begin in past observations?
- How will intensity-duration-frequency (IDF) characteristics of precipitation and floods change?
- What is the relative influence of natural variability (over short and long timescales) and climate change on trends in precipitation and floods?
- With respect to nonstationarity, what part of the past is relevant to the future and how should statistics of the past be adjusted to reflect expected futures?
- Can current observing systems adequately record extreme events, and which ones are not recorded by current monitoring systems?
- Do models have the right sensitivity for analyzing extreme events?
    - For example, recent research points to models underestimating drought.
- How useful are paleoflood data for water planning?
- What are the projected changes in storm frequency and intensity and how will the changes challenge storm water systems?
- What are the projected precipitation extremes in the finest resolution models?
- How will ecologies transition from one state to another as the climate changes?
    - For example, in the Southwest, landscape change will likely occur because of disease outbreaks and fires—these events both instigate and accelerate landscape change.

Perspectives on Extreme Events

- Potential sources of and influences on heavy precipitation events include fronts, cyclonic storms, orographic uplift, tropical storms, convergence zones, atmospheric rivers, blocked atmospheric patterns, El Niño-Southern Oscillation, Madden Julian Oscillation, and perhaps human effects.
- Decadal-scale climate variability likely impacts the likelihood of extreme events.
- It is not sufficient to have abundant atmospheric moisture within a region, there must also be a mechanism to extract it.
- Heavy precipitation events almost always require moisture to be advected into the region to replenish the local moisture source, especially at time scales greater than a few hours.
- The hydrologic system can act as a filter such that extremes in the drivers (i.e. precipitation) may differ from those in the response (i.e. floods).
- In California, a relatively small number of winter storms determine the water year outcome. The presence of a few additional large events or the absence of the typical number of larger events determines whether the year will be wet or dry. Tropical storms, although rare, do make landfall in California.
- Because topography influences precipitation, it can be difficult to extrapolate from one basin to the next.

Sea level rise (SLR) and storm surges

- SLR will likely cause storm surges to be even higher in the future.
    - Sea level events that exceed a “high” threshold occur increasingly more often at the end of the century because of the combined affects of SLR and storm events.
- SLR in California did not increase during the 1992–2005 period likely as a result of natural variability. However, when the variability flips to accentuates SLR, California may experience accelerated SLR.
- Winter tides along the California coast are highest in the early morning, which means events that are not forecasted or underestimated may strike at unfavorable times.
- Estimates of future global SLR have increased over last few years.
- In some settings, SLR can compound riverine flooding in coastal areas through creation of backwater effects that reduce river channel capacity.
- Climate models only provide loose guidance on the amount of SLR—physically-based models are still under developed.
- Big storms, high tides, and El Niño events will likely continue to be the most potent combination that leads to coastal damage and erosion during the next few decades.
- The key to understanding the coastal effects of future SLR is to measure the wave-driven beach and cliff erosion and flooding occurring today in order to construct data-based models of future shoreline retreat and inundation.

Paleofloods

- Watershed–based hydrometeorology studies should continue to be a key component of watershed and flood management practice.
- Studies of floods in Arizona concluded that categorizing floods by their driving mechanism such as convection, synoptic scale, or tropical storm are better for estimating the probability and type of extremely rare floods than a single “100-year flood” calculated from flood data not subdivided. Flooding in other areas of the West can be less meteorologically diverse, having only a single driving mechanism.
- Examining all the observed flood peaks (e.g., the peaks above base) and not just the annual flood series can provide a better understanding of the links between floods and climate.
- The most extreme floods evolve from uncommon locations of typical circulation features, unusual combinations of atmospheric processes, rare configurations in circulation patterns, and exceptional persistence of a specific circulation pattern.

Modeling & Forecasts

- Changes in the mechanisms of extreme events may become visible before changes in their distributions are recognized.

- Higher resolution models will not solve (most of) the modeling problems alone.
- There are concerns that extreme events are not well modeled in atmospheric models, and models may be underestimating their magnitude and frequency.
- Blocking patterns are important synoptic drivers of floods. However, models currently do not simulate well blocking patterns.
- Models do not simulate well monsoons and tropical storms.
- It is problematic to extract precipitation information from models that do not incorporate accurate topography.
- Confidence in model results decreases inland from the coast in part because of topography.
- Big events are harder to forecast accurately in part because forecasters are reluctant to go out on a limb.
- Models are best used to address well-posed questions, preferably ones that investigate processes and phenomena; models have a greater utility than solely characterizing probability distributions.
- Models are useful to test assumptions, even if numbers cannot be accurately extracted from them.
- Large model ensembles are likely not needed to characterize the probability distributions of extreme events; on the other hand, short simulations using regional climate model provide little basis for frequency analysis of extreme events.
- Models capture winter storms well.
- Investigating extreme events in models will require new methodologies, including ones that involve statistically downscaling extreme events.
- Because southern California has only 3–5 extreme events each year, models need to accurately simulate the number of events to be useful for this region.
- Methods to analyze extreme events with models is evolving and include:
  - Brute force approach: Simulate everything and extract the extremes. However, the generating processes of the extreme events may not be captured at these scales.
  - Event-based approach: Pick extreme events from a larger scale simulation and try to model them in detail. However, this likely causes errors of omission.
  - Historic event-based case approach: Select historic examples, model them, and then tweak models to conform to a “what if the environment had been different” scenario. However, this approach is better for convective process scales and not as good for AR or winter snow events that rely on synoptic patterns.
  - Composite-environment approach: Pick composite environments from larger scale simulations and model them intensely.
- Bottlenecks in obtaining good hydrologic model simulations include:
  - Climate model bias: Currently large bias corrections are made to climate models in order to fit them into hydrology models.

    - Coupling: Bias-correction and the lack of historical data to perform bias correction for non-temperature and non-precipitation parameters leads to “awkward” approaches.
    - Hydrologic model calibration: Model calibration needs to be altered to make it more compatible with the physical hydrology of climate change.

How Water Managers Manage

- Applications of flood hydrology include infrastructure design and analysis, flood control projects, dam operations, stormwater management, and floodplain hazard mapping.
- Engineering standards of practice have historically relied heavily on federal information products, such as NOAA’s hydrometeorology reports for Probable Maximum Precipitation (PMP) or Bulletin 17B for flood frequency analysis. Hydrologic design criteria are based on these factors such as precipitation-depth-duration frequency curves and flood frequency analyses.
- Managers manage for a range of conditions, not just extremes. They are just as concerned, if not more concerned, with changes in the frequency of 5-, 10-, or 20-year events as the 100-year and 500-year events.
    - For example, California Department of Transportation is just as interested in 5- and 20-year recurrence intervals as the 100-year event for design of structures such as culverts.
- It is likely that climate change will cause changes to be observable sooner in the higher probability, lower impact events than in the low probability, high impact events.
    - California has more hydraulic structures that would be affected by these more frequent events than the less frequent ones.
- Floods cause lawsuits. Accounting for climate change impacts creates additional challenges in defending against flood litigation.
- The California Environmental Quality Act requires disclosure of climate change impacts associated with a proposed governmental action, and impact mitigation where appropriate. Judges have ruled against projects that did not address climate change in project design and analysis.
- U.S. Geological Survey Bulletin 17b is the standard reference for flood frequency analysis, but it is outdated with respect to observed historical hydrology. It also does not address climate change.
    - Although use of 17b is not legally mandated, following the standards within it can be considered a minimum standard of engineering practice and helps protect against lawsuits and/or serves as a robust defense in litigation.
- There are many existing tools to manage risk associated with extreme events, including engineering safety factors and zoning and floodplain management.

- PMP analysis is the standard of practice for major infrastructure projects such as dams. PMP data are published by NOAA but NOAA's analyses do not address future non-stationarity.
- Physical infrastructure and human behaviors are built around (1) central tendencies—the high number, high probability, and low consequence events—and (2) the tails of the probability distribution—the few, low probability, and high consequence events.
- Long lead times and technical maturity are necessary for management actions involving regulatory frameworks.
    - The design life of hydraulic infrastructure varies with the importance of the facilities. Culverts, for example, may have a design life of only 30–50 years, whereas 100 years would be used for major facilities. A 200-year level of flood protection is a common design standard for urban levees. However, many California levees do not provide this level of protection, especially in the Central Valley. Local agency capital improvement plans for water infrastructure typically use a 2030–2040 timeframe (20 to 30 years in the future).

Challenges and Constraints Climate Extremes Present to Water Managers

- Limitations and barriers to flood hydrology applications include:
    - Observed records are relatively short and don't capture the full potential spectrum of extreme events.
    - Non-stationarity in the climate and changes in land-use can confound the observed record.
    - Many uncertainties are involved in preparation of FEMA's flood insurance rate maps. The uncertainties from inadequate topographic maps can easily outweigh uncertainties associated with the hydrologic analyses.
    - Key hydrologic data sets and analytical methods are not being updated.
    - Hydrology research is not keeping pace with climate science.
    - New hydrologic analysis methodologies are very slow to be incorporated in engineering practice; not only is little relevant hydrology research being conducted, but the transfer of research to operations is minimal.
- Assimilating information about climate change and extreme events into operations will require long-term efforts that include developing new and updating existing federal technical manuals and standards of practice.
- Most decision support tools and procedures are not built for extremes.

Next Steps and Opportunities

- Some California Department of Water Resources priorities include:

  - the development of new methodologies for flood frequency analysis that incorporate non-stationarity and process-based understanding of floods.
  - conducting and facilitating science that supports flood control and emergency response operations, including forecasting.
  - supporting science that advances the understanding of atmospheric rivers, climate change effects on coastal storm surges and wave heights for analyzing coastal inundation, and theoretical limits like probable maximum precipitation and floods.
  - analyzes of the flood hydroclimatology of California.
  - supporting science that supports and improves the design of observing systems and networks.
- In the near-term, seasonal to interannual climate forecasts and longer-lead event-based forecasts provide the most return on investment.
- The federal agencies responsible for flood frequency analysis and PMP estimation should update their guidance materials to explicitly address climate non-stationarity.
- Develop a better understanding of how sectors are affected by extreme events and what kind of extreme events matter to them.
- More decision support tools and procedures are needed for extreme events.
- Analyzing past extreme events to understand the conditions and patterns that occurred can help inform modeling studies and model development.
- Analyze high-resolution models to test the hypothesis that finer scale models, which resolve topography more realistically, significantly improve results.
- Develop studies that analyze the effects of sea level rise, storm surges, and tides on estuarine inundation in the Bay-Delta during winter storm events.
- Advance social science research on perception of risk and how well probabilistic concepts are understood, which are often used in the communication of climate science.
- Analyze how reservoir operations create cascading downstream effects, as well the sensitivity of those effects to different reservoir operations.
- Catalog atmospheric river events by direction—direction, combined with topography, is a crucial flood-controlling parameter.
- Use high-resolution models to analyze precipitation efficiency, or the amount of water that is extracted from the atmosphere.
- Analyze the sensitivity of floods on the western side of the Sierra Nevada Mountains to the orientation of the corresponding basins; compare and contrast atmospheric river events and the historically largest floods for those basins.
- Analyze existing large ensembles and long simulation runs to characterize the modeled extremes.
- Investigate future atmospheric rivers in models.
- Develop a better understanding of relationships between phenomena such as the Arctic Oscillation and the Madden Julian Oscillation (MJO) with observed weather on the West Coast.

Low Hanging Fruit

- Identify atmospheric patterns that produced historical big events and analyze the influence of the Pacific Decadal Oscillation (PDO) and the El Niño–Southern Oscillation (ENSO), among other natural climate fluctuations, in order to understand if these events constrain the magnitude, timing, and frequency of extreme events.
- Identify basins that are particularly sensitive to extreme events, which can help focus future modeling events.
    - For example, two degrees Celsius warming in the Merced River Basin can cause extreme floods because more area receives rain instead of snow.
- Develop flood matrices by selected basins to compare: (1) peak discharge for observed the record, (2) peak discharge from paleoflood record, and (3) calculated PMF.
- Catalog and articulate how past extreme events impact different sectors.
- Create outreach materials such as a document written for laypeople that details the connection between climate and floods and characterizes impacts of key past events.
- Analyze an atmospheric river event with an without a model that resolves convection and compare the modeled precipitation efficiency.
- Examine the paleoflood and PMP relationship.
- Start Building a coalition of people working on extreme events.
- Convene a meeting in the fall that leverages and contributes to the National Climate Assessment activities.
- Create an extremes working group under the CDWR-NOAA memorandum of agreement, to develop a longer-term workplan/research plan for extreme events in the water sector.