Tahoe Valley South Subbasin (6-005.01) Alternative
MEETING NOTES
Wednesday, August 24, 2022; 2:00 pm - 5:00 pm
Location: MS Teams On-Line Meeting

SAG ATTENDEES: (correct after workshop)
John Thiel, PE; Ivo Bergsohn, PG, HG (STPUD); Kyle Ericson, PE (El Dorado Water Agency); Karen Bender, REHS (El Dorado County – EMD); Russell Wigart (EDC DOT); Brian Grey, P.G., (Lahontan Regional Water Quality Control Board); Jason Burke (City of South Lake Tahoe); Jacob Stock (Tahoe Regional Planning Agency; Nicole Bringolf (USFS-LTBMU); Jennifer Lukins (Lukins Brothers Water Co); Harold Singer (Retired); Shelly Thompsen (STPUD); Jeff Brooks (Waterboards); Scott Carroll (CTC); Abby Cazier (Waterboards); John Thiel (STPUD); Barrett Kaasa (DWR); Gary Kvistad (STPUD); Paul Nickles (?); Jeffrey O'Connell (?); Rick Lind (?) Mark Hausner (DRI);

Participants: 22

BASIN MANAGEMENT OBJECTIVES:
1. Maintain a sustainable long-term groundwater supply.
2. Maintain and protect groundwater quality.
3. Strengthen collaborative relationships with local water purveyors, governmental agencies, businesses, private property owners and the public.
4. Integrate groundwater quality protection into local land use planning activities.
5. Assess the interaction of water supply activities with environmental conditions.
6. Convene an on-going Stakeholders Advisory Group (SAG) as a forum for future groundwater issues.
7. Conduct technical studies to assess future groundwater needs and issues.
8. Identify and obtain funding for groundwater projects.

WORKSHOP OBJECTIVES
1. Learn about plans for monitoring the potential impact of groundwater withdrawals on groundwater dependent ecosystems (GDEs)
2. Learn about drought planning and water conservation activities affecting the TVS Subbasin.
3. Learn about recent findings from the South "Y" Plume Regional Plume Characterization and the status of future work.
4. Consider potential projects for application to DWR for Sustainable Groundwater Management (SGM) Grant Program Funding.

TVS Basin (6-5.01) - Open Forum (Group)

Current groundwater-related topics outside Agenda

Attendee, Affiliation - note

I. Bergsohn, STPUD – Meeting Material Items -Drought related

- DWR Fact Sheet Drought Well Permitting Requirements (EO N722)
  - This came out of Governors Executive Order earlier this year. We will discuss it when we get into the drought portion of the workshop.
- California Water Supply Strategy (Ca Agencies, Aug 2022)
  - The Governor released this earlier this month. It is a high-level view of what the State would like to do to best manage this drought.
- Climate Change in increasing the risk of a California mega flood (Huang and Swain, August 2022)
  - Interesting topics, especially if you live in the Tahoe Basin, and consider how mega flood events could potentially isolate the Tahoe Basin. It is another impact of climate change 180 degrees from potential impacts from drought. Demonstrates extremes anticipated from climate change and need to considerat both sides of the coin.

- 2022 SAG Workshop 1 Meeting Notes and Presentations (January12, 2022) are posted on District's Groundwater Page

Consultant Report Groundwater Dependent Ecosystem Monitoring

Handouts: Groundwater Dependent Ecosystem Monitoring Plan Presentation Slides

GDE Monitoring, Mark Hausner, DRI – Presentation

- Based on site inspections DRI is proposing new monitoring wells near Pope Marsh at the bike path/walking path. The other SEZ locations on the map seem to be covered.
- Discussion was had on the installation and the functionality of the monitoring well which would be installed for a period of two years.
- We are looking at putting together a GDE Monitoring Program for a period of 5 years until the next required update to the plan.
- DRI would like to invite stakeholders to come out and see the site.

Q&A

- Scott Carrol said that he knows about 100 existing shallow groundwater monitoring wells that installed by CTC that could be considered for inclusion in the GDE monitoring program. What are the risks on the SEZ map based on?
- Mark Hausner said the risk maps are based on model simulated head results and allowable threshold values for shallow groundwater levels within SEZs. These are used to identify potentially vulnerable SEZs to shallow groundwater level changes caused by climate change including long-term changes in Lake Tahoe stage elevation.
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- Jason Burke believes that the SEZ map is incorrect. He did provide a link in the chat to a the current SEZ shapefile used by TRPA. MH apologized for including old SEZ shapefile

in presentation, current SEZ shapefile is used in GDE evaluation presented in Alternative Plan.

2022 Drought Groundwater Management Activities in response to Drought

Handouts: Water Supply and Demand Assessment Presentation Slides

SB552 Drought Planning, K, Ericson, EDWA – Presentation

- Kyle Ericson reported that El Dorado County has established a SB552 Drought Task Force and an Implementation Schedule has been developed. The Consultant, Stantec, has been brought online to help gather data from all parties. The State Task Force, in conjunction with DWR, is developing, a guidebook that can be used state-wide by the County Task Force(s) with contacts and emergency protocols in the event of a drought emergency.

Q&A

- Ivo B. saw a reference to the domestic well mitigation plan. What is it and what might it entail.
- Kyle E. said that one element is that they have noticed that there are smaller properties that have new wells put on them but there are no records of old wells being decommissioned. There are other elements as well. It has been tough to get information.

Local Water Conservation Measures

- Lukins Brothers Water Company (LBWC), Jennifer Lukins
  - Last summer LBWC had their treatment plant at LBWC #5 go into operation. The GAC treatment plant is a major source for drinking water in the LBWC water system.
  - LBWC also installed an emergency intertie to the TKWA water system.
  - LBWC has seen a decrease of an average of 15% in water usage from 2020-2022. Their water conserve program puts out consistent messaging in conjunction with STPUD. Soil moisture sensors are being supplied along with toilet tablets, garden hose nozzles, and magnets with watering schedule on it. When they get a complaint from other customers LBWC will provide them with these tools and educate them that even though we live in Tahoe we are still having a drought.
- Tahoe Keys Water Company (TKWC), Jennfier Lukins
  - There was no irrigation allowed last summer in Tahoe Keys. This Summer they came out with a very strict emergency irrigation schedule by zone. So far it has been going very well.
  - Compared to 2020, free for all, Tahoe Keys watering to 2022 averaging about a 25% reduction in water usage. From 2021 when no irrigation was allowed to 2022 with the restrictions the increase is close to a 77% reduction. It is a noticeable difference in water usage.
  - Will see what the board decides to do for next summer utilizing this data. They did create a new landscape book of guidelines with drought tolerant landscaping.
  - Ken Payne from El Dorado Water Association (EDWA) thanked Jennifer L. for all the work she is doing.

- STPUD, Shelly Thomsen, South Tahoe Public Utility District (STPUD) – Presentation
  - Shelly L. Gave a slide presentation regarding STPUD efforts toward the drought and the Governors executive order on the water shortage contingency plan.
  - STPUD utilizes towers (AMI) that collect meter data that customers can log into and interface called WaterSmart. They can then see their usage and receive leak alerts. STPUD has saved 26 million gallons of water by utilizing the leak alerts.
  - STPUD has a free Waterwise Landscape Consultation available from a Staff member that is a Master Gardner (Seasonal). We also have Waterwise House calls where Staff will come out to the property and assist with water conservation efforts.
  - STPUD has a Turf Buyback Program where there is a rebate of $1.50 per square foot for folks to remove grass and put in drought friendly landscape.
  - STPUD has had a toilet and clothes washer rebate in effect since 2007, but most new clothes washers are water use efficient.

- Q&A
  - Ivo B. asked what triggers conservation measures used by the District. Is it something the District determines internally?
  - Shelly T. reported that to date CA has been very active during drought periods either mandating or asking for voluntary reductions. For us moving to the next tier of water conservation is watering two days a week instead of three days of week. Today it is mostly being driven by the State. That being said STPUD has water conservation measures in place year around all the time whether there is a drought or not. This has helped STPUD reduce production by 30% in the last 10-15 years.

- County Well Permitting, Karen Bender, El Dorado County Environmental Management Department (EMD)
  - There is a process for people to go through to apply for to drill a well. It is illegal to drill a well without a permit, but EMD is not really seeing a lot of well permits being issued in the Tahoe basin. Since 2007 we have had a total of 8 wells drilled in our area. Five of those have been in the Tahoma Area. Most recently last year on Grass Lake Road. Not a whole lot of well activity.
  - Only one well deepen permit was issued down by Stateline, NV. Their well was kind of shallow and not producing very good, however, they are planning to consolidate with either STPUD or LBWC.
  - In terms of dry wells there have been no reports in the basin. There have been some up on Echo Summit (outside of TVS Subbasin area).
  - EMD strongly pushes for consolidation. We have approx. ½ of the 141 small water systems mentioned by Kyle E. Have had 16 consolidations since 2013.
  - There was one permit denied early this year on Rubicon Drive in the Tahoma area. They were a Vacation Home Rental (VHR) and were denied because they were already in the area of a large water system.

- Water Supply and Demand Assessment, I. Bergsohn, STPUD
  - Ivo B. presented slides on the annual Water Supply and Demand Assessment for the current year. A Copy is available on the STPUD website (a link to the document is in the chat).

- On Water Supply and Demand Assessment that was released you see precipitation in our area that is normal or above normal but typically, at least for STPUD, the water conservation measures are State mandated action and may or may not reflect our actual local hydrological conditions.
- Starting in 2022, Urban Water Suppliers providing more than 3,000-acre feet of water, or having 3,000 connections, are required to produce an annual Water Supply Demand Assessment and report to the California Department of Water Resources by July 1st of each year. This is a new requirement going forward. The report is required to provide an assessment of local water supply including hydrogeologic conditions, water demands for the current year and also for a following dry year.
- Close to 100% of the water supply in our area is from Ground Water. The primary source of groundwater recharge to the TVS Subbasin is precipitation. STPUD uses Hagan's Meadow SNOTEL #508 station to monitor precipitation. It has proven to be reliable and has a strong correlation to recharge used in the South Tahoe Groundwater Model to calculate water balances.
- For the annual Supply and Demand Assessment for our current water year, based on precipitation, it is a normal year at 29.6 inches as of 8/18/22. For using a following dry year we used historical records from water year 2001 which was 16.4 inches and a historically dry year for our area.
- Ivo shared slides outlining how we obtained the data for the report.

Open Discussion-None

<u>South "Y" PCE Plume</u> progress of the Regional Plume Characterization of the South "Y" Plume (RPC) and status of the proposed CAO's recently issued by LRWQCB

<u>Handouts:</u> Regional PCE Plume Investigation Update Presentation Slides; Proposed Cleanup and Abatement Order Presentation Slides

- Regional Plume Characterization Report, Edmond Tarter, PE, AECOM
  - Edmond T. works for AECOM, the consulting engineer that has been working on this project for Lahontan Regional water Quality Control Board for the past 3 years now.
  - Edmond T provided a slide presentation and summary of what AECOM has been doing in the South Y area; An overview of the Site Cleanup Subaccount Program (SCAP); Observations from the Regional PCE Plume Groundwater Investigation; Current and Future SCAP Activities; and Recommended Future Actions.
  - Findings show that the PCE Plume roughly extends 8,000 feet South to North, just Southwest of the Y, and then up toward Tahoe Keys and then would go to the lake.
  - AECOM installed Sentry Wells at Tahoe Keys 1, 2 and at LBWC wells 1, 2, 3, 5 last summer. First sampling was in October 2021 and will sample again in April 2023.

Q&A

- Jennifer L. has been managing TKWA since December 2021 and one thing that what to the Board of Directors over there is that the contamination that TKWC Well #1 is seeing is not from the regional plume it is from a separate plume. Based on this presentation that is not apparent but shows TKWC Well #1 is part of the regional plume.
- Edmond T. said he is not aware of another plume out there that may be impacting Tahoe Keys Well #1

- Brian Grey (LRWCB) said Ed should talk about the data points and EBS Model where it does not look like there is a disconnected plume.
- Edmond T., there may be another source that is contributing, which would be the data gaps, but not in the data set that they have. It looks like just one plume.
- Abby Cazier (LRWQCB?), it is really important to note that there was limited boring coverage near Tahoe Valley Elementary and Tahoe Keys Blvd (data gap through this area). If we did have more investigation in that area the connectivity would be more clear.
- Tyler ?-EDWA, as far as the planning horizon goes what is the point where we will actually develop a mitigation plan on how we are going to contain this plume? Is there a timeline that has been established?
- Brian G. said the next portion of the presentation will show what they are planning with issuance of Cleanup and Abatement Orders (CAO) and compliance within the CAO's.

LRWQCB CAOs, Brian Grey, LRWQCB

- Brian Grey is the -Engineering Geologist part of team overseeing the Lake Tahoe Laundry Works (LTLW), Former Norma's Cleaners, and Big O tires. He gave a slide show and discussed the three proposed (CAO's) that are currently out for public comment.
- Brian G. gave a brief background on the PCE contamination and Primary sources (Source Area Inventory). The comment period for all three CAO's has been extended to 9/19 and LRWQCB will review and respond to all comments and adjust the CAO's based on review of comments. Hopefully this will be done by the end of the year, but it is possible that there will be another 30-day extension.
- Jennifer L. Thanked LRWQCB for the thorough CAO.

Q&A

- John Thiel, at the coin operated dry cleaners is there a theory as to how the release actually occurred?
- Brian G., both Norma's Cleaners and LTLW both had similar operations. Based on the data that has been collected it does seem that releases did occur during delivery activities and the O&M of the unit itself. For example, the highest concentrations were found in the parking lot out front of the Dry Cleaner and not under the machine itself.
- Jason Burke asked if the release from the Big O site that went through the storm drain system into the Tucker Avenue Stormwater Retention Basin was before the basin was constructed and it was an open ditch or after the Tucker Avenue Basin was constructed and the stormwater pipe was extended.
- Brian G., the data that they have was at the storm drain inlet, The samples show elevated levels but in trying to determine time frame it is much more difficult.
- Ivo B., if as far as the expected migration pathways and PCE contaminant data that was provided, Is the finding greater than 500 micrograms per liter (µg/L) of PCE at 50ft consistent with infiltration of PCE in the dissolve phase from land surface or is there something else that should be added as a potential pathway?
- Brian G., with respect to the 500 µg/L, that dissolve phase concentration is below the 1% Dense Nonaqueous Phase Liquids (DNAPL) threshold that you expect to have DNAPL's observed at. So, with respect to other sources and concentration gradients that have been seen within the regional plume those concentrations can be attributed to

upgradient sources. The 500 µg/L is not necessarily an indication of a DNAPL source in that area.
- Ivo B., what type of dissolved concentration at the surface would you need to result at 500 µg/L at depth?
- Brian G., with the data that has been collected, the highest concentrations that they observed was above 5,000 µg/L at the LTLW site in shallow groundwater. In terms of concentration of 500 µg/L that would be reasonable to conclude that could be from dissolved phase transport.
- Edmond T. would agree with Briain and it is consistent with other locations in California.
- Ivo B., what does the apparent similar association of the plume with the Stormwater collection system indicate?
- Brian G., in terms of data collected there does seem that there is preferential transport that is occurring via the stormwater conveyance system and that is being illustrated through the shallow ground water concentrations that we are seeing.
- Ivo B., does that rule out the possibility of direct illicit discharges to the storm drains?
- Brian G., no, we just have indications that there is PCE in shallow ground water and it coincides with the stormwater drainage system alignment.
- Ivo B. thanked AECOM and LRWQCB for their presentations and Jennifer L. for all her efforts during this long process.

SGM Grant Program SGM Grant Program and potential projects for SGM grant funding consideration
Handouts: 2022 TVS Subbasin Implementation Projects List

- Round 2 Proposal Solicitation, Barrett Kassa, DWR
  - Barrett K. is the new point of contact at DWR for the TVS Subbasin. He will give a brief slide presentation. They are still waiting on the legislature to appropriate some funding so there is chance that the Proposal Solicitation Package requirements may change.
  - Round 2 solicitation is expected to be in late 2022 or early 2023. Minimum $200 million of funding with up to $50 million of additional funding. Barret gave an overview on how the solicitation will be conducted. Other than the funding questions the guidelines and scoring will be the same as Round 1.
  - Eligibility: GSAs and Member Agencies, other Agencies authorized to represent a GSA
  - Only one application per basin or subbasin but it can have multiple projects or components. Funding: minimum of $1 million with maximum of $20 million per basin or subbasin He believed there are 94 basins that are applying. It will be competitive so priority will go to subbasins that have not received funding before. Local cost share not required; If you have a min of 5% cost share you will obtain the max points for scoring. Projects must be consistent with the goals of the Budget Act of 2021 and Prop 68.
  - Applications with multiple projects/components will have each component scored individually then averaged to derive final application scoring.
  - Ivo B., no allowance for weighting when averaging individual projects/components? Is there some type of priority presented in the application?
  - Barrett K. there is leeway in the application process to award funding for certain components and not others.
  - Ivo B., any value in submitting the applications early? How would we start the process?
  - Barret K. does not believe you can submit early. He will email as soon as he hears.
  - DWR just announced Urban Community Drought Relief funding. You are able to look at the guidelines and PSP on the website now but it is not expected to be open until

September. Any public agency can apply for this funding but it does have a 25% cost share. The minimum award amount is 5 million because this has almost 300 million worth of funding. A lot of these have been first come first serve as long as the project scores well. Not part of the SGMA program.

Potential Projects List, I. Bergsohn, STPUD

- Ivo B. put together a table of potential projects that are derived from the Alternative Plan (included with meeting materials). He also created a scoring sheet with three different criteria based on scoring from 1-10. He will email out the scoring sheet and based on scores will rank them. Give an idea as to which one would be most favorable with respect to your agency's level of interest..
- There are 8 projects listed in table with a brief description of each project on the list. If anyone has other projects that they fill should be added please put them on the list with a description and eligibility for a SGM grant. Hopefully we can continue the evaluation and ranking process over the next few weeks.
- After we have a good idea on prioritizing these projects then we can have a better idea on how to put together a proposal package for the upcoming solicitation for SGM Grant Round 2 funding.
- All meeting materials will be compiled and posted to the District Webpage but if anyone would like to see them sooner email Ivo and he will send it to them.

Next Workshop: TBD 2023

ADJOURN (5:00 PM)

AGENDA

DATE	Wednesday, August 24th, 2022; 2:00 PM – 5:00 PM (PST)
LOCATION	Click here to join the meeting
STAKEHOLDER ADVISORY GROUP LIST	Ken Payne, P.E., (El Dorado Water Agency, Rick Lind (EN2R) ; Karen Bender, REHS, RD (El Dorado County -EMD); Russ Wigart (EDC DOT); Jason Burke (City of South Lake Tahoe); Scott Carroll (CA Tahoe Conservancy); Andrea Buxton (Tahoe Resource Conservation District); Brian Grey, P.G. (Lahontan Regional Water Quality Control Board); Jacob Stock (TRPA); Nicole Bringolf (USFS – LTBMU); Nakia Foskett (Lakeside Park Water Co.); Jennifer Lukins (Lukins Brothers Water Co); Open (Tahoe Keys Water Co.); Harold Singer (Community Rate Payer); and John Thiel, PE (South Tahoe PUD)
PLAN MANAGER	Ivo Bergsohn, PG, HG (South Tahoe PUD)

BASIN MANAGEMENT OBJECTIVES (BMO)

1. Maintain a sustainable long-term groundwater supply.
2. Maintain and protect groundwater quality.
3. Strengthen collaborative relationships with local water purveyors, governmental agencies, businesses, private property owners and the public.
4. Integrate groundwater quality protection into local land use planning activities.
5. Assess the interaction of water supply activities with environmental conditions.
6. Convene an on-going Stakeholders Advisory Group (SAG) as a forum for future groundwater issues.
7. Conduct technical studies to assess future groundwater needs and issues.
8. Identify and obtain funding for groundwater projects.

WORKSHOP OBJECTIVES

OBJECTIVES

1. Learn about plans for monitoring the potential impact of groundwater withdrawals on groundwater dependent ecosystems (GDEs)
2. Learn about drought planning and water conservation activities affecting the TVS Subbasin.
3. Learn about recent findings from the South “Y” Plume Regional Plume Characterization and the status of future work.
4. Consider potential projects for application to DWR for Sustainable Groundwater Management (SGM) Grant Program Funding.

SEE REVERSE FOR AGENDA

AGENDA

Time	Description	
2:00	**Roll call (5-Minutes)**	**SAG**
2:05	**TVS Subbasin (6-005.01) - Open Forum (10-Minutes)** **Topics outside the subject matter of the SAG and not listed on the Agenda.**	**Round Robin**
2:15	**Consultant Report** • **GDE Monitoring**	**M. Hausner/ S. Rybarski DRI**
2:30	**2022 Drought** • **SB552 Drought Planning, K. Ericson** • **Water Conservation Measures, J. Lukins, LBWC, S. Thomsen, STPUD** • **County Well Permitting, K. Bender, EDC EMD** • **Water Supply Demand Assessment, I. Bergsohn, STPUD** • **Open Discussion**	**SAG Round Robin**
3:15	**South "Y" PCE Plume** • **Regional Plume Characterization Report** • **2022 Activities** • **LRWQCB CAOs** • **Q & A**	**E. Tarter AECOM B. Grey, P.G. LRWQCB**
4:00	**10-minute BREAK**	
4:10	**SGM Grant Program** • **Round 2 Proposal Solicitation** • **Potential Projects List** • **Q & A**	**B. Kaasa, DWR SAG Round Robin**
4:50	**Adjourn**	

Open Forum

Drought Well Permitting Requirements

Drought Executive Order N-7-22

On March 28, 2022 Governor Newsom issued Drought Executive Order N-7-22 that included new well permitting requirements for local agencies to prepare for and lessen the effects of drought conditions (Action 9).

Well Permitting Authority and Groundwater Management Oversight

In California, regulatory authority over well construction, alteration, and destruction activities resides with local agencies (cities, counties, or water agencies), who have the authority to adopt a local well ordinance. Well permits are administered and enforced by local agencies (or local enforcing agencies, LEAs), often the Department of Environmental Health within a given county.

With the enactment of the Sustainable Groundwater Management Act (SGMA) in 2014, local public agencies – called groundwater sustainability agencies or GSAs – formed to provide specific oversight and management of groundwater resources, and to achieve sustainable groundwater management within 20 years through the development and implementation of groundwater sustainability plans (GSPs) and associated projects and management actions. The local GSAs are required to include in their GSPs a discussion of how they will coordinate these efforts with local land use authorities, including local well permitting agencies.

Drought Well Permitting Requirements

Local well ordinances authorize the conditions for agencies to issue a well permit or permit modification. Given the record drought conditions the state has faced over the last three years, Drought Executive Order N-7-22 requires additional actions be taken by local well permitting agencies prior to issuing a well permit.

Excerpt of Action 9 from Drought Executive Order N-7-22:

9. To protect health, safety, and the environment during this drought emergency, a county, city, or other public agency shall not:

a. Approve a permit for a new groundwater well or for alteration of an existing well in a basin subject to the Sustainable Groundwater Management Act and classified as medium- or high-priority without first obtaining written verification from a Groundwater Sustainability Agency managing the basin or area of the basin where the well is proposed to be located that groundwater extraction by the proposed well would not be inconsistent with any sustainable groundwater management program established in any applicable Groundwater Sustainability Plan adopted by that Groundwater Sustainability Agency and would not decrease the likelihood of achieving a sustainability goal for the basin covered by such a plan; or

b. Issue a permit for a new groundwater well or for alteration of an existing well without first determining that extraction of groundwater from the proposed well is (1) not likely to interfere with the production and functioning of existing nearby wells, and (2) not likely to cause subsidence that would adversely impact or damage nearby infrastructure.

This paragraph shall not apply to permits for wells that will provide less than two acre-feet per year of groundwater for individual domestic users, or that will exclusively provide groundwater to public water supply systems as defined in section 116275 of the Health and Safety Code.

Local well permitting agencies retain existing well permitting authorities, including reviewing and administering well permits. Under the Executive Order Action 9, local well permitting agencies must take the following steps during the well permitting process for wells intending to extract groundwater:

1. Consultation with the GSA – If the proposed well would be in a high or medium priority groundwater basin, the well permitting agency must consult with the GSA and receive written verification from the GSA that the proposed well location is generally consistent (not inconsistent) with the applicable GSP and will not decrease the likelihood of achieving the sustainability goals that the GSAs have developed under SGMA.

2. Permit Evaluation – For every well permit application, the local well permitting agency must determine before issuing a well permit that extraction of groundwater from the proposed well is not likely to interfere with the production and functioning of existing nearby wells and is not likely to cause subsidence that would adversely impact or damage nearby infrastructure.

These requirements do not apply to wells that pump less than 2 acre-feet per year (de minimus users) and wells that exclusively provide groundwater to public water supply systems as defined in section 116275 of the Health and Safety Code.

State Resources Available to Local Agencies

The California Department of Water Resources (DWR) provides technical and other support services to local agencies to support decision-making. The following resources are available to help local agencies navigate the well permitting requirements in this Drought Executive Order:

- To find the **groundwater basins subject to SGMA** and classified as medium or high priority: Basin Prioritization Dashboard

- To find the **Groundwater Sustainability Agency** managing the applicable basin or area of the basin: GSA Map Viewer

- To find the **Groundwater Sustainability Plan** adopted by the local Groundwater Sustainability Agency: GSP Map Viewer

- To view **existing nearby wells** (domestic, irrigation, public supply and reported dry wells): California's Groundwater Live – Well Infrastructure

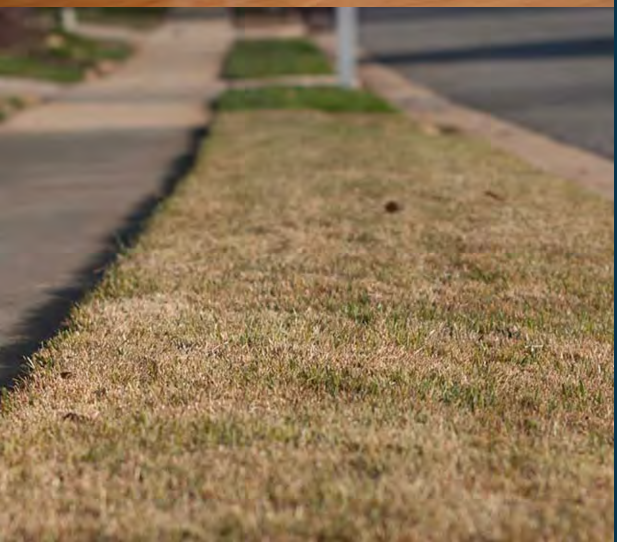
- To view **groundwater levels and trends**: California's Groundwater Live – Groundwater Levels

- To view **subsidence data** and nearby infrastructure: California's Groundwater Live – Subsidence Data

For more information or questions, please contact DWR's Sustainable Groundwater Management Office at: SGMPS@water.ca.gov.

AUG 2022

CALIFORNIA'S WATER SUPPLY STRATEGY
Adapting to a Hotter, Drier Future



Introduction

Our climate has changed. We are experiencing extreme, sustained drought conditions in California and across the American West caused by hotter, drier weather. Our warming climate means that a greater share of the rain and snowfall we receive will be absorbed by dry soils, consumed by thirsty plants, and evaporated into the air. This leaves less water to meet our needs.

This is our new climate reality, and we must adapt.

During his first months in office, Governor Newsom issued an **executive order** calling on State Agencies to create a comprehensive **Water Resilience Portfolio**. The Portfolio prioritized 10 key actions to secure California's water future. *Over the last two years we've **made major progress** that includes*: bringing our groundwater basins into balance; updating infrastructure to move water throughout the state; restoring river systems, including the nation's largest dam removal effort on the Klamath River; and improving water management through new voluntary agreements and technology improvements.

California is investing billions of dollars into these actions to secure the future of California's water supply.

Over the last three years, **state leaders have earmarked more than $8 billion to modernize water infrastructure and management**. The historic three-year, $5.2 billion investment in California water systems enacted in 2021-22 has enabled emergency drought response, improved water conservation to stretch water supplies, and scores of projects by local water suppliers to become more resilient to current and future droughts. The 2022-23 budget includes an *additional* $2.8 billion for drought relief to hard-hit communities, water conservation, environmental protection for fish and wildlife, and long-term projects to permanently strengthen drought resilience.

Over the last two years, scientists and water managers have been alarmed by the accelerating impacts of the warming climate on our water supply. **We now know that hotter and drier weather could diminish our existing water supply by up to 10% by 2040**. So we are ***taking action***.

We have invested billions in securing the future of California's water supply and this focused *Water Supply Strategy* updates state priorities based on new data and accelerating climate change.

To ensure California has the water needed for generations to come, this Strategy includes:

- **Create storage space for up to 4 million acre-feet of water**, allowing us to capitalize on big storms when they do occur and store water for dry periods

- **Recycle and reuse at least 800,000 acre-feet of water per year by 2030**, enabling better and safer use of wastewater currently discharged to the ocean

- Free up 500,000 acre-feet of water for new purposes each year by **permanently eliminating water waste** and using water more efficiently

- Make new water available for use by **capturing stormwater and desalinating ocean water and salty water in groundwater basins**, diversifying supplies and making the most of high flows during storm events

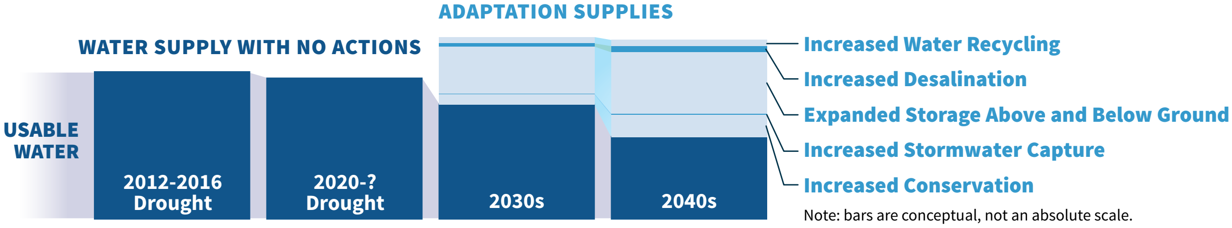
To match the pace of climate change, California must move smarter and faster to update our water systems. **The modernization of our water systems will help replenish the water California will lose due to hotter, drier weather, and generate enough water for more than 8.4 million households.**

CALIFORNIA'S WATER SUPPLY STRATEGY
Adapting to a Hotter, Drier Future

This document outlines California's strategy and priority actions to adapt and protect water supplies in an era of rising temperatures.

Over the next 20 years, California could lose 10 percent[1] of its water supplies.

Our climate has changed, and the West continues to get hotter and drier. As it does, we will see on average less snowfall, more evaporation, and greater consumption of water by vegetation, soil, and the atmosphere itself.

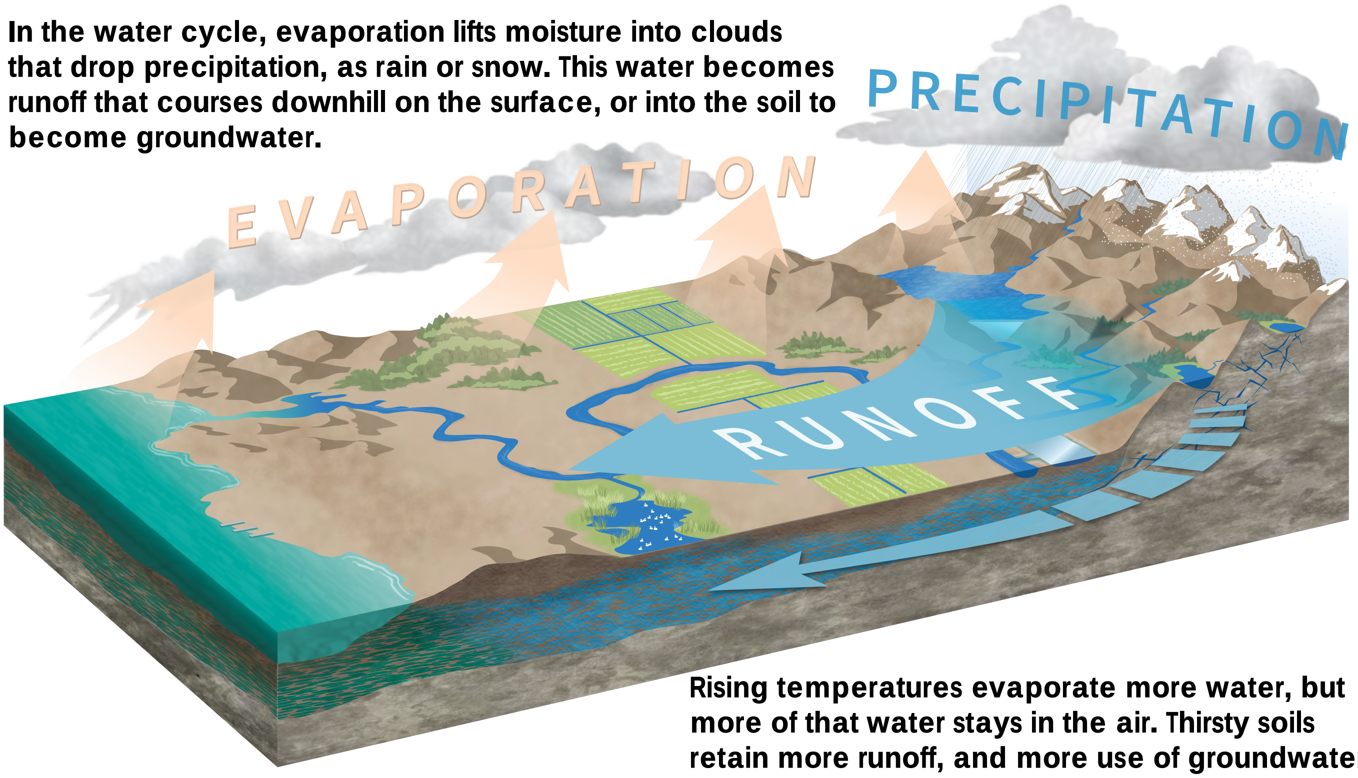


Note: bars are conceptual, not an absolute scale.

In previous droughts the ratio of precipitation to evaporation to runoff has been similar. However, as temperatures rise, evaporation increases, with the consequence of a fall in runoff. As average temperatures continue to increase, the increase in evaporation will continue, with a concurrent drop in runoff.

The coming water cycle: the air claims more

In the water cycle, evaporation lifts moisture into clouds that drop precipitation, as rain or snow. This water becomes runoff that courses downhill on the surface, or into the soil to become groundwater.



Rising temperatures evaporate more water, but more of that water stays in the air. Thirsty soils retain more runoff, and more use of groundwater requires more water for recharging watertables.

[1] DWR estimates a 10% reduction in water supply by 2040 is a planning scenario that considers increased temperatures and decreased runoff due to a thirstier atmosphere, plants, and soils. According to the California Water Plan Update, California's managed water supply ranges from 60-90 MAF per year so the effect of a dryer climate results in a disappearance of about 6-9 MAF of water supply.

California's precipitation always has swung between drought and flood. Those swings are becoming more severe. Regardless of drought or flood, in this changed climate there will be less water available for people to use than there would have been in a cooler climate because of the way plants, soils, and the atmosphere use water as temperatures rise.

The volume of water used by people in California for agriculture, urban, and environmental purposes ranges from 60 million acre-feet per year to 90 million acre-feet per year. A loss of 10 percent of that volume to hotter, drier conditions could mean the disappearance of about six million acre-feet to nine million acre-feet of water supply. For comparison's sake, California's largest reservoir – Shasta – holds 4.5 million acre-feet.

Water underpins much of what we care about as Californians. To thrive and grow as a state, we will have to make up for a loss of supply. We must innovate, conserve, store, reuse, and repurpose water.

This document outlines four sets of actions the State will pursue to prepare California for its new climate reality.

These targeted actions aim to secure supplies for people, so that homes, schools, and businesses do not suffer disruptions, and the state's agricultural economy continues to thrive.

In concert with these actions, the State is working to protect fish and wildlife populations by removing stream barriers, restoring aquatic habitat, bolstering stream flows at ecologically important times, and expanding floodplains and wetlands.

The State also continues to make progress extending clean, safe drinking water to all Californians; in the last three years, the number of people impacted by failing water systems has fallen from 1.6 million to 934,000, and the state has delivered emergency drinking water assistance to 9,456 households and 150 water systems in this drought.

The actions in this strategy aim primarily to support the urban and suburban water systems that serve most Californians and to stabilize water supplies for agriculture. But benefits from these actions will extend to environmental protection and fulfillment of the right of every Californian to safe drinking water, and the State continues to advance those efforts apart from this strategy.

How California is taking action to protect community water supplies

The Water Resilience Portfolio has guided State water policy since July 2020 and will continue to do so. It is a comprehensive suite of actions that support local water resilience. However, the record-breaking temperatures and aridity of the 2012-16 drought, followed so closely by another stretch of similar conditions beginning in the winter of 2020-21, send a strong climate signal that we must heed. These new, more extreme conditions make clear that to secure water supplies, we must double down on a set of actions within the Water Resilience Portfolio, with haste.

Executing this strategy will require coordination with local, tribal, and federal partners to:

1) Develop new water through recycling and desalination.

2) Capture and save more stormwater, above ground and below ground.

3) Reduce use of water in cities and on farms.

4) Improve all water management actions with better data, forecasting, conveyance, and administration of water rights.

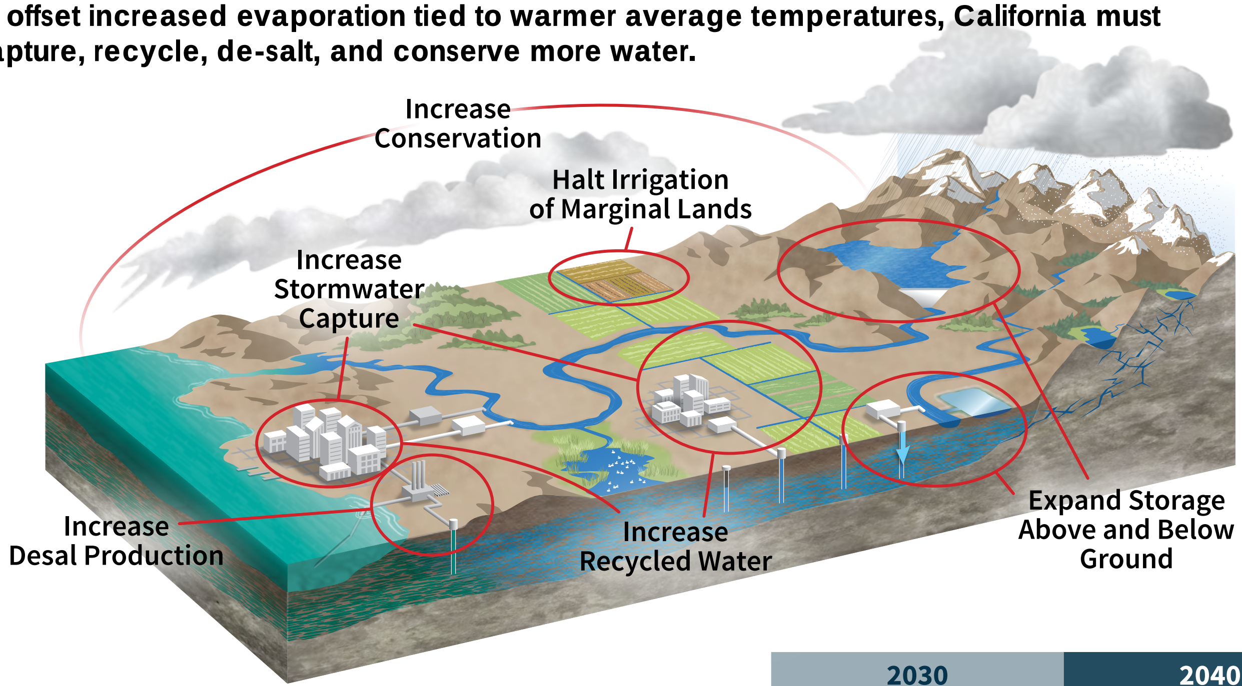
1. Develop New Water Supplies

With investments in technology, wastewater and saltwater can help drought-proof communities.

1.1 Reuse at least 800,000 acre-feet of water per year by 2030 and 1.8 million acre-feet by 2040, with most of that additional recycling involving direct wastewater discharges that are now going to the ocean.

Closing the evaporative gap

To offset increased evaporation tied to warmer average temperatures, California must capture, recycle, de-salt, and conserve more water.



	2030		2040	
Increase Recycled Water	.8 MAF	About 5 MAF	1.819 MAF	About 7 MAF
Increase Desal Production	44,000 AF		84,000 AF	
Increase Stormwater Capture	.25 MAF		.5 MAF	
Increase Conservation	.5 MAF		.5 MAF	
SUBTOTAL FOR RECYCLED, DESAL, STORMWATER AND CONSERVATION	1.1 MAF		2.9 MAF	
Expand Storage Above and Below Ground*	3.7 MAF		4 MAF	
Total	4.8 MAF		6.9 MAF	

*Additional storage capacity does not equate to a similar volume of new water supply. MAF – million acre-feet.

Currently, recycled water offsets about nine percent of the state's water demand, about 728,000 acre-feet per year. The State Water Resources Control Board (State Water Board) has invested a total of $1.8 billion in recycled water projects statewide over the last five years that are in various stages of development. Once completed, those projects will generate an additional 124,000 acre-feet of new water supply.

Approximately 1.5 million acre-feet per year of treated wastewater is currently discharged to California's ocean waters. Not all of this can be recycled, as some water is needed to discharge brine, and wastewater in some places provides critical streamflow for fish and wildlife. But in many places, communities can tap this resource to build water supply resilience.

Current regulations enable communities to use recycled water for drinking via a reservoir or aquifer, and in 2023, the State Water Board will establish direct potable reuse regulations that allow suppliers to distribute recycled water without first putting it into a reservoir or aquifer.

Implementation Steps:

- The State will consider greater investments and leverage federal dollars where possible to build on the $3.2 billion in financing for water recycling projects that the State Water Board has provided to 94 projects since 2012. At roughly $15,000 an acre-foot, it would require a state, local, and federal investment of approximately $10 billion to achieve the 2030 goal and $27 billion to achieve the 2040 goal of recycling an additional 1.8 million acre-feet of water.
- By January 1, 2024, the State Water Board will work with local water and sanitation agencies to identify recycled water projects that hold the potential to be operational by 2030 and by no later than 2040.
- The State Water board will formalize a process currently underway by convening a strike team to identify and resolve permitting and funding obstacles.
- The State Water Board will track the permitting and funding status of recycled water projects with a public, digital dashboard.
- The State will support local water sustainability plans that include water recycling, including (but not limited to):
  - Operation NEXT/Hyperion 2035 (city of Los Angeles)
  - Pure Water San Diego (city of San Diego)
  - Integrated Water Resources Plan and Climate Action Plan (Metropolitan Water District of Southern California)
  - Water Supply Management Program 2040 (East Bay Municipal Utility District)
- The State Water Board will act on direct potable reuse regulations by December 2023.

1.2 Expand brackish groundwater desalination production by 28,000 acre-feet per year by 2030 and 84,000 acre-feet per year by 2040 and help guide location of seawater desalination projects where they are cost effective and environmentally appropriate.

There are 14 seawater desalination plants across the state, with a combined production capacity of approximately 89,000 acre-feet per year. Some are not operating at full capacity and could be positioned to generate additional water supplies in drought, much as "peaker" power plants operate in short bursts to support electricity reliability at times of peak demand. Another 23 brackish groundwater desalination plants have a combined production capacity of 139,627 acre-feet per year. Brackish groundwater requires significantly less energy to treat than seawater.

Proposals to build desalination projects along the coast must be approved under the Coastal Act, in addition to other regulatory requirements. As California becomes hotter and drier, we must become more resourceful with the strategic opportunity that 840 miles of ocean coastline offer to build water resilience.

Implementation Steps:

- By January 1, 2024, the Department of Water Resources (DWR) and the State Water Board, in coordination with local agencies, will identify the brackish desalination projects that have the potential to be operational by 2030 and by no later than 2040. The State will consider investing in grants to local agencies for planning and building desalination projects.
- By January 1, 2024, the State Water Board will review groundwater basins impaired by salts and nutrients and determine the volume of water available for brackish groundwater desalination.
- As the State's representative on the U.S. Department of Energy's five-year, $100 million desalination innovation hub, DWR will continue to guide research investments towards technological breakthroughs that solve California desalination challenges.
- The State will help streamline and expedite permitting to provide better clarity and certainty to further desalination projects. To this end, by June 30, 2023, the State Water Board, Coastal Commission, DWR and other State entities (e.g. State Lands Commission) will develop criteria for siting of desalination facilities along the coast and recommend new standards to facilitate approval.
- Within the following year, these agencies will identify potential available mitigation sites to facilitate the expedited approval of desalination facilities. The State Water Board will consider amendments to the Desalination Policy in its Ocean Plan to streamline permits that meet the recommended siting and design standards for projects located in the identified priority areas.

2. Expand water storage capacity above and below ground by four million acre-feet.

While creating more space to store water in reservoirs and aquifers does not create more precipitation, and whether enough rain and snow fall to fill storage space is out of our control, we need diversion infrastructure, more places to park runoff, and the conveyance to eventually move the water to where it is needed to take advantage of fast-moving storms. Expanding storage capacity improves the ability to capture runoff when diversions cause the least harm to the environment. Furthermore, apart from a hotter and drier climate, capturing water runoff is needed to help correct decades of over-pumping of groundwater basins.

2.1 Expand average annual groundwater recharge by at least 500,000 acre-feet.

Vast capacity to store water exists underground in California. Intentional, directed recharge of groundwater is one of the fastest, most economical, and widely available ways to harness the bounty of wet years to cope with dry years. It has the additional advantage of helping to halt or prevent land surface collapse due to over-pumping, which can damage roads, canals, and bridges. Expanding groundwater recharge requires adherence to laws, so that the environment and water users upstream and downstream are not harmed when streamflow is directed underground. With the multi-faceted suite of actions below, the State intends to help local water agencies to accelerate the pace and scale of groundwater recharge. These actions center on helping local agencies understand the best locations for recharge, analyze the impact of their recharge proposals on the environment and other water users, and expeditiously permit their projects.

Local agencies are developing groundwater recharge projects around the state. By the end of next year, the State cumulatively will have invested $350 million in local assistance for recharge projects. In planning documents, local agencies have proposed more than 340 new recharge projects that, if built, could result in as much as 2.2 million acre-feet of additional stored water in a single wet year by 2030. Until those projects are permitted, it is unclear how much water those projects will have the capacity to divert to underground storage; multiple proposals may rely on the same sources of unappropriated water. But an additional 500,000 acre-feet is a reasonable estimate of the additional average annual recharge volume that may be obtained after these projects are vetted, permitted, and constructed.

California must be ready to respond to future wet winters. Fortunately, several processes already are in place that could be used to divert water from high-flow events to underground storage. Additional outreach, education, and technical assistance will be critical for preparing diverters for a potentially wet winter so that permits can be put in place before the start of the rainy season.

Should local actions become too fragmented or inefficient to maximize recharge opportunities, the state should consider a coordinated, state-level approach to provide for orderly, efficient disbursement of rights to high winter flows.

Implementation Steps: To help achieve this target, DWR and the State Water Board will continue to provide regulatory and technical assistance to local agencies that have received State funds to ensure that groundwater recharge project proponents can successfully navigate the regulatory processes. The State will weigh the following actions. Some would require additional investments and, possibly, regulatory changes.

- **Outreach:**
  - DWR and the State Water Board will conduct a series of outreach activities to highlight temporary permitting pathways in advance of winter, to assess the status of

proposed recharge projects, and to better align state and local agencies to advance groundwater recharge. The outreach would focus on the use of an existing 180-day temporary permit process and would note that permit applications should be received no later than October 1 to be ready for diversions in January.

- By December 2022, DWR will evaluate a process whereby it files for 180-day temporary permits in certain watersheds on behalf of local agencies, in order to advance the development of the permit terms and conditions. DWR also would pay the filing fee, which could help facilitate local willingness to participate.

Technical Assistance:

- DWR will provide outreach and assistance to help connect potential diverters with State Water Board permitting staff to answer specific questions and provide information that enables effective permit applications.
- By October 2022, the State Water Board water right permitting staff will prioritize groundwater recharge permits.

- **Incentives:**
  - The State will weigh immediate and long-term incentives for recharge project applicants to pursue the State Water Board's streamlined recharge permitting pathway. Incentives could include:
  - Waiving of application costs partially or fully for a two-year period.
  - Connecting infrastructure funding to applications that use the State Water Board's streamlined underground storage permitting approach.
  - Prioritization of State funding for groundwater recharge projects that target high-flow events, which raise fewer concerns about the environment and other water right holders than projects that seek to capture water in "shoulder" seasons of spring, summer, and fall.
  - DWR will expand its watershed modeling tools to better assess water available for recharge on a watershed basis.
- **Regulatory Streamlining:**
  - The State will streamline water right permits for recharge projects receiving DWR grants or conducted under DWR's Flood-Managed Aquifer Recharge Program.
  - The State Water Board will develop permanent regulations for water availability analyses that specify methodologies, data, and alternatives for conducting such analyses.
  - The Administration will pursue legislation to revise the water right application process to deliver decisions more quickly.
- **State Administration of Potential Recharge Flows**:
  - DWR and the State Water Board will develop a mechanism to create a more consistent, economical, and equitable approach for allocation of water rights for groundwater recharge. The initial proposal would focus on the State securing all reasonably available future flood flows in the Central Valley, allowing the State to

then allocate the available water in an orderly, holistic, equitable, and integrated approach. The process would:

- Level the playing field for local agencies, especially those that lack the resources to navigate the water right process.
- Set clear water availability metrics for every potential applicant, allowing for fair comparisons among applicants.
- Address equity concerns, including, for example, the need to protect domestic wells or abate subsidence.
- Leverage other funding opportunities.
- Spur tight coordination between the State Water Board and DWR in the allocation of water rights.

2.2 Work with local proponents to complete the seven Proposition 1-supported storage projects and consider funding other viable surface storage projects.

Seven locally-driven projects are underway to increase the state's overall capacity to store water by 2.77 million acre-feet – nearly three times the capacity of Folsom Lake. The seven projects are on track to receive a combined $2.7 billion in state funding from Proposition 1, the 2014 water bond, once they meet the requirements imposed in the bond law. Four of the projects involve groundwater storage and three involve creation of a new or expanded reservoir. Two of these seven projects are likely to begin construction next year, with the other five expected to begin construction in 2024 or 2025. Project proponents are working now to obtain permits, arrange financing, finalize environmental documents, and negotiate contracts with state agencies for the delivery of public benefits from the projects, including environmental flows.

Implementation Steps:

- To formalize, streamline and continue existing efforts, the California Natural Resources Agency and the California Environmental Protection Agency will establish an interagency strike team to facilitate state permitting and support completion of these projects.
- Water Commission staff will continue to monitor development of the seven Proposition 1 projects closely.
- Permit teams from the California Department of Fish and Wildlife (CDFW) and the State Water Board will continue working with applicants and with other state agencies inform and advance the development of contracts for administration of public benefits.
- Water Commission, DWR, CDFW, and State Water Board teams will continue robust coordination. and working with applicants to draft and execute contracts for administration of public benefits.

2.3 Expand San Luis Reservoir by 135,000 acre-feet.

The federal government is proposing to expand San Luis Reservoir in Merced County to capture more winter storm runoff. In extremely wet years like 2017, San Luis fills and

California misses an opportunity to capture and store even more water for use during subsequent dry years. The project would expand the capacity of the two-million acre-foot reservoir by 130,000 acre-feet -- enough to supply nearly 400,000 homes a year. DWR is working with the U.S. Bureau of Reclamation (Reclamation) on this proposed project and sees it as an important part of a set of inter-related joint projects to benefit the Central Valley Project and State Water Project, which include upgrading the San Luis Reservoir dam for earthquake safety, modernizing conveyance of water through the Sacramento-San Joaquin Delta, and restoring capacity lost due to subsidence at major Central Valley canals.

Implementation Steps:

- In December 2019, Reclamation and DWR announced a partnership to move forward on the seismic upgrade. Reclamation and DWR celebrated the groundbreaking of the project in June 2022. Construction is expected to finish in 2028. DWR will continue to work with Reclamation to complete the seismic upgrade and expansion.

2.4 Rehabilitate dams to regain storage capacity.

As of May, 112 California dams are rated “less than satisfactory” by State dam inspectors, and the reservoirs behind 41 of those dams cannot be filled beyond a certain level in order to protect public safety. The loss of storage is about 350,000 acre-feet per year. Accelerating dam safety repairs would help local water districts regain lost storage capacity and improve public safety. While this has historically been a federal or local obligation, the Legislature and Administration enacted additional funding to support dam owners faced with costly repairs.

Implementation Steps:

- DWR will administer the $100 million in the 2022-23 budget for local dam safety projects and flood management.

2.5 Support local stormwater capture projects in cities and towns with the goal to increase annual supply capacity by at least 250,000 acre-feet by 2030 and 500,000 acre-feet by 2040.

Over the last 30 years, an average of approximately 324,000 acre-feet of stormwater a year has been captured and recharged in communities in the South Coast alone. While this value varies from year to year, during the exceptionally wet winter of 2004-05 over 900,000 acre-feet of runoff was captured and infiltrated into the local groundwater basins.

The size, cost, and feasibility of stormwater capture projects vary greatly by location. It is extremely difficult for stormwater agencies to accurately measure stormwater capture volume and to predict potential due to uncertainties with annual precipitation.

Implementation Steps:

- Through permitting and funding, the State will incentivize local agencies to develop stormwater capture projects and help offset the cost of completing these projects, including through stormwater crediting systems to encourage public-private partnerships.

- The State Water Board will hire a contractor to provide an estimate of current stormwater capture and use statewide and then re-evaluate every five years progress towards the 2030 and 2040 goals.

3. Reduce Demand

3.1 Build upon the conservation achievements of the last two decades to reduce annual water demand in towns and cities by at least half a million acre-feet by 2030.

During the 2012-2016 drought, Californians did their part to conserve water, with many taking permanent actions that continue to yield benefits; per capita residential water use statewide declined 21 percent between the years 2013 and 2016 and has remained on average 16 percent below 2013 levels as of 2020. Californians are stepping up again in this current drought. The State set a target of 15 percent for statewide conservation. Californians have made progress toward that goal in the summer of 2022, but more is needed to cope with the intense drought at hand and for the long term.

California enacted laws in 2018 to set new efficiency standards for how people use water in homes and businesses in ways that make sense in each region. These standards will drive fully-efficient water use in communities and eliminate water waste, even as communities continue to grow. The 2018 legislation calls for these standards to be met by 2030. The State Water Board is on track to set those new standards, informed by extensive data collection and analysis and recommendations from DWR. The recommended standards for indoor and outdoor water use for residential, commercial, industrial, and institutional water use could save 450,000 acre-feet per year starting in 2030. This amount of water would support 1.35 million homes, and the savings would prevent urban water use from rising as much as it would otherwise as population grows and more housing is built. These new standards would not apply to individual Californians, but local water suppliers must ensure the standards are met.

Given the acute need to conserve water in a potentially fourth dry year, the State Water Board will develop emergency conservation measures that expedite implementation of conservation in a way that is already mandated through the 2018 laws. If drought conditions persist, the new short-term requirements could take effect no later than spring 2023. The new requirements would consider the relative efficiency of each supplier. These new efficiency targets would therefore work as a bridge to take California from voluntary measures to efficiency-based, water-use budgets that account for differences in climate zones, landscape area, population, and other factors.

In addition, the Administration sponsors a robust campaign to motivate urban Californians to save water and is working to accelerate the transition of turf to landscapes that use less water. To this end, the State will partner with local agencies to convert 500 million square feet of ornamental turf by 2030, with corresponding investments in programs and policies that incentivize turf conversion. Removal of 500 million square feet of turf could generate 66,000 acre-feet of water savings each year at an estimated cost of $1 billion.

Implementation Steps:

- The State Water Board will develop short-term efficiency-based conservation targets for every urban retail water supplier based on their unique characteristics like climate zone, water demand, residential landscape area, and population. The Board will compare water suppliers' actual use to their estimated efficient use target and assign them a percent reduction, with a higher reduction target for suppliers whose actual use is further from their efficient use target.
- DWR and the State Water Board will target grants to help local water districts achieve efficiency targets, using funding recently approved by the Legislature.
- The State-run Save Our Water campaign will continue to educate Californians about the severity of the current drought and the need to make water conservation a permanent, daily practice.
- DWR will establish a grant program to support local efforts to replace ornamental turf with drought-tolerant landscaping and—where schools and parks require turf—to make turf irrigation and maintenance more efficient, with a focus on disadvantaged communities.
- The State Water Board will advance adoption of new long-term water use efficiency standards, per existing statute (2018).
  - Once DWR provides its formal recommendations, the State Water Board will begin the process for enacting the regulation to ensure the rule will be in effect by January 1, 2024.

3.2 Help stabilize groundwater supplies for all groundwater users, including a more drought-resilient agricultural economy.

California irrigated agricultural acreage declined by 1 million acres between 2002 and 2017. The approximately eight million acres of irrigated farm and ranchland will shrink by at least an estimated additional 500,000 acres to one million acres between now and 2040 as local agencies transition to groundwater use that is sustainable over coming decades. The conserved water should support a more drought-resilient agricultural economy that retains its vitality.

Implementation Steps:

The State will:

- Continue to implement the Sustainable Groundwater Management Act (SGMA) to protect communities, agriculture, and the environment against prolonged dry periods and climate change, preserving water supplies for existing and potential beneficial use.
- Support local water demand management that includes changes to cropping patterns and fallowing by building upon this year's investment of $40 million in grants to regional organizations working to reduce groundwater reliance and create local environmental and economic opportunities through land-use changes.
- Continue to support conservation and water efficiency practices by agricultural producers.
- Support flexibility in local land use decisions to protect beneficial uses and users.

- Continue direct investment and technical assistance in drought relief for agriculture with dedicated funding to assist socially disadvantaged and underserved populations.

4. Improve Forecasting, Data, and Management, including Water Rights Modernization

Crucial to achieving the water supply actions described here is a common, readily-available set of facts about water supply and use, better forecasting, and integrated use of data and technology. Water rights modernization and reform is a critical component of ensuring we can efficiently and effectively adapt to a changing climate.

4.1 Improve data collection and modernize forecasts for a changed climate.

Sierra snowpack provides about a third of the water people use in California, yet the existing approach to forecasting snowmelt runoff dates to the 1950s.

To account for climate change, we must simulate the physics of interactions among the atmosphere, water as rain or snow, and the land surface – and we need to do this for individual watersheds, incorporating site-specific features like slope orientation and depth of soil. This requires timely data collection.

Implementation Steps:

The State will:

- Continue to invest in the human and technical resources needed to improve predictions and forecasting for water supply planning.
- Advance a multi-agency effort to install 430 new stream gages and upgrade or re-activate 200 more across the state. These gages provide real-time surface water data for enhanced drought management and flood response.
- Work with the U.S. Army Corps of Engineers leadership to accelerate the pace at which the manuals guiding reservoir operations are updated to reflect a changed climate.

4.2 Improve the flexibility of current water systems to move water throughout the state.

California depends upon aging, damaged, or increasingly risk-prone infrastructure to transport water between different areas of the state. Modern infrastructure and tighter coordination between the state's two major water projects would expand capacity to move water when it is available.

The state and federal water projects are fed by levee-lined channels in the Sacramento-San Joaquin Delta. This Delta infrastructure faces serious threat of failure due to storm surge, sea level rise, and earthquakes that could collapse levees. Loss of this water supply for any amount of time poses significant risk to farms, businesses, and most California homes. South of the Delta, major canals have been damaged by subsidence caused by the over-pumping of groundwater, restricting the capacity to move water when it is available.

DWR proposes to modernize State Water Project (SWP) conveyance in the Delta. Had the proposed project been operational in 2021, the project could have captured and moved an additional 236,000 acre-feet of water into San Luis Reservoir during that winter's few large storms.

Administrative hurdles also limit flexibility to move water. Every year for the last 10 years, the federal and state water projects have applied to the State Water Board for temporary flexibility in the locations where water diverted by either project may be used. These "consolidations of the authorized places of use" of the SWP and the Central Valley Project last only a year and require repetitive work by all parties involved. A permanent change to allow for consolidated place of use among the projects would make water transfers easier and lay the groundwork for discussions about future operation of the two projects.

Implementation Steps:

- DWR will advance the design of and the draft environmental impact report for the proposed Delta conveyance project, which would construct new intakes along the Sacramento River and a tunnel under the Delta to safeguard SWP deliveries and ensure that the SWP can make the most of big but infrequent storm events.
- DWR will disburse $100 million included in the 2022-23 state budget to support costs of repairing four major San Joaquin Valley canals damaged by subsidence.
- DWR and the State Water Board will chart a work plan to address the resources needed for preparation, submittal, and consideration of a joint place of use petition from the federal and state water projects.

4.3 Modernize water rights administration for equity, access, flexibility, and transparency.

The foundation of how California manages water rights dates to the Gold Rush and has not evolved in step with changing public values and management needs. The State Water Board is challenged to provide timely, useful, and meaningful information to guide state and local water management decisions, which are especially vital during periods of drought.

Other western states including Washington, Oregon, Nevada, and Idaho manage water diversions much more nimbly than California, which puts them in better position to adjust to what many call "aridification" – the transition to a drier climate. The ability to adjust diversions quickly also is crucial to protecting fish and wildlife, other water right holders, and public health. To make a century-old water right system work in this new era, the State Water Board needs accurate and timely data, modern data infrastructure, and increased capacity to halt water diversions when the flows in streams diminish. These improvements are a necessary predicate to modernize our water rights system in a manner that respects water right priorities and aligns with current public values and needs.

Implementation Steps:

The State Water Board will:

- Continue to build upon efforts started last summer with the investment of $30 million to digitize existing paper records and rebuild the state's water right data management system.

- Develop pilot projects in two or three watersheds over the next five years to collect real-time diversion data and integrate the data into the State Water Board's water rights data system, with lessons learned and outcomes used to inform statewide tools needed for administering an efficient and effective water rights system.
- Develop data and analytical tools for implementing the water right priority system for an estimated 10 to 15 watersheds.
- Support modeling staff to develop more robust supply/demand models for the Delta watershed.
- Consider adopting regulations that would allow for curtailments of water rights in years when there is not a declared drought emergency. The State currently lacks the authority in most years to implement the priority water rights system without a declared drought emergency.
- Support enforcement staff to help address illegal and unauthorized diversions during dry conditions.
- Consider regulations, legislation, and pursuing resources needed to streamline and modernize the water right system, clarify senior water rights, and establish more equitable fees.

Why target these actions?

The last three years of record-breaking drought made painfully real the hotter, drier pressures on water systems. These four major sets of actions would put to use water that would otherwise be unusable, stretch supplies with efficiency, and expand our capacity to bank water from big storms for dry times. They are designed, in other words, for a climate prone to weather whiplash.

These actions alone will not eliminate local water supply risk. The variability of rain and snow is too great, as is the uncertainty about which projects local agencies will implement. These actions aim to spur local agency adaptation to a new reality and change the way the State does business in order to better support local and regional water management efforts.

Who will carry out this strategy?

The state and federal governments each operate large water delivery systems in California, but local water districts and counties have primary responsibility for getting supplies to homes and businesses. Thousands of local and regional entities play a role in water management. Implementation of this strategy will require decisive state action. It will also require partnerships, as local agency leaders, federal partners, farmers, other business owners, and individual Californians are essential actors in carrying out this plan. To ensure successful implementation in such a decentralized system, the State must lead, set goals, provide incentives, and be prepared to exert greater authority when necessary.

The State will prioritize its funds and human resources to support local projects that satisfy state planning and permitting requirements to protect natural resources and help us collectively reach the targets outlined above. The State will invest in forecasting and data and water right administration – including real-time tracking of water use – to improve all water management actions by state, local, federal, and private entities. The State will also ensure that California's response advances equity and takes into account communities that are most at risk from climate change and that have experienced environmental injustices.

Water affordability is key to ensuring the human right to water – established in California law -- in the face of a hotter, drier state. The State has made strides in promoting affordability through provision of low-interest loans and grants to support infrastructure and planning for water systems, and by addressing pandemic-related water debt. However, the increased investments in infrastructure necessary to meet our future water supply needs will put additional pressure on affordability. The State will identify how best to support low-income households and address community affordability of water systems. Electric and communication utilities have programs to ease cost burdens on low-income members of the community, and it is important to address this in the water utility sector in a way that Is workable and sustainable from a state budget perspective.

Where local agencies fail to build water resilience, the State will exert greater regulatory authority or work with the Legislature to gain authority to do so.

Moving Smarter and Faster

Climate change uniquely affects California's regions. This document articulates statewide targets for certain water management strategies, but achieving those overarching goals requires solutions at the local level, where the opportunities and challenges of each watershed vary tremendously. To encourage collaboration across watersheds that leads to greater statewide water resilience, the State will work with stakeholders and the Legislature to create:

- A funding program that incentivizes water users to develop regional targets for recycling, desalination, storage, efficiency, and other water management strategies.
- An expedited permitting path for water projects that help regions achieve those targets.

In order to deliver the pace and scale of projects necessary to meet this unprecedented climate challenge, we must modernize regulatory structures and expand staff capacity so that State agencies can assess, permit, fund and implement projects at the pace this climate emergency warrants.

The Administration will work with the Legislature and stakeholders to pursue the following:

- A more expeditious process for completing, reviewing and finalizing California Environmental Quality Act (CEQA) reviews and Water Code proceedings for critical water infrastructure projects to build drought and flood resilience.
- A voluntary permitting process for water infrastructure projects administered by the Governor's Office of Planning and Research (OPR). State agencies would retain authority to review, identify, and address environmental impacts, but the OPR would expedite the collective permitting process. This proposed process would not be an

option for water projects already under environmental review. The Administration would work with the Legislature to determine eligibility criteria for this voluntary process.

- Legislation, where appropriate, and regulations that would allow for curtailments of water rights in years when there is not a declared drought emergency. The State currently lacks the authority in most years to implement the priority water rights system without a declared drought emergency.

The Administration will:

- Develop water availability analysis guidelines for water right applications that account for high-flow periods on fully appropriated streams and the way climate change is shifting the seasonality and intensity of runoff. Develop permanent State Water Board regulations that specify the data and methodologies to be used for conducting such analyses in order to remove the current ambiguity about regulatory requirements.
- Establish a State Water Board, DWR and the California Department of Food and Agriculture "Groundwater Recharge Coordinating Committee" to jointly implement the groundwater recharge initiatives.
- Establish programmatic permitting for projects of a similar nature (such as water recycling or habitat restoration) in order to lower costs, simplify process, and speed permit approval.
- Institutionalize early alignment and regular internal coordination across state agencies on the permitting of water supply adaptation projects.

Conclusion

The world is getting hotter. The increased heat will intensify the natural swings in California's climate and shrink water supplies. Targeted state funds and focus will support local efforts to conserve, capture, recycle, and de-salt enough water to allow California communities to prosper in a hotter, drier climate.

CLIMATOLOGY

Climate change is increasing the risk of a California megaflood

Xingying Huang[1]*† and Daniel L. Swain[2,3,4]*†

Despite the recent prevalence of severe drought, California faces a broadly underappreciated risk of severe floods. Here, we investigate the physical characteristics of "plausible worst case scenario" extreme storm sequences capable of giving rise to "megaflood" conditions using a combination of climate model data and high-resolution weather modeling. Using the data from the Community Earth System Model Large Ensemble, we find that climate change has already doubled the likelihood of an event capable of producing catastrophic flooding, but larger future increases are likely due to continued warming. We further find that runoff in the future extreme storm scenario is 200 to 400% greater than historical values in the Sierra Nevada because of increased precipitation rates and decreased snow fraction. These findings have direct implications for flood and emergency management, as well as broader implications for hazard mitigation and climate adaptation activities.

INTRODUCTION

California is a region more accustomed to water scarcity than overabundance in the modern era. Between 2012 and 2021, California experienced two historically severe droughts—at least one of which was likely the most intense in the past millennium (*1*, *2*)—resulting in widespread agricultural, ecological, and wildfire-related impacts (*3*, *4*) and ongoing drought-focused public policy conversations. Yet, historical and paleoclimate evidence shows that California is also a region subject to episodic pluvials that substantially exceed any in the meteorological instrumental era (*5*)—potentially leading to underestimation of the risks associated with extreme (but infrequent) floods. Observed extreme precipitation and severe subregional flood events during the 20th century—including those in 1969, 1986, and 1997—hint at this latent potential, but despite their substantial societal impacts, none have rivaled (from a geophysical perspective) the benchmark "Great Flood of 1861–1862" (henceforth, GF1862). This event, which was characterized by weeks-long sequences of winter storms, produced widespread catastrophic flooding across virtually all of California's lowlands—transforming the interior Sacramento and San Joaquin valleys into a temporary but vast inland sea nearly 300 miles in length (*6*) and inundating much of the now densely populated coastal plain in present-day Los Angeles and Orange counties (*7*). Recent estimates suggest that floods equal to or greater in magnitude to those in 1862 occur five to seven times per millennium [i.e., a 1.0 to 0.5% annual likelihood or 100- to 200-year recurrence interval (RI)] (*5*, *8*).

The extraordinary impacts resulting from GF1862 provided motivation for a 2010 California statewide disaster scenario—known as "ARkStorm" (ARkStorm 1.0)—led by the U.S. Geological Survey in conjunction with a large, interdisciplinary team (*9*). The meteorological scenario underpinning the ARkStorm 1.0 exercise involved the synthetic concatenation of two nonconsecutive extreme storm events from the 20th century (*10*). Subsequent analysis suggested that such an event would likely produce widespread, catastrophic flooding and subsequently lead to the displacement of millions of people, the long-term closure of critical transportation corridors (*9*), and ultimately to nearly $1 trillion in overall economic losses (2022 dollars) (*11*).

Meanwhile, a growing body of research suggests that climate change is likely increasing the risk of extreme precipitation events along the Pacific coast of North America (*12*, *13*), including California (*14*–*16*), and of subsequent severe flood events (*17*, *18*). The primary physical mechanism responsible for this projected regional intensification of extreme precipitation is an increase in the strength of cool-season atmospheric river (AR) events (*19*–*21*). Previous analyses have suggested that the thermodynamically driven increase in atmospheric water vapor with warming is directly responsible for most of this projected AR intensification [e.g., (*16*)], with the remainder contributed by shifts in regional atmospheric circulation. There is also evidence that increased radiative forcing may result in an eastward shifted expression of atmospheric circulation anomalies associated with both the Madden-Julian Oscillation (*22*) and the El Niño–Southern Oscillation (ENSO)–forced component of the Pacific North American pattern (*23*)—both of which would increase the subseasonal variability of cool season precipitation over and near California. Compounding the increase in extreme precipitation associated with AR events are warming temperatures themselves (*24*)—which raise the mean elevation of snow accumulation in mountainous areas (*25*), increase instantaneous runoff rates as rain falls at the expense of snow (*18*), and raise the risk of "rain on snow" events (*26*). Collectively, these previous research findings motivate the question of whether climate change may substantially affect the odds of "low probability but high consequence" flood events.

Here, we describe the overall design and implementation of, as well as results from, "ARkStorm 2.0"—a new severe storm and flood scenario reimagined for the climate change era. Leveraging recent advances in atmospheric modeling by coupling a high-resolution weather model to a climate model large ensemble, we assess the meteorological characteristics of extreme storm sequences (henceforth referred to as "megastorm" events) as well as the subsequent extreme runoff and adverse hydrologic outcomes such meteorological conditions (henceforth, "megaflood" events) would produce under both present-day and warmer future climate regimes. This work builds

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upon previous research by explicitly considering long-duration (30-day) storm sequences (rather than single-storm events) most relevant to flood hazard management and disaster preparedness, characterizing large-scale ocean and atmosphere conditions associated with such severe storm sequences, and assessing the likelihood of these events over a wide range of potential levels of global warming. We find that climate change has already increased the risk of a GF1862-like megaflood scenario in California, but that future climate warming will likely bring about even sharper risk increases.

RESULTS

Large-scale and regional climate conditions associated with megaflood scenarios

We design two separate megastorm scenarios capable of causing a megaflood in California—one drawn from the recent historical climate (circa 1996–2005; henceforth "ARkHist") and another from a hypothetical warmer future climate (2071–2080 in the "high warming" RCP8.5 emissions scenario; henceforth "ARkFuture"). Each scenario comprises a multiweek sequence of consecutive severe winter storm events similar to what is reported to have occurred during the peak of the GF1862 event. Specific events are selected by ranking the 30-day cumulative precipitation on a California statewide basis simulated by the 40-member Community Earth System Model Large Ensemble (CESM1-LENS) and subsequently choosing from among the top 3 ranked events in each climate era to dynamically downscale using a high-resolution weather model [the Weather Research and Forecasting (WRF) model v4.3]. Further details can be found in Materials and Methods.

We find that both ARkHist and ARkFuture events occur during simulated warm-phase ENSO (El Niño) years, although the El Niño event that co-occurs with ARkFuture is much stronger [Niño 3.4 sea surface temperature (SST) anomaly = +1.48 K] than that with ARkHist (+0.56 K). Both events have maximum SST anomalies located in the tropical central Pacific (Fig. 1, A and B), which would be consistent with so-called "central Pacific" or "Modoki" El Niño (*27*). Warm (positive)

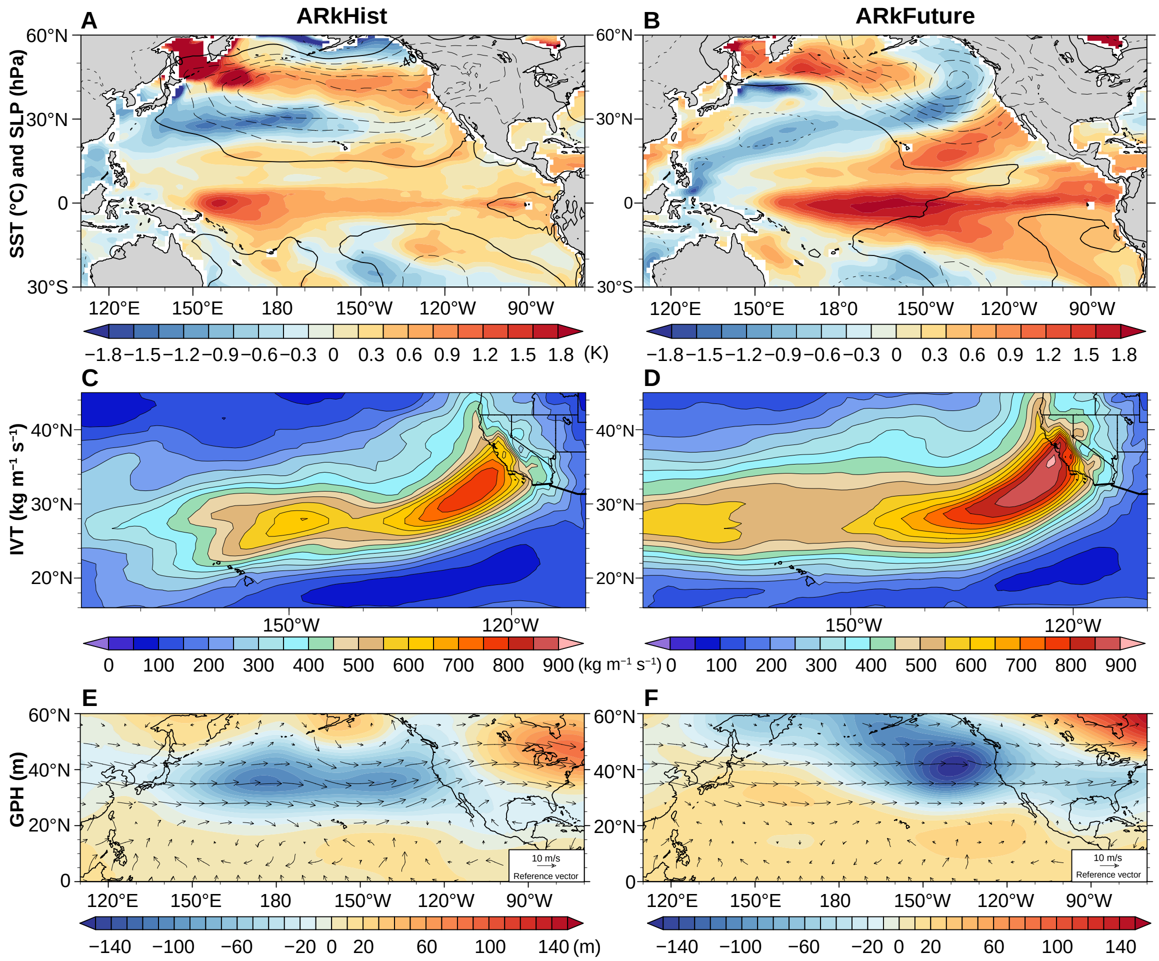

Fig. 1. Large-scale conditions during California megastorm scenarios. (**A** and **B**) Mean SST anomalies (color contours, K) and mean SLP (hPa) anomalies (dashed/solid contours) during ARkHist (A) and ARkFuture (B). SST and SLP are detrended before anomaly calculation using monthly data from each corresponding CESM1-LENS member (baseline period 1980 to 2005 for ARkHist; 2060–2090 for ARkFuture); solid (dashed) SLP contours denote positive (negative) anomalies in increments of 2 hPa. (**C** and **D**) Composite instantaneous vertically IVT (kg m^{-1} s^{-1}) for all hours in which California mean precipitation exceeds 1.5-mm ARkHist (C) and ARkFuture (D) using WRF 81-km simulations. Mean 30-day 500-hPa geopotential height (GPH, detrended) anomalies (color contours, m) and mean absolute 850-hPa wind vectors (m/s) (black arrows) during ARkHist (**E**) and ARkFuture (**F**).

SST anomalies are also present in the western Bering Sea and Sea of Okhotsk, as well as along the immediate California coast, in both cases. In addition, a broad region of negative sea level pressure (SLP) anomalies is centered over the Gulf of Alaska and adjacent portions of western North America—consistent with traditional El Niño teleconnections—although the zone of negative SLP anomalies extends farther westward across the North Pacific in ARkHist.

We acknowledge, however, that these large-scale patterns and associations with ENSO are drawn from only two individual scenario instances, and we cannot determine from this analysis alone whether these relationships are robust across a wider range of potential megastorm events. To offer a more systematic assessment, we consider the top 4 ranked 30-day California precipitation events in the CESM1-LENS historical and warmer future snapshot periods (fig. S1). We find that all eight such events are associated with anomalously warm conditions in the tropical Pacific Ocean, and Niño 3.4 SST anomalies are uniformly positive (+0.33, +0.56, +2.28, and + 1.56 K for the top 4 historical events and + 1.17, +1.95, +1.48, and + 1.39 K for future events, respectively, using detrended SST). However, it has recently been demonstrated that dynamic ENSO indices can better capture the spatial diversity of ENSO events and their subsequent western U.S. hydroclimate teleconnections (*28*). We thus calculate the ENSO Longitude Index (ELI)—an ENSO metric that tracks the average longitudinal position of ENSO-associated deep convection and accounts for the nonlinear response of convective activity to SST (*29*). As with Nino 3.4 SST anomalies, all eight such events are again associated with anomalously warm conditions in the tropical Pacific Ocean, but ELI values more clearly illustrate a wider range of ENSO spatial variability and dynamical intensity (ELI = 169.9°E, 171.6°E, 185.1°E, and 181.5°E for the top 4 historical events and ELI = 174.2°E, 181.0°E, 176.8°E, and 179.1°E for future events, respectively, using detrended SST).

Using the ELI categorizations defined in (*29*), this suggests that two of four events each in the historical and future simulations occur under "strong El Niño" conditions (ELI ≥ 179°E), and one of four historical and two of four future events occur under "moderate El Niño" conditions (170°E ≤ ELI < 179°E), with the final historical event falling nominally under the "moderate" threshold. Collectively, seven of eight historical and future potential California megastorm events occur under moderate or strong El Niño conditions as defined by the ELI (eight of eight, if rounding to the nearest degree of longitude). These findings strongly suggest that there is a substantially elevated likelihood of month-long storm sequences capable of producing very large precipitation accumulations during moderate to strong El Niño conditions and that the conspicuous anomalous deepening of the Gulf of Alaska low present in most of these eight events (fig. S3) is plausibly linked to El Niño teleconnections [which would be consistent with (*28*)].

Much previous work has focused on the critical role AR storms ("ARs") play in California hydroclimate—both as beneficial bolsterers of water supply and as the cause of hazardous floods (*30–32*). Composite analysis of 30-day averaged vertically integrated water vapor transport (IVT) and animations of IVT over the 30-day scenarios (movies S1 and S2) confirm that ARs are the primary storm mode during both ARkHist and ARkFuture (Fig. 1, C and D) scenarios, with a well-defined moisture transport axis extending northeastward from just north of the Hawaiian Islands to central California. This alignment is suggestive of 30-day mean storm trajectories capable of entraining large quantities of subtropical moisture (i.e., a "Pineapple Express"–type pattern), although with considerable upstream longitudinal extension of the IVT corridor westward of Hawaii (particularly in the future scenario; Fig. 1, C and D). This overall zonal pattern (but with localized meridional flow near California) is consistent with that recently associated with "AR families" occurring during El Niño conditions (*33*), which tend to be characterized by a strengthened subtropical Pacific jet stream and a persistently anomalous Gulf of Alaska cyclone that together favor long-duration periods of successive AR activity across California. While the general spatial structure of IVT is similar for both scenarios, ARkFuture exhibits mean 30-day composite IVT values that are ~25% higher than ARkHist.

Both severe storm sequences are associated with strong westerly (zonal) winds throughout nearly the entire atmospheric column (fig. S4), with a pronounced vertical maximum of ~60 m/s located around jet stream level (200 to 250 hPa) between 30°N and 35°N. Zonal winds are stronger in ARkFuture, especially in the upper troposphere (by >10 m/s above ~400 hPa). Analysis of 500-hPa geopotential height fields (Fig. 1, E and F) indicates that both events are associated with a broad region of negative mid-tropospheric height anomalies over the North Pacific to the west of California, although the negative height anomaly is more localized to the northeastern Pacific in ARkFuture. This suggests that both ARkStorm scenarios are associated with a robust Pacific jet, which is dynamically consistent with the eastward extension of the wintertime Pacific jet associated with both El Niño (Fig. 1, A and B) [e.g., (*28*)] and climate change [e.g., (*34*)], although the 30-day mean low-level (850-hPa) flow pattern exhibits a slightly more zonal pattern (with less of a meridional component over the northeastern Pacific) in ARkFuture relative to ARkHist. Visual inspection of movies S1 and S2 further confirm that both 30-day scenario storm sequences are characterized by the occurrence of multiple deep extratropical cyclones just west of or over California, which is consistent with recent results in (*35*), which found that AR-associated precipitation in the San Francisco Bay Area increased more for ARs directly associated with extratropical cyclones than those without.

We also find that composite atmospheric instability is relatively high during both ARkStorm scenarios. A 30-day composite convective available potential energy (CAPE) exhibits a broad region of >300 J/kg west of the northern California coast during ARkHist, with an even wider region of CAPE (>300 J/kg) (and locally >400 J/kg) in ARkFuture (fig. S5). The values might be unremarkable in a different geographic context, but in coastal California, ARs are typically associated with primarily stratiform or dynamically forced precipitation, and California ARs tend to be characterized by moist-neutral (versus conditional unstable) vertical profiles (*36*). Modest increases in atmospheric instability have been associated with outsized impacts during certain historical California storm events, increasing the risk of flash flooding/debris flows (*37*) and severe wind gusts (*38*) (fig. S6).

Cumulative and extreme precipitation

In both ARkHist and ARkFuture, 30-day cumulative precipitation is extremely high. In ARkHist, we find broad regions exceeding 500 mm of cumulative precipitation, with widespread areas exceeding 1000 mm in the Sierra Nevada (SN) and more isolated pockets exceeding 1000 mm in the Coast Ranges, Transverse Ranges, and far southern end of the Cascade Range (domain maximum of ~2150 mm; Fig. 2A). In ARkFuture, spatial patterns of event total precipitation

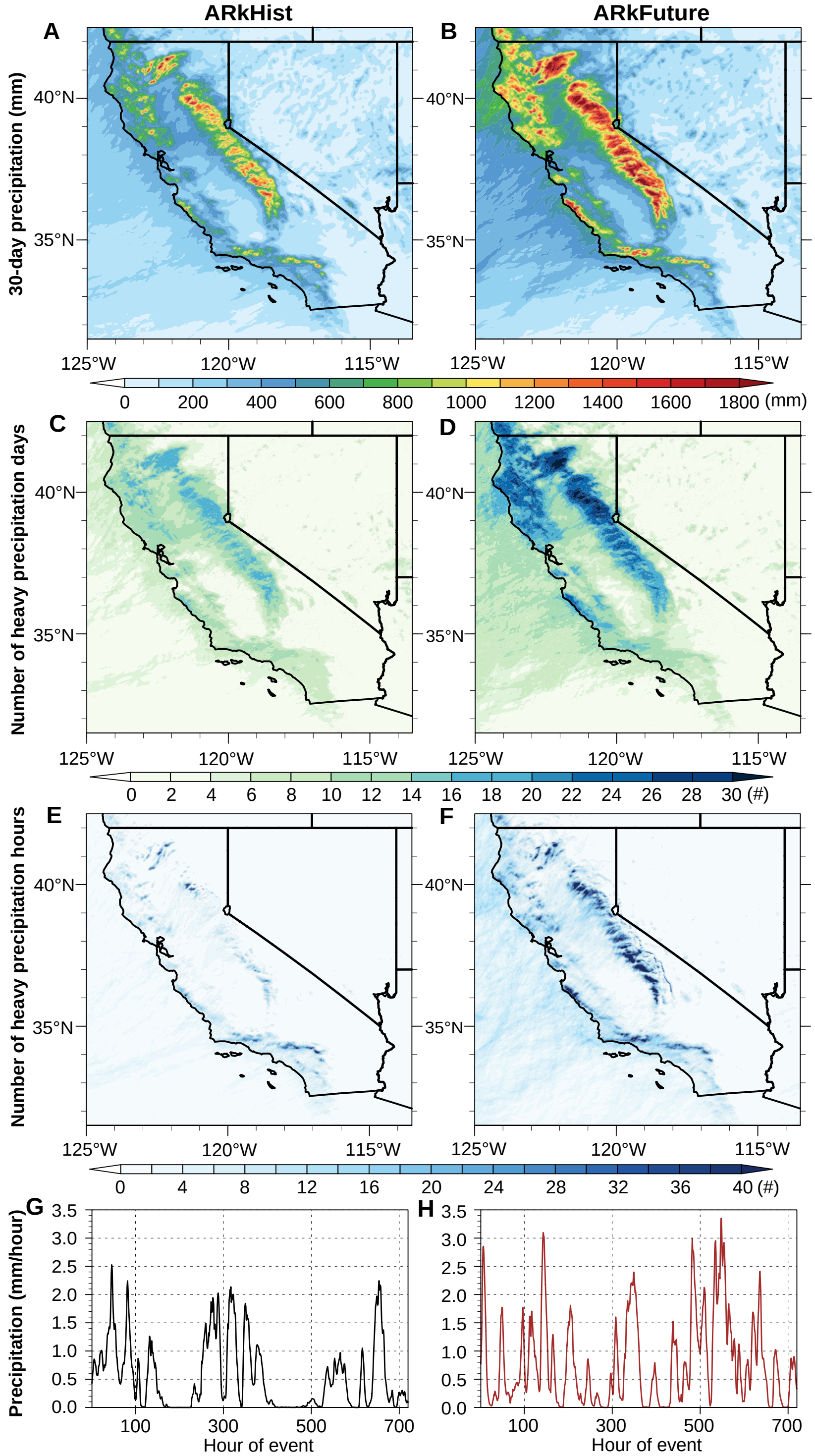

Fig. 2. Precipitation associated with California megastorm scenarios. (**A** and **B**) Cumulative 30-day precipitation (mm) during ARkHist (A) and ARkFuture (B). (**C** and **D**) Cumulative number of heavy precipitation days (days with precipitation > 20 mm/day) during ARkHist (C) and ARkFuture (D). (**E** and **F**) Cumulative number of heavy precipitation hours (hours with precipitation >10 mm/hour) during ARkHist (E) and ARkFuture (F). (**G** and **H**) Time series depicting hourly precipitation (mm/hour) on a cumulative California statewide basis during ARkHist (G) and ARkFuture (H). Data depicted in all panels are from the innermost 3-km WRF domain.

are similar but are uniformly characterized by heavier accumulations, with broad areas in both northern and southern California exceeding 700 mm and widespread areas in the abovementioned mountain areas above 1400 mm (domain maximum of ~3200 mm; Fig. 2B). We note that these values are comparable to maximum precipitation informally reported during the GF1862, which exceeded 2500 mm in at least two locations on the SN western slope over a slightly longer (~40-day) period (*6*). In general, cumulative precipitation in ARkFuture is between 35 and 60% higher than in ARkHist for northern and central California (although locally >80% higher), with lesser increases in far southern California (fig. S7, A and B). On a statewide average basis, 30-day precipitation is ~45% higher in ARkFuture.

Although absolute increases in cumulative precipitation are highest in mountainous areas (fig. S7A), relative increases in event total precipitation are greatest in areas that are not prone to orographic enhancement of precipitation during prevailing southwesterly winds (fig. S7B). Thus, some of the largest relative increases in precipitation (locally >80%) instead occur in regions that are less historically accustomed to receiving extreme precipitation during these events, such as inland valleys and otherwise wind-shadowed areas, which is consistent with earlier work (*16*).

Both ARkStorm scenarios are also notable for their very high precipitation intensities. We quantify this on several time scales, focusing on the frequency (over the 30-day scenario periods) with which precipitation intensity exceeds fixed daily and hourly thresholds [the number of days with precipitation > 20 mm/day and the number of hours with precipitation > 10 mm/hour, henceforth "heavy precipitation days" (HPDs) and "heavy precipitation hours" (HPHs)]. In ARkHist, we find that nearly all coastal areas experience at least 8 (of 30) days with precipitation exceeding 20 mm, and most mountain areas exceed 14 such days (except the Transverse Ranges in southern California, Fig. 2C). In ARkFuture, we find a sharp increase in the number of HPDs, especially in northern and central California, where most coastal areas exceed 16 (of 30) HPDs and most mountain areas exceed 20 such days (Fig. 2D and fig. S7, C and D). In some small pockets in the northern SN and far southern Cascades, all 30 days of the ARkFuture scenario are HPDs. HPD increases are substantially smaller in magnitude across southern California (mostly on the order of one to five additional days) but still nearly ubiquitous (fig. S7C).

Because of their particular relevance in the context of flash flood and debris flow risk (*39*), we specifically consider the occurrence of short-duration precipitation extremes in both ARkStorm scenarios. We find that the highest number of such hours occur in orographically favored areas, with the highest frequency of occurrence in the southern California Transverse Ranges and the Feather River watershed in the northern SN during ARkHist (Fig. 2, E and F). In ARkFuture, we report large and widespread increase in the occurrence of HPHs across essentially the entire domain. The largest increases [+25 to 40 cumulative hours (fig. S7, E and F)] occur broadly across the SN and (locally) in Santa Lucia Mountains—shifting the domain-wide maximum in HPH from southern to northern California. We find large relative increases (~200 to 300%) in the frequency of HPH and a large increase in the spatial extent of affected regions in ARkFuture. On a statewide average basis, we find that the frequency of HPH is ~220% higher in ARkFuture versus ARkHist (Fig. 2, G and H). Oakley *et al.* (*40*) conducted a literature review on published hourly rainfall rates in California and/or similar Mediterranean climate regions thought to be sufficient to trigger shallow landslides and debris flows in susceptible terrain, noting a range (5 to 20 mm/hour) that encompasses our HPH threshold (10 mm/hour) in the present study. These findings, therefore, likely have large implications from a flash flood and debris flow risk perspective.

California-wide average cumulative precipitation during the 30-day periods encompassing both extreme storm sequence scenarios represents a considerable fraction of the total annual [October-September water year (WY)] precipitation occurring during both ARkHist (~447 mm or 46% of the WY total) and ARkFuture (~586 mm, of 40% of the WY total). Compared to the climatological mean WY precipitation across all 40 ensemble members during the baseline periods (1996–2005 and 2071–2080, respectively); however, these events represent an even larger fraction of average annual precipitation—60% of WY precipitation in ARkHist and 71% of WY precipitation in ARkFuture. This also means that both the ARkHist and ARkFuture occur during anomalously wet WYs overall (32 and 77% wetter than the contemporaneous averages in ARkHist and ARkFuture, respectively). This would be dynamically consistent, from an ENSO teleconnection perspective, with the strong relationship between moderate to strong El Niño events (as characterized by the ELI) and anomalously wet cool-season conditions in California (*29*). It also has significant implications from a potential flood hazard perspective, as soil conditions are likely to be more saturated than average during anomalously wet WYs, likely amplifying runoff and further elevating the risk of flooding.

To systematically contextualize the precipitation-related results arising from these two specific downscaled extreme storm scenarios drawn from CESM1-LENS relative to all top-ranked 30-day precipitation events in multiple large ensembles—including the CanESM2, GFDL-CM3, and CSIRO-Mk3.6 ensembles [as described in (*41*)]. We conducted an intercomparison of these events during the historical and future study periods. We found that of the top 4 ranked megastorm events (as quantified by California-wide cumulative 30-day precipitation), all 16 events across the four single-model large ensembles have larger cumulative precipitation in the warmer future scenario versus their counterparts drawn from cooler historical climate snapshot period (fig. S1). We further show that hourly precipitation maxima are also higher in future versus historical megastorm events in all four large ensembles (fig. S2).

We also note that there are substantial differences across the large ensembles regarding the absolute magnitude of the 30-day precipitation associated with the top four ranked storm sequences, with CESM1-LENS exhibiting the largest precipitation accumulations (fig. S1). However, a direct comparison between these absolute precipitation values is not possible in this context because of the widely differing number of ensemble members and potential and biases in the representation of extreme precipitation in specific models. Nevertheless, we emphasize that the overall consistency of the response of both 30-day cumulative and hourly precipitation in the warmer future versus cooler historical megastorms, in relative terms within each respective large ensemble, suggests that many of the key conclusions drawn from the two synthetic case studies drawn from CESM1-LENS and emphasized in this analysis are likely to be generalizable.

Precipitation phase, freezing level height, and snow water equivalent

The heaviest precipitation during both ARkStorm scenarios occurs over mountainous terrain—particularly in the SN—and a substantial fraction of that high elevation accumulation falls in the form of snow. In ARkHist, a substantial fraction of the higher elevation portions of the SN receives more than 1000 mm (Fig. 3A) of snow water equivalent (SWE) over the 30-day event (yielding a domain maximum of 7.7 m of accumulated snowfall). Estimates of peak on-the-ground SWE range from around ~300 mm in the southern Sierra to 470 mm in the central Sierra (fig. S8), with even higher maxima over localized mountain peaks (Fig. 3). This extremely heavy snowfall would likely be highly disruptive to infrastructure and emergency response activities.

In ARkFuture, we find that the event-averaged precipitation phase changes from primarily snow to primarily rain at low to mid-elevations (~1200 to 2000 m) but remains primarily snow at very high elevations (≥2500 m) in the SN (Fig. 3, D and E). This results in a spatial dipole pattern of SWE changes, with large (>50%) SWE decreases at lower elevations but large SWE increases at the highest elevations (≥3000 m) of the SN and southern Cascades (locally >50%, yielding cumulative total SWE as high as 1800 mm and a domain maximum of 10.4 m of accumulated snowfall) (Fig. 3, B and C). Further, there is a stark contrast between the large SWE and snow-to-rain ratio decrease in the northern SN versus a substantial SWE increase and lesser snow-to-rain ratio decrease in the southern SN (Fig. 3F) (likely because of lower elevations in the northern Sierra). We report widespread increases in the mean atmospheric freezing level height during ARkFuture (statewide freezing level of ~2230 m for the 30-day window) versus ARkHist (freezing level of ~1940 m; Fig. 3, G and H)—supporting prior studies finding that warmer temperatures during future extreme storm events will fundamentally alter mountain hydrology and subsequent watershed response [e.g., (*18*) and (*25*)].

Very large increase in cumulative and peak runoff during ARkFuture

We find that both ARkStorm scenarios are likely to generate very high runoff across a wide range of watersheds and topographies. Projected increases in ARkFuture runoff, however, are widespread and extremely high in magnitude. On a statewide basis, peak runoff during ARkFuture is more than double that during ARkHist (Fig. 3, I and J). In certain key watersheds, however, the relative differences are even larger: In all three SN subregions, the peak runoff is 200 to 400% higher in ARkFuture (fig. S9). A ~100% increase in peak runoff is also observed in the South Coast and Cascade subregions, with a 60% increase along the North Coast.

Event total cumulative runoff increases are similarly large, with increases of 100% or more across most of the SN western slope, the southern Cascades, the Santa Lucias, and also in several major urban areas with a high impervious surface fraction (including the Los Angeles, Sacramento, and San Jose metropolitan areas; fig. S9B). Even greater fractional increases are found for extreme runoff periods (defined as hours with surface runoff of >10 mm/hour; fig. S9, C and D), which increase from being almost negligible in ARkHist (generally three or fewer total hours, except in the Los Angeles Basin) to being widespread across nearly all of California's major urban areas and mountain ranges (with many locations experiencing >10 such extreme runoff hours). In addition, we find that runoff efficiency during ARkFuture relative to ARkHist (measured as the ratio of total 30-day runoff to 30-day precipitation) increases by ~50% (from ~0.19 to ~0.29)—suggesting that a considerably higher fraction of precipitation is likely to immediately contribute to potential food risk in the warmer future scenario.

Given the geographic concentration of numerous critical pieces of water and flood management infrastructure on the western slopes of the SN Mountains and in California's Central Valley, we conduct additional analysis focused on the Sacramento and San Joaquin River watersheds that encompass these regions [as defined by their respective U.S. Geological Survey (USGS) Hydrologic Unit Code (HUC) footprints; fig. S10]. We find large and ubiquitous increases in the upper tail of the empirical distribution of both precipitation and surface runoff at both hourly and 24-hour temporal aggregations in ARkFuture relative to ARkHist, although the relative increases are larger for the San Joaquin basin than the Sacramento Basin (Fig. 4). Here, again, we find that the relative increases in the uppermost tail of the surface runoff distributions are much larger than that of the precipitation distributions. At the 24-hour aggregation level, the upper tail of the surface runoff distributions is largely nonoverlapping in both basins (Fig. 4, G and H)—with virtually no overlap at all in the San Joaquin basin during ARkFuture relative to ARkHist. This points to the potential for historically unprecedented surface runoff regimes during future extreme storms in a strong warming scenario—especially in the watersheds draining the western slopes of the central and southern SN, with major implications for operation of critical water infrastructure in these regions.

We attribute these notably high increases in runoff, which greatly exceed fractional increases in precipitation, to the nonlinear hydrologic effects of increasing both total precipitation (via increased AR intensity) and decreasing the snow-to-rain fraction (due to AR warming and the solid-to-liquid phase change of precipitation). This so-called "double whammy effect," whereby both the volume of precipitation falling on watersheds and the fraction of that precipitation that immediately becomes runoff at higher elevations increases substantially, can be responsible for unexpectedly large increases in runoff volume (*18*). We also suggest that there is arguably a "triple whammy" effect at play in the case of ARkFuture: In addition to the previous two factors, there is evidence for multiple intense "rain on snow" events (*26*) in both scenarios (Fig. 3, G and H) that correspond temporally with event-maximum runoff peaks (Fig. 3, I and J). However, we acknowledge that antecedent hydrologic conditions—particularly soil moisture and the extent/moisture content of snowpack leading up to the event—could potentially have large influences on simulated runoff and ultimately on potential flood risks. In this analysis, we only consider the specific antecedent conditions that were actually present in the respective large ensemble members leading up to the simulated events. Although a comprehensive assessment of the various antecedent hydrological contributors to surface runoff is beyond the scope of the present manuscript, more systematic assessments will be conducted in later stages of the ARkStorm 2.0 project.

Megaflood risk increases robustly as function of climate warming

We assess the cumulative and annual likelihood of a 30-day megastorm sequence capable of causing a California megaflood and find that both increase strongly as a function of climate warming. On a high warming emissions trajectory (RCP8.5), we find that the cumulative likelihood of an ARkHist level event begins to accelerate after the year ~2020 period, with corresponding accelerations becoming apparent earlier (~2000) for lesser (50-year RI) and later (~2030) for higher magnitude (200-year RI) events (Fig. 5A).

To accommodate the various Earth system and sociopolitical uncertainties that complicate future predictions of possible greenhouse gas emission trajectories and to facilitate direct comparison

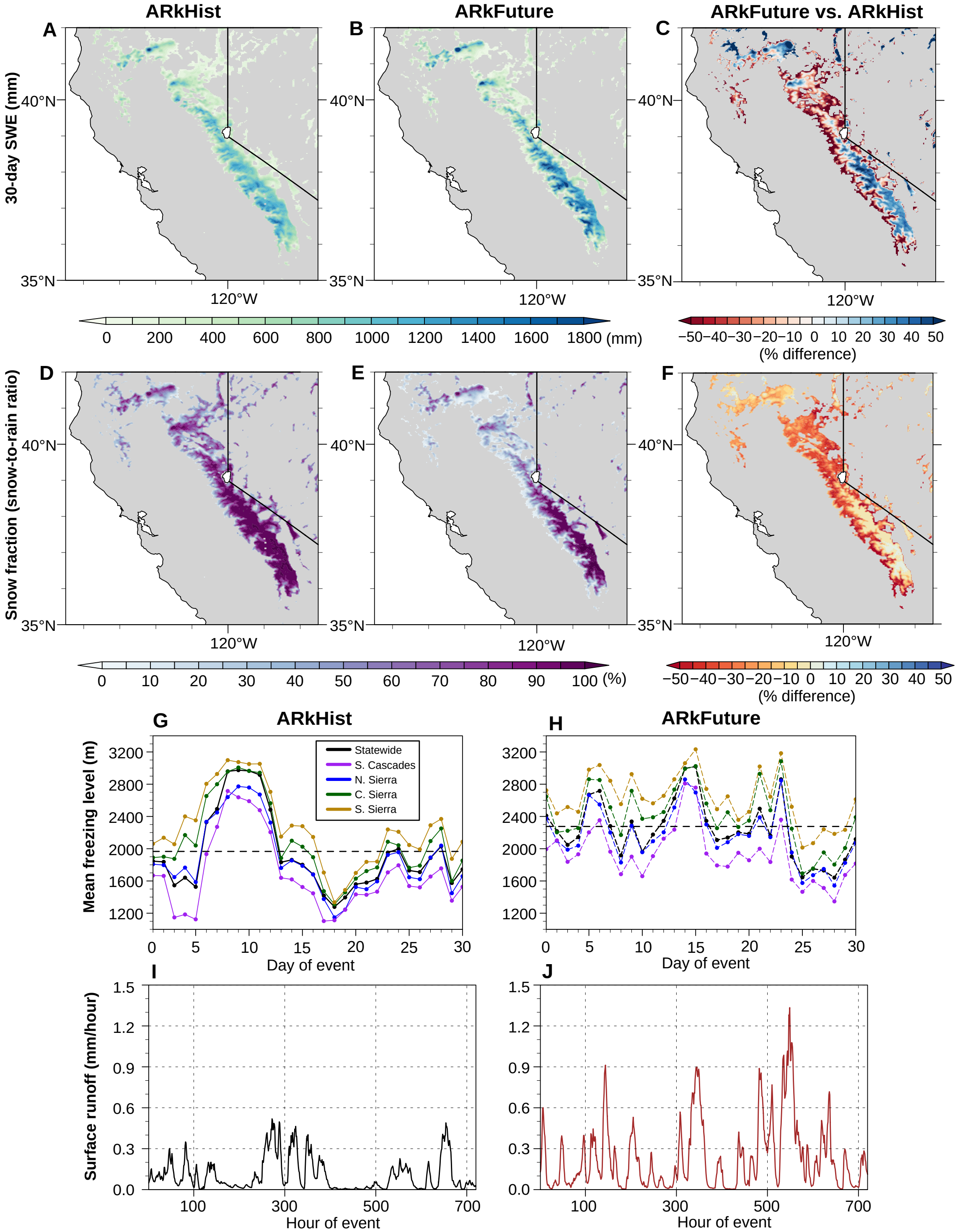

Fig. 3. Snowfall and surface runoff associated with California megastorm scenarios. (**A** and **B**) Cumulative 30-day gross SWE (mm) during ARkHist (A) and ARkFuture (B). (**C**) Difference in cumulative SWE (mm) between ARkFuture and ARkHist. (**D** and **E**) Mean snow fraction (snow-to-rain ratio, in percent) during ARkHist (D) and ARkFuture (E). (**F**) Difference (%) in mean snow fraction between ARkFuture and ARkHist. (**G** and **H**) Mean freezing level (m) during ARkHist (G) and ARkFuture (H). (**I** and **J**) Time series depicting hourly surface runoff (mm/hour) on a cumulative California statewide basis during ARkHist (I) and ARkFuture (J). Data depicted in all panels are from the innermost 3-km WRF domain.

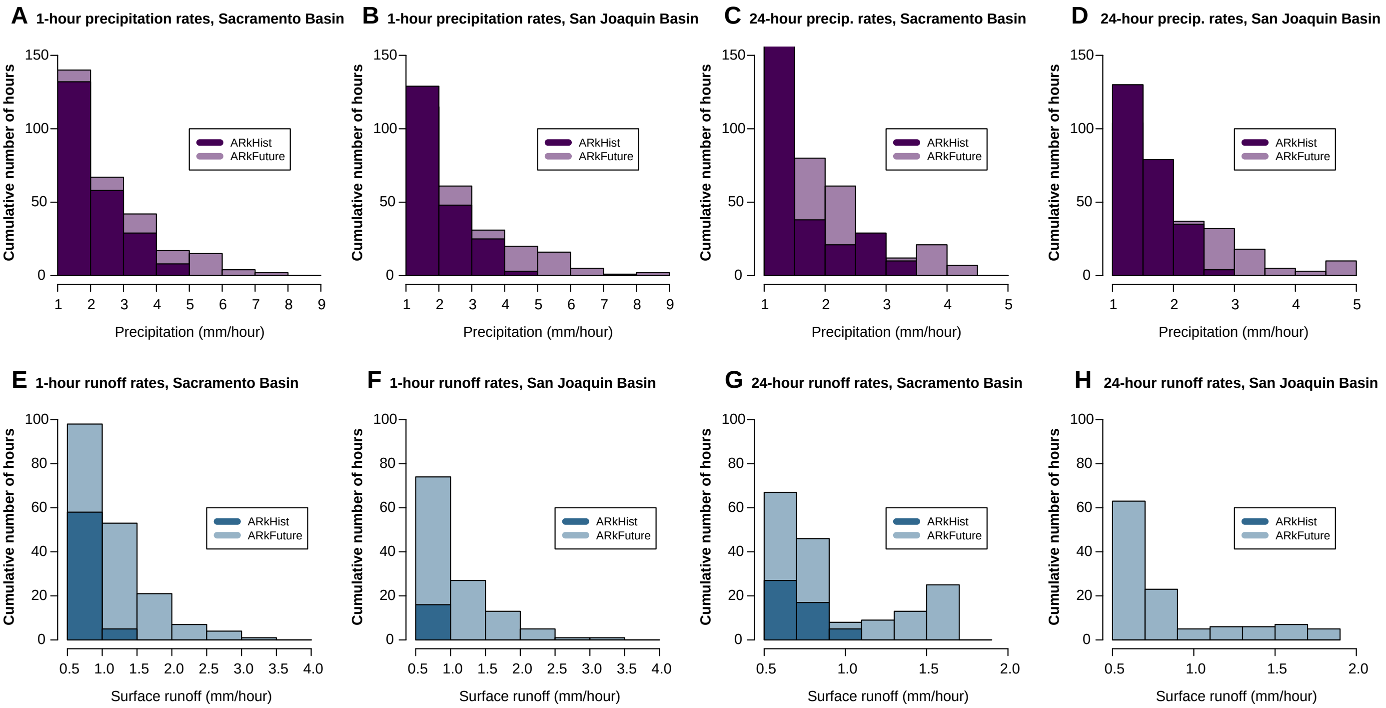

Fig. 4. Upper tail of precipitation and surface runoff distribution for Sacramento and San Joaquin River watersheds. Empirical histograms depicting the cumulative number of hours (over the 30-day scenarios) at or above specific precipitation [purple bars (**A** to **D**)] and surface runoff [blue bars (**E** to **H**)] thresholds (in units of mm/hour) at two levels of temporal aggregation (1 hour and 24 hours) for two key California watersheds as outlined by HUC Subregion 1802 (the Sacramento River watershed) and HUC subregion 1804 (the San Joaquin River watershed). Data are drawn from the WRF 3-km domain for ARkHist (darker bars) and ARkFuture (lighter bars) and are calculated as average values for each entire watershed. Values less than 1 mm/hour for precipitation and 0.5 mm/hour for surface runoff are excluded from this upper tail analysis.

with various proposed targets linked to specific planetary warming levels, we conduct further analysis to estimate changes in megastorm risk as a function of the warming itself. We find that the annual likelihood of an ARkHist level event increases rapidly for each 1°C of global warming [by ~0.012/year per degree C from a baseline of ~0.01/year]; Fig. 5B) and that this approximately linear relationship ($P < 0.001$) appears to hold even at very high levels of warming (~+4°C). We find that climate change to date (as of 2022) has already increased the annual likelihood of an ARkHist event by ~105% relative to 1920 in the CESM1-LENS ensemble and of an even higher magnitude (200-year RI) event by ~234%. This finding is consistent with prior work reporting progressively larger increases in projected extreme precipitation events for increasing event magnitudes [e.g., (*42*)]. We further find that by ~2060, on a high emissions trajectory, the annual likelihood of an ARkHist level event increases by ~374% and by ~683% for a formerly 200-year RI event. These statistics represent notably large increases in risk of California megastorm events due to climate change, as they transform an event that previously would have occurred once every two centuries into one that may occur approximately three times per century.

DISCUSSION

Our analyses suggest that the fundamental characteristics of the plausible worst-case California megafloods of the future will be familiar: Similar to their contemporary and historical counterparts, they will be characterized by a week-long sequences of recurrent, strong to extreme ARs during the cool season and coinciding with a persistently strong Pacific jet stream. Yet, we also find evidence of some critical differences: Future extreme storm sequences will bring more intense moisture transport and more overall precipitation, along with higher freezing levels and decreased snow-to-rain ratios that together yield runoff that is much higher than that during historical events. In addition, we find even larger increases in hourly rainfall rates during individual storm events, which have high potential to increase the severity of geophysical hazards such as flash flooding and debris flows. This is especially true in the vicinity of large or high-intensity wildfire burn areas, which are themselves increasing due to climate change (*39*) and yielding large increases in associated compound hazards (*43*).

An extensive body of existing research has linked climate change to increasingly extreme precipitation events [e.g., (*44*–*47*)], even in locations where changes in mean precipitation are nonrobust (*48*, *49*). There is further evidence that climate warming increases the intensity of ARs in many regions (*20*), including California (*16*, *19*). The strongest ARs are expected to strengthen considerably at the expense of the weakest—shifting the balance from "primarily beneficial" AR events to "primarily hazardous" ones (*21*)—an intensification brought about primarily via the direct thermodynamic effect of warming (*16*).

Our analysis goes beyond these prior works to demonstrate that climate change is robustly increasing both the frequency and magnitude of extremely severe storm sequences capable of causing megaflood events in California. Our analysis suggests that the present-day (circa 2022) likelihood of historically rare to unprecedented 30-day precipitation accumulations has already increased substantially and that even modest additional increments of global warming will

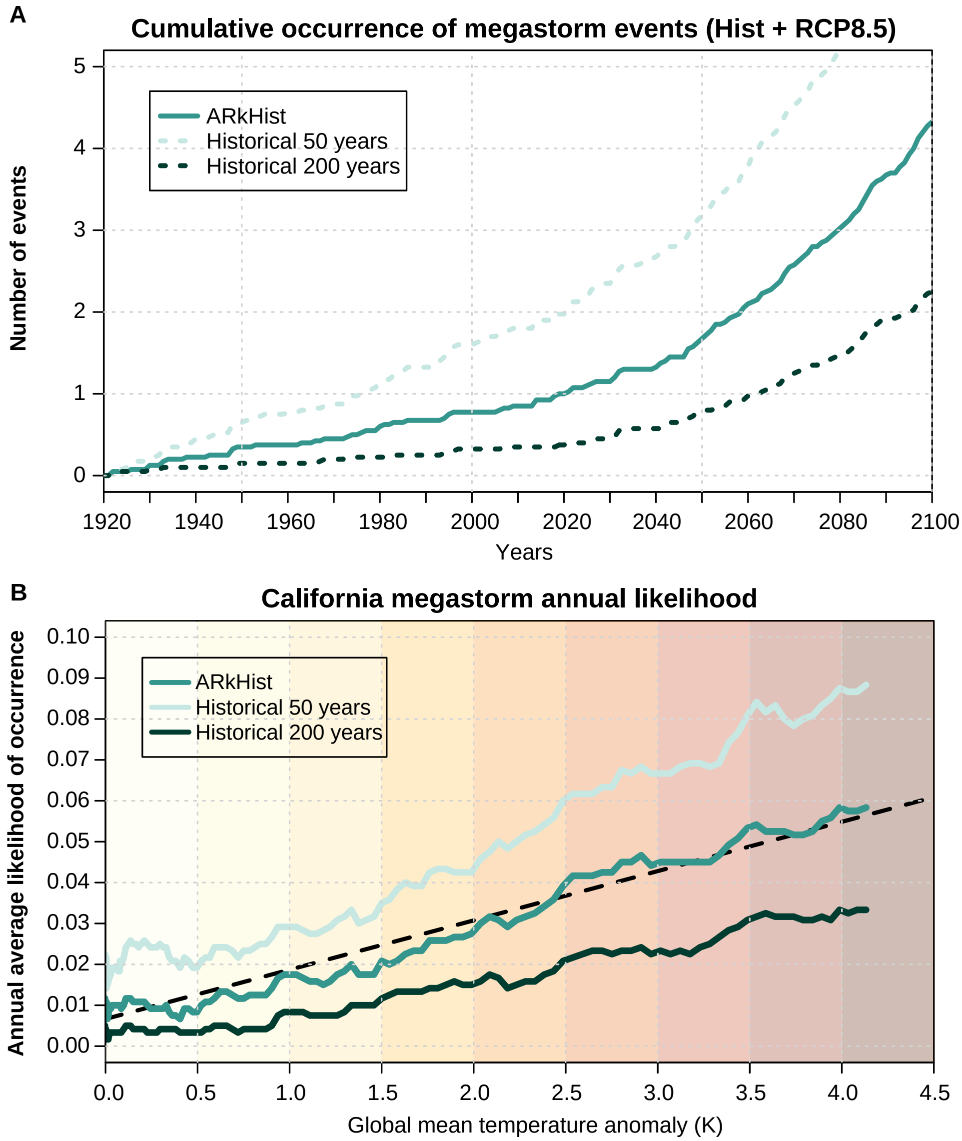

Fig. 5. Climate change and California megastorm risk. (**A**) Cumulative occurrence of extreme 30-day precipitation accumulations on a California statewide basis as simulated by the CESM1-LENS ensemble. The three blue-green curves denote cumulative occurrence of events equal or greater in magnitude to the ARkHist scenario, as well as for events with approximate RIs of 50 and 200 years. Data are drawn from the historical CESM1-LENS simulations for 1920–2005 and from the RCP8.5 scenario for 2006–2100. (**B**) Annual likelihood of extreme 30-day cumulative precipitation events as a function of projected global mean surface temperature (GMST; K) anomaly across the 40-member ensemble. Blue-green curves correspond to definitions in (A). GMST anomaly is defined relative to a baseline calculated from the CESM1-LENS preindustrial control run, and both annual likelihood and GMST are smoothed on a 30-year running mean basis.

bring about even larger increases in likelihood. Critically, this finding means that existing international emissions policies, which are estimated to yield cumulative warming of well over 2°C (*50*), will entail large further increases in the likelihood of a California megaflood event. We further find that all of the most intense 30-day megastorm events in the CESM1-LENS ensemble occur during moderate to strong ENSO warm phase (El Niño) conditions—both in the historical and warmer future scenarios—suggesting that these events may potentially exhibit some degree of predictability at seasonal scale. For these reasons, we emphasize that recognizing and mitigating the societal risks associated with this subtly but substantially escalating natural hazard is a critically important consideration from a climate adaptation perspective.

Recent evidence suggests that increases in western United States flood risk caused by anthropogenic warming may have been counteracted in recent decades by natural variability, but that further warming and shifts in natural variability will eventually "unmask" this accumulated increase in regional flood risk (*51*). Additional work suggests that the response of flood risk to climate change is likely to exhibit threshold behavior, at least in certain climatological and hydrological regimes (*52*), with a precipitation extremeness threshold dictating whether flood risk decreases (for smaller events, due to the antecedent soil aridification effect of warming temperatures) or increases (for the largest events, due to the overwhelming effect of large increases in precipitation intensity). Both of these considerations are especially germane to California—a region where most contemporary public policy and climate adaptation efforts emphasize drought and wildfire risk due to lack of recent experience with widespread severe floods. Collectively, the findings from previous work and this study illustrate the growing urgency of planning for and mitigating the hazards from potentially catastrophic floods in California in a warming climate.

The extreme storm scenario development and subsequent analyses described here represent the first phase of the broader ARkStorm 2.0 exercise, which is eventually expected to encompass a full suite of follow-on hydrologic and inundation modeling, hazard assessments, and tabletop disaster response exercises. We plan to work with local, regional, and federal stakeholders to integrate quantification of physical hazards resulting from an "ARkStorm"-level event in California within disaster resilience and climate adaptation frameworks. Our initial atmospheric modeling results presented here demonstrate that extremely severe winter storm sequences once thought to be exceptionally rare events are likely to become much more common under essentially all plausible future climate trajectories—suggesting that 20th century hazard mapping, emergency response plans, and even physical infrastructure design standards may already be out of date in a warmer 21st century climate. Still, region-wide and high-resolution runoff inundation modeling capable of accounting for the effects of various active and passive flood management infrastructure will be required to fully quantify the extent of flood-related hazards and associated societal impacts resulting from these two ARkStorm 2.0 scenarios, and these simulations are actively being planned for the project's future phases.

Yet, potential solutions to increasing flood risk do exist. Examples of climate-aware strategies that have the potential to mitigate harm during a 21st century California megaflood include floodplain restoration and levee setbacks, which would lessen flood risk in urban areas while offering environmental cobenefits (*53*); forecast-informed reservoir operations, which would afford reservoir operators greater flexibility in the face of uncertainty (*54*); and revised emergency evacuation and contingency plans that accommodate the possibility of inundation and transportation disruption extending far beyond that which has occurred in the past century. Some of these interventions—such as flood-managed aquifer recharge—even have the potential to reduce flood damages while simultaneously improving resilience to future regional droughts (*55*). Ultimately, our hope is that the analysis described here can serve as a geographically portable framework for scenario-based emergency response and regional adaptation endeavors in the climate change era, both within and beyond California.

MATERIALS AND METHODS

Overall ARkStorm 2.0 scenario design

ARkStorm 2.0 is a wide-reaching extreme storm and flood scenario for California that seeks to build upon previous disaster contingency and emergency response planning efforts. This endeavor is intended to build upon previous efforts in the original ARkStorm exercise (ARkStorm 1.0), which was completed in 2010 (*9*) and involved a broad consortium of local, state, and federal agencies. It was found that the hypothetical storm scenario used in ARkStorm 1.0 would have produced widespread, deep inundation of a large fraction of the Sacramento and San Joaquin valley floors, as well as widespread, life-threatening flooding in other highly populated parts of California. Total economic losses (the sum of direct damages and indirect losses due to business and economic disruption) were projected to exceed $750 billion [2010 dollars (*11*)]. This would be equivalent to approximately $1 trillion in 2022 dollars, making it the most expensive geophysical disaster in global history to date. Partly for this reason, this hypothetical event was informally dubbed California's "other Big One:" Such a flood event in modern California would likely exceed the damages from a large magnitude earthquake by a considerable margin.

In ARkStorm 1.0, the scenario design involved the artificial concatenation of two of the most intense individual storm sequences in the observed 20th century climate [from January 1969 to February 1986; (*9*)], with additional manual adjustments to the persistence of individual ARs to amplify cumulative precipitation totals. Historical atmospheric reanalysis data were used to obtain boundary conditions for simulating these concatenated events using the Weather Research and Forecasting Model (v3.0.1) at spatial resolution ranging from 2 to 6 km across California. Precipitation and other variables from this single simulation were then used to estimate flood and other related impacts.

In ARkStorm 2.0, we update and upgrade the methods used in ARkStorm 1.0 in several fundamental ways. First, we use a hypothetical extreme event selection method that is both systematic and internally consistent from an atmospheric dynamical perspective: Rather than artificially concatenating multiple historical events, we leverage the large sample size afforded by large ensemble climate model simulations to draw upon a much wider range of physically plausible event sequences that are available by considering the roughly century-long observational record alone (and we make no manual adjustments to storm sequencing). Second, we use a newer and more sophisticated weather model (WRF V4.3) with generally higher spatial resolution (3 km across all of California and adjacent regions). Last and most critically, we design and implement two separate scenarios—ARkHist and ARkFuture—with the combined aim of comparing a "lesser" present era severe storm sequence to a much more intense but physically plausible future sequence amplified by climate change. The overall approach of embedding a high-resolution weather model within existing climate model large ensemble simulations is similar to that described in (*16*) and has the dual advantage of not only expanding the statistical sample size of physically plausible but observationally rare or unprecedented precipitation events (in CESM1-LENS) but also attaining the high degree of physical realism afforded by simulating extreme ARs in a high-resolution setting (*38*).

Selection of specific extreme storm sequences

Both ARkHist and ARkFuture are intended to capture multiweek sequences of discrete severe storm events that produce extremely high cumulative precipitation over a 30-day period. The use of a 30-day accumulation period is motivated by the desire to conduct a realistic emergency management contingency exercise as part of ARkStorm 2.0 and the prior knowledge that multiple successive storm events often challenge infrastructure and response systems to a greater degree than shorter-duration events. We first calculate the cumulative 30-day precipitation for the state of California from all 40 ensemble members from the CESM1-LENS (*56*) from two decade long "snapshot" intervals during which high-frequency (6 hourly) data are available for dynamical downscaling: 1996–2005 (using the historical scenario, which aims to replicate real-world aerosol and greenhouse gas climate forcings) and 2071–2080 (using the RCP8.5 scenario, which assumes continued rapid growth of greenhouse gas emissions over the 21st century).

Among the available global climate model large ensemble datasets, CESM1-LENS stands out with its comprehensive suite of three-dimensional, high-frequency (6 hourly) atmospheric variables, which provide the forcing conditions required for dynamical downscaling simulations. We note that, while it might otherwise be desirable to sample from a wider time period than the two specific decades included in these snapshots, these are the only two such intervals for which a comprehensive suite of three-dimensional, high-temporal frequency (6 hourly) atmospheric conditions were retained in the original CESM1-LENS experiment, and so, it is not possible to conduct high-resolution WRF simulations during other intervals because of the unavailability of needed initial and boundary conditions. However, as the snapshot periods include data from 40 independent ensemble members initialized decades before the assessment period—each with their own sequences of internal variability—these snapshot periods nonetheless include a wide range of potentially relevant internal ocean-atmospheric oscillations.

We also note that although real-world greenhouse gas forcings are likely to be lower than assumed in the RCP8.5 scenario (*57*), this is the only scenario for which high-frequency data are available as part of the CESM1-LENS dataset (*56*). We further emphasize that although RCP8.5 is considered to be a high warming scenario, we explicitly intend to design a plausible "worst case scenario" storm and flood sequence in this analysis, and therefore, the use of a high-end emissions trajectory is appropriate.

We then rank all such 30-day cumulative precipitation events from each CESM1-LENS snapshot period, drawing from an effective sample size of 400-model years in each instance (10 years × 40 ensemble members). To ensure statistical independence of the dataset and that long-lasting events are not double counted, we require at least a 30-day separation between storm sequences. From among the top 3 ranked events in each period, we manually select a single 30-day storm sequence that exhibits large precipitation intensity peaks in both northern and southern California, as well as a pattern of 30-day cumulative precipitation that is spatially well distributed throughout both northern and southern portions of the state. This subjective aspect of the extreme event scenario selection process is critically important from the broader perspective of ARkStorm 2.0, which is designed to be a statewide exercise in which flood and emergency management capacity is severely tested. Therefore, we manually selected the respective ARkHist and ARkFuture events from among the top three ranked events such that each would bring a high level of impacts to the entire state rather than just a portion of the region. In so doing, we ultimately select the second ranked event for ARkHist (calendar date range: 2 September 2002 to 3 December 2002 in ensemble member #20) and the third ranked event for ARkFuture (calendar date range: 11 January 2072 to 11 February 2072 in ensemble member #2). Further analysis suggests that the selected ARkHist event has an approximate RI of ~85 years in the 1971–2020 era climate, and the ARkFuture event has an approximate RI of ~333 years in a 2051–2100 era high warming climate and is empirically unprecedented (i.e., a >400-year RI) in the 1971–2020 era climate (fig. S11).

LENS-WRF event-targeted downscaling approach

For each selected 30-day storm sequence, we use a high-resolution (3 km), nonhydrostatic regional weather model (WRF V4.3) embedded within initial and boundary conditions from CESM1 large ensemble (a framework known as "LENS-WRF") to perform dynamical downscaling as originally developed by (*16*). We use a full suite of three-dimensional atmospheric initial and boundary conditions from the high-frequency (6 hourly) temporal data available from the CESM1-LENS output files and conduct ~50-day long WRF simulations for each 30-day scenario event (allowing for ~1 week of model spin-up and ~1 week of event follow-up). Land surface initial and boundary conditions (including three-dimensional soil temperature, soil moisture, and snow depth) are drawn from the corresponding model member at monthly frequency (as this is the highest temporal resolution retained for three-dimensional land surface conditions in CESM1-LENS) such that they are spatiotemporally congruent with the atmospheric conditions.

In this analysis, we use a nonhydrostatic configuration of WRF-ARW (V4.3) including four nested domains with progressively finer spatial resolutions of 81, 27, 9, and 3 km (see fig. S12 for the detailed domain configuration). The outer three domains cover a large portion of the northeastern Pacific Ocean and the innermost 3-km domain also covers a broad oceanic region—as well as all of California and Nevada—to better represent near-coastal processes and sea-air interactions. WRF is configured using 44 vertical levels (with model top pressure at 50 hPa and vertical velocity damping turned on) and forced with time-varying SST (from CESM1-LENS). A higher density of vertical levels is prescribed near the surface to improve the representation of lower-level processes.

WRF physics parameterizations applied in these simulations include the Thompson graupel scheme (*58*), the Kain-Fritsch (new Eta) cumulus scheme (*59*) (for 81-, 27-, and 9-km domains only; cumulus parameterizations are turned off for the innermost 3-km domain), the Dudhia shortwave radiation scheme (*60*); the "rrtm" longwave radiation scheme (*61*), the Yonsei University (YSU) boundary layer scheme (*62*), the revised MM5 Monin-Obukhov surface layer scheme (*63*), and the Noah-multiple parameterization (MP) land surface model (*64*). The Noah-MP model includes a multilayer snowpack capable of liquid water storage and melt/refreeze cycles, direct representation of heat exchange due to phase changes, and a snow interception component allowing for canopy interception (*64*).

Model validation and fitness for purpose

The overall performance of both CESM (as implemented in CESM1-LENS) and WRF have been previously assessed and validated in the context of both mean and extreme cool season precipitation in California. Swain *et al.* (*14*) found that the simulated distribution of CESM1-LENS cool-season precipitation was statistically indistinguishable from observations during the recent historical period in both northern and southern California. In addition, Huang *et al.* (*38*) found that high-resolution (3 km), nonhydrostatic WRF simulations nested within boundary and initial conditions from atmospheric reanalysis (i.e., pseudo-observations) were capable of simulating real-world extreme AR events (including extreme IVT) and associated extreme precipitation—including spatial patterns of orographic enhancement. However, we acknowledge that this validation does not obviate the potential for parametric and/or structural uncertainties that could lead to model biases that are difficult to quantify (as it is not possible to directly validate large ensemble climate model representation of specific extreme events). Nonetheless, the LENS-WRF configuration used in the present analysis is capable of generating physically realistic extreme storm events and is an appropriate tool for use in the context of "plausible worst case" scenario development.

Contextualization of CESM1-LENS relative to other large ensembles

We conduct additional analysis using daily precipitation data from several other large single-model ensembles [the 50-member CanESM2 (Canadian Earth System Model, Second Generation) at ~2.8° × 2.8° horizontal resolution, 20-member GFDL-CM3 (Geophysical Fluid Dynamics Laboratory Coupled Model, Version 3) at 2.0° × 2.5° horizontal resolution, and 30-member CSIRO-Mk3.6 (Commonwealth Scientific and Industrial Research Organisation Model, Version 3) at ~1.875° × 1.875° horizontal resolution] to aid in contextualization of the study's primary focus on results driven by CESM1-LENS (40 members at 1° × 1° horizontal resolution). We note that CESM1-LENS has the highest horizontal resolution, by a wide margin, as well as the second largest number of ensemble members of these four large ensembles. To conduct as systematic an intercomparison as possible, we extract precipitation data for each of the top 4 ranked events in each ensemble and during each ARkHist and ARkFuture snapshot period. The results of this analysis are discussed in Results and can be visualized in figs. S1 and S2.

HUC region precipitation and runoff analysis

We select two "four-digit/subregional" HUC regions, as defined by the USGS, for more detailed analysis of regional precipitation and surface runoff during ARkHist and ARkFuture scenarios: HUC 1802 (Sacramento subregion, which includes the Sacramento River basin and Goose Lake watershed) and HUC 1804 (San Joaquin subregion, which includes the San Joaquin River basin; see fig. S10 for geographic outlines). We select these HUC regions, particularly, because they encompass most or all of the major SN western slope water storage and flood control reservoirs, as well as broad swaths of land in California's Central Valley that are highly susceptible to large-scale flooding and are home to numerous flood control structures. We extract precipitation and runoff data from the WRF 3-km domain at 1 hour frequencies from geographic regions delineated by the respective HUC subregion shapefiles made available via the USGS (at https://apps.nationalmap.gov/downloader). We then plot empirical histograms of the upper tail of the precipitation (all values above 1 mm/hour) and runoff (all values above 0.5 mm/hour) distributions for each selected HUC region temporally aggregated at two different durations (1 and 24 hours) in both historical and future scenarios (Fig. 4).

Public availability of ARkStorm 2.0 atmospheric simulation data

Boundary and initial condition input files (derived from CESM1-LENS) and output files from the WRF simulations are archived on the DesignSafe web platform (*65*) via DOI: 10.17603/ds2-mzgn-cy51 (*66*).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abq0995

REFERENCES AND NOTES

1. D. Griffin, K. Anchukaitis, How unusual is the 2012–2014 California drought? *Geophys. Res. Lett.* **41**, 9017–9023 (2014).
2. S. Robeson, Revisiting the recent California drought as an extreme value. *Geophys. Res. Lett.* **42**, 6771–6779 (2015).
3. M. Goss, D. L. Swain, J. T. Abatzoglou, A. Sarhadi, C. A. Kolden, A. P. Williams, N. S. Diffenbaugh, Climate change is increasing the likelihood of extreme autumn wildfire conditions across California. *Environ. Res. Lett.* **15**, 094016 (2020).
4. D. J. McEvoy, D. W. Pierce, J. F. Kalansky, D. R. Cayan, J. T. Abatzoglou, Projected changes in reference evapotranspiration in California and Nevada: Implications for drought and wildland fire danger. *Earth's Future* **8**, e2020EF001736 (2020).
5. F. P. Malamud-Roam, B. Lynn Ingram, M. Hughes, J. L. Florsheim, Holocene paleoclimate records from a large California estuarine system and its watershed region: Linking watershed climate and bay conditions. *Quat. Sci. Rev.* **25**, 1570–1598 (2006).
6. J. Null, J. Hulbert, California washed away: The great flood of 1862. *Weatherwise* **60**, 26–30 (2007).
7. W. N. Engstrom, The California storm of January 1862. *Quatern. Res.* **46**, 141–148 (1996).
8. I. L. Hendy, L. Dunn, A. Schimmelmann, D. K. Pak, Resolving varve and radiocarbon chronology differences during the last 2000 years in the Santa Barbara Basin sedimentary record, California. *Quat. Int.* **310**, 155–168 (2013).
9. K. Porter, A. Wein, C. Alpers, A. Baez, P. Barnard, J. Carter, A. Corsi, J. Costner, D. Cox, T. Das, M. Dettinger, J. Done, C. Eadie, M. Eymann, J. Ferris, P. Gunturi, M. Hughes, R. Jarrett, L. Johnson, Hanh Dam Le-Griffin, D. Mitchell, S. Morman, P. Neiman, A. Olsen, S. Perry, G. Plumlee, M. Ralph, D. Reynolds, A. Rose, K. Schaefer, J. Serakos, W. Siembieda, J. Stock, D. Strong, I. S. Wing, A. Tang, P. Thomas, K. Topping, C. Wills, L. Jones, C. Scientist, D. Cox, *Overview of the ARkStorm scenario* (U.S. Geological Survey, 2011).
10. M. D. Dettinger, F. Martin Ralph, M. Hughes, T. Das, P. Neiman, D. Cox, G. Estes, D. Reynolds, R. Hartman, D. Cayan, L. Jones, Design and quantification of an extreme winter storm scenario for emergency preparedness and planning exercises in California. *Nat. Hazards* **60**, 1085–1111 (2012).
11. I. S. Wing, A. Z. Rose, A. M. Wein, Economic Consequence Analysis of the ARkStorm Scenario. *Nat. Hazards Rev.* **17**, A4015002 (2016).
12. K. E. Kunkel, North American trends in extreme precipitation. *Nat. Hazards* **29**, 291–305 (2003).
13. M. C. Kirchmeier-Young, X. Zhang, Human influence has intensified extreme precipitation in North America. *Proc. Natl. Acad. Sci.* **117**, 13308–13313 (2020).
14. D. L. Swain, B. Langenbrunner, J. D. Neelin, A. Hall, Increasing precipitation volatility in 21st-century California. *Nat. Clim. Chang.* **8**, 427–433 (2018).
15. L. Dong, L. R. Leung, J. Lu, Y. Gao, Contributions of extreme and non-extreme precipitation to California precipitation seasonality changes under warming. *Geophys. Res. Lett.* **46**, 13470–13478 (2019).
16. X. Huang, D. L. Swain, A. D. Hall, Future precipitation increase from very high resolution ensemble downscaling of extreme atmospheric river storms in California. *Sci. Adv.* **6**, eaba1323 (2020).
17. T. W. Corringham, F. M. Ralph, A. Gershunov, D. R. Cayan, C. A. Talbot, Atmospheric rivers drive flood damages in the western United States. *Sci. Adv.* **5**, eaax4631 (2019).
18. X. Huang, S. Stevenson, A. D. Hall, Future warming and intensification of precipitation extremes: A "double whammy" leading to increasing flood risk in California. *Geophys. Res. Lett.* **47**, e2020GL088679 (2020).
19. M. Dettinger, Climate change, atmospheric rivers, and floods in California - A multimodel analysis of storm frequency and magnitude changes. *J. Am. Water Resour. Assoc.* **47**, 514–523 (2011).
20. A. E. Payne, M. E. Demory, L. R. Leung, A. M. Ramos, C. A. Shields, J. J. Rutz, N. Siler, G. Villarini, A. Hall, F. M. Ralph, Responses and impacts of atmospheric rivers to climate change. *Nat. Rev. Earth Environ.* **1**, 143–157 (2020).
21. A. M. Rhoades, M. D. Risser, D. A. Stone, M. F. Wehner, A. D. Jones, Implications of warming on western United States landfalling atmospheric rivers and their flood damages. *Weather Clim. Extremes* **32**, 100326 (2021).
22. W. Zhou, D. Yang, S.-P. Xie, J. Ma, Amplified Madden-Julian oscillation impacts in the Pacific–North America region. *Nat. Clim. Chang.* **10**, 654–660 (2020).
23. Z.-Q. Zhou, S.-P. Xie, X.-T. Zheng, Q. Liu, H. Wang, Global warming–induced changes in El Niño teleconnections over the North Pacific and North America. *J. Climate* **27**, 9050–9064 (2014).
24. K. R. Gonzales, D. L. Swain, K. M. Nardi, E. A. Barnes, N. S. Diffenbaugh, Recent warming of landfalling atmospheric rivers along the West Coast of the United States. *J. Geophys. Res. Atmos.* **124**, 6810–6826 (2019).
25. E. R. Siirila-Woodburn, A. M. Rhoades, B. J. Hatchett, L. S. Huning, J. Szinai, C. Tague, P. S. Nico, D. R. Feldman, A. D. Jones, W. D. Collins, L. Kaatz, A low-to-no snow future and its impacts on water resources in the western United States. *Nat. Rev. Earth Environ.* **2**, 800–819 (2021).
26. F. V. Davenport, J. E. Herrera-Estrada, M. Burke, N. S. Diffenbaugh, Flood size increases nonlinearly across the Western United States in response to lower snow-precipitation ratios. *Water Resources Res.* **56**, e2019WR025571 (2020).
27. M. B. Freund, B. J. Henley, D. J. Karoly, H. V. McGregor, N. J. Abram, D. Dommenget, Higher frequency of Central Pacific El Niño events in recent decades relative to past centuries. *Nat. Geosci.* **12**, 450–455 (2019).
28. C. M. Patricola, J. P. O'Brien, M. D. Risser, A. M. Rhoades, T. A. O'Brien, P. A. Ullrich, D. A. Stone, W. D. Collins, Maximizing ENSO as a source of western US hydroclimate predictability. *Climate Dynam.* **54**, 351–372 (2020).

29. I. N. Williams, C. M. Patricola, Diversity of ENSO events unified by convective threshold sea surface temperature: A nonlinear ENSO index. *Geophys. Res. Lett.* **45**, 9236–9244 (2018).
30. M. D. Dettinger, F. M. Ralph, T. Das, P. J. Neiman, D. R. Cayan, Atmospheric rivers, floods and the water resources of California. *Water* **3**, 445–478 (2011).
31. B. Guan, D. E. Waliser, F. M. Ralph, E. J. Fetzer, P. J. Neiman, Hydrometeorological characteristics of rain-on-snow events associated with atmospheric rivers. *Geophys. Res. Lett.* **43**, 2964–2973 (2016).
32. F. M. Ralph, J. J. Rutz, J. M. Cordeira, M. Dettinger, M. Anderson, D. Reynolds, L. J. Schick, C. Smallcomb, A scale to characterize the strength and impacts of atmospheric rivers. *Bull. Am. Meteorol. Soc.* **100**, 269–289 (2019).
33. M. A. Fish, J. M. Done, D. L. Swain, A. M. Wilson, A. C. Michaelis, P. B. Gibson, F. M. Ralph, Large-scale environments of successive atmospheric river events leading to compound precipitation extremes in California. *J. Climate* **35**, 1515–1536 (2022).
34. I. R. Simpson, T. A. Shaw, R. Seager, A diagnosis of the seasonally and longitudinally varying midlatitude circulation response to global warming. *J. Atmos. Sci.* **71**, 2489–2515 (2014).
35. C. M. Patricola, M. F. Wehner, E. Bercos-Hickey, F. V. Maciel, C. May, M. Mak, O. Yip, A. M. Roche, S. Leal, Future changes in extreme precipitation over the San Francisco Bay Area: Dependence on atmospheric river and extratropical cyclone events. *Weather Clim. Extremes* **36**, 100440 (2022).
36. D. Swain, B. Lebassi-Habtezion, N. Diffenbaugh, Evaluation of nonhydrostatic simulations of Northeast Pacific atmospheric rivers and comparison to in situ observations. *Mon. Weather Rev.* **143**, 3556–3569 (2015).
37. N. S. Oakley, J. T. Lancaster, M. L. Kaplan, F. M. Ralph, Synoptic conditions associated with cool season post-fire debris flows in the Transverse Ranges of southern California. *Nat. Hazards* **88**, 327–354 (2017).
38. X. Huang, D. L. Swain, D. B. Walton, S. Stevenson, A. D. Hall, Simulating and evaluating atmospheric river-induced precipitation extremes along the U.S. Pacific Coast: Case studies from 1980 to 2017. *J. Geophys. Res. Atmos.* **125**, e2019JD031554 (2020).
39. N. S. Oakley, A warming climate adds complexity to post-fire hydrologic hazard planning. *Earth's Future* **9**, e2021EF002149 (2021).
40. N. S. Oakley, J. T. Lancaster, B. J. Hatchett, J. Stock, F. M. Ralph, S. Roj, S. Lukashov, A 22-year climatology of cool season hourly precipitation thresholds conducive to shallow landslides in California. *Earth Interact.* **22**, 1–35 (2018).
41. C. Deser, F. Lehner, K. B. Rodgers, T. Ault, T. L. Delworth, P. N. DiNezio, A. Fiore, C. Frankignoul, J. C. Fyfe, D. E. Horton, J. E. Kay, R. Knutti, N. S. Lovenduski, J. Marotzke, K. A. McKinnon, S. Minobe, J. Randerson, J. A. Screen, I. R. Simpson, M. Ting, Insights from Earth system model initial-condition large ensembles and future prospects. *Nat. Clim. Chang.* **10**, 277–286 (2020).
42. D. L. Swain, O. E. J. Wing, P. D. Bates, J. M. Done, K. A. Johnson, D. R. Cameron, Increased flood exposure due to climate change and population growth in the United States. *Earth's Future* **8**, e2020EF001778 (2020).
43. D. Touma, S. Stevenson, D. L. Swain, D. Singh, D. A. Kalashnikov, X. Huang, Climate change increases risk of extreme rainfall following wildfire in the western United States. *Sci. Adv.* **8**, eabm0320 (2022).
44. P. A. Gorman, T. Schneider, The physical basis for increases in precipitation extremes in imulations of 21st-century climate change. *Proc. Natl. Acad. Sci.* **106**, 14773–14777 (2009).
45. M. G. Donat, A. L. Lowry, L. V. Alexander, P. A. O'Gorman, N. Maher, More extreme precipitation in the world's dry and wet regions. *Nat. Clim. Chang.* **6**, 508–513 (2016).
46. E. M. Fischer, R. Knutti, Observed heavy precipitation increase confirms theory and early models. *Nat. Clim. Chang.* **6**, 986–991 (2016).
47. S. Pfahl, P. A. O'Gorman, E. M. Fischer, Understanding the regional pattern of projected future changes in extreme precipitation. *Nat. Clim. Chang.* **7**, 423–427 (2017).
48. A. G. Pendergrass, R. Knutti, F. Lehner, C. Deser, B. M. Sanderson, Precipitation variability increases in a warmer climate. *Sci. Rep.* **7**, 17966 (2017).
49. C. W. Thackeray, A. M. DeAngelis, A. Hall, D. L. Swain, X. Qu, On the connection between global hydrologic sensitivity and regional wet extremes. *Geophys. Res. Lett.* **45**, 11,343–311,351 (2018).
50. Emissions Gap Report 2021: The heat is on—A world of climate promises not yet delivered (2021).
51. B. Bass, J. Norris, C. Thackeray, A. Hall, Natural variability has concealed increases in Western US flood hazard since the 1970s. *Geophys. Res. Lett.* **49**, e2021GL097706 (2022).
52. M. I. Brunner, D. L. Swain, R. R. Wood, F. Willkofer, J. M. Done, E. Gilleland, R. Ludwig, An extremeness threshold determines the regional response of floods to changes in rainfall extremes. *Commun. Earth Environ.* **2**, 173 (2021).
53. J. Opperman Jeffrey, G. E. Galloway, J. Fargione, J. F. Mount, B. D. Richter, S. Secchi, Sustainable floodplains through large-scale reconnection to rivers. *Science* **326**, 1487–1488 (2009).
54. C. J. Delaney, R. K. Hartman, J. Mendoza, M. Dettinger, L. D. Monache, J. Jasperse, F. M. Ralph, C. Talbot, J. Brown, D. Reynolds, S. Evett, Forecast informed reservoir operations using ensemble streamflow predictions for a multipurpose reservoir in Northern California. *Water Resour. Res.* **56**, e2019WR026604 (2020).
55. X. He, B. P. Bryant, T. Moran, K. J. Mach, Z. Wei, D. L. Freyberg, Climate-informed hydrologic modeling and policy typology to guide managed aquifer recharge. *Sci. Adv.* **7**, eabe6025 (2021).
56. J. E. Kay, C. Deser, A. Phillips, A. Mai, C. Hannay, G. Strand, J. M. Arblaster, S. C. Bates, G. Danabasoglu, J. Edwards, M. Holland, P. Kushner, J. F. Lamarque, D. Lawrence, K. Lindsay, A. Middleton, E. Munoz, R. Neale, K. Oleson, L. Polvani, M. Vertenstein, The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Am. Meteorol. Soc.* **96**, 1333–1349 (2015).
57. P. M. Forster, A. C. Maycock, C. M. McKenna, C. J. Smith, Latest climate models confirm need for urgent mitigation. *Nat. Clim. Chang.* **10**, 7–10 (2020).
58. G. Thompson, P. R. Field, R. M. Rasmussen, W. D. Hall, Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Monthly Weather Rev.* **136**, 5095–5115 (2008).
59. J. S. Kain, The Kain-Fritsch convective parameterization: An update. *J. Appl. Meteorol.* **43**, 170–181 (2004).
60. J. Dudhia, Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.* **46**, 3077–3107 (1989).
61. E. J. Mlawer, S. J. Taubman, P. D. Brown, M. J. Iacono, S. A. Clough, Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *J. Geophys. Res. Atmos.* **102**, 16663–16682 (1997).
62. M. Nakanishi, H. Niino, An improved Mellor-Yamada level-3 model: Its numerical stability and application to a regional prediction of advection fog. *Bound.-Lay. Meteorol.* **119**, 397–407 (2006).
63. P. A. Jiménez, J. Dudhia, J. F. González-Rouco, J. Navarro, J. P. Montávez, E. García-Bustamante, A revised scheme for the WRF surface layer formulation. *Mon. Weather Rev.* **140**, 898–918 (2012).
64. G.-Y. Niu, Z. L. Yang, K. E. Mitchell, F. Chen, M. B. Ek, M. Barlage, A. Kumar, K. Manning, D. Niyogi, E. Rosero, M. Tewari, Y. Xia, The community Noah land surface model with multiparameterization options (Noah-MP): 1. Model description and evaluation with local-scale measurements. *J. Geophys. Res. Atmos.* **116**, D12109 (2011).
65. E. Rathje, C. Dawson, J. E. Padgett, J.-P. Pinelli, D. Stanzione, A. Adair, P. Arduino, S. J. Brandenberg, T. Cockerill, C. Dey, M. Esteva, F. L. Haan Jr, M. Hanlon, A. Kareem, L. Lowes, S. Mock, G. Mosqueda, *DesignSafe: A New Cyberinfrastructure for Natural Hazards Engineering* (ASCE Natural Hazards Review, 2017).
66. X. Huang, D. L. Swain, ARkStorm2.0: Atmospheric Simulations Depicting Extreme Storm Scenarios Capable of Producing a California Megaflood (DesignSafe-CI, 2022); https://doi.org/10.17603/ds2-mzgn-cy51.

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Science Advances

Climate change is increasing the risk of a California megaflood

Xingying HuangDaniel L. Swain

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Consultant Report

Groundwater Dependent Ecosystem Monitoring Plan

Mark Hausner and Susie Rybarski

Desert Research Institute

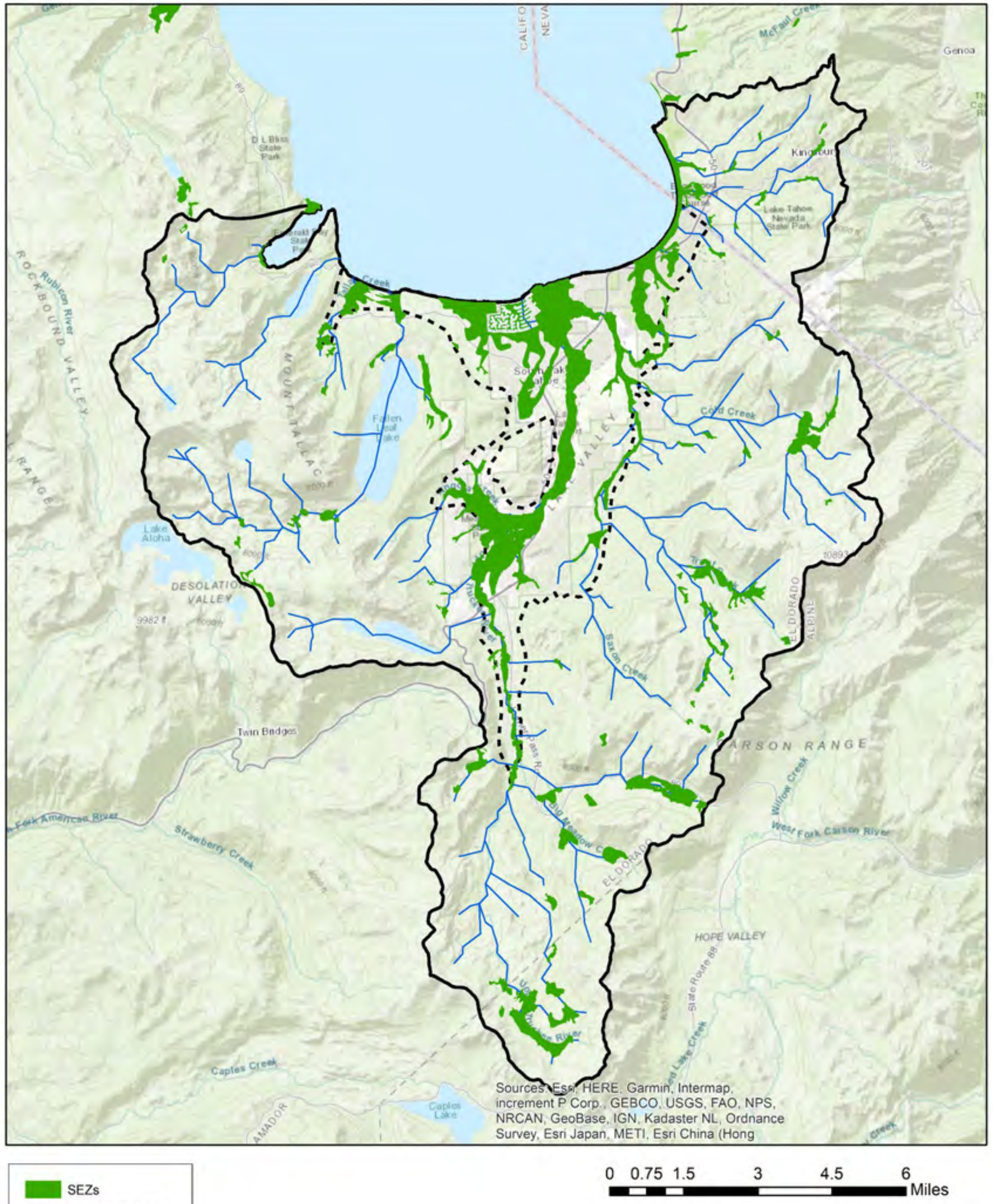
Plan Documents

- Alternative Plan for Tahoe Valley South Subbasin (6-005.01): First Five-Year Update, Volume I (Rybarski et al., 2022a). https://stpud.us/asset/9813
- Alternative Plan for Tahoe Valley South Subbasin (6-005.01): First Five-Year Update, Volume II: Appendices (Rybarski et al., 2022b). https://stpud.us/asset/9814
  - Appendix G: Assessment of Groundwater Dependent Ecosystems within the Tahoe Valley South Subbasin

8.3.2 Groundwater Dependent Ecosystems

- Sustainability Goal: To maintain a shallow water table that supports riparian vegetation in areas where riparian vegetation currently exists.
- Undesirable Result: Replacement of riparian vegetation by upland vegetation and loss of associated ecosystem services.
- Sustainability Indicator: Water table elevation.
- Minimum Threshold: Having average groundwater elevations within the interquartile range of historical variability.

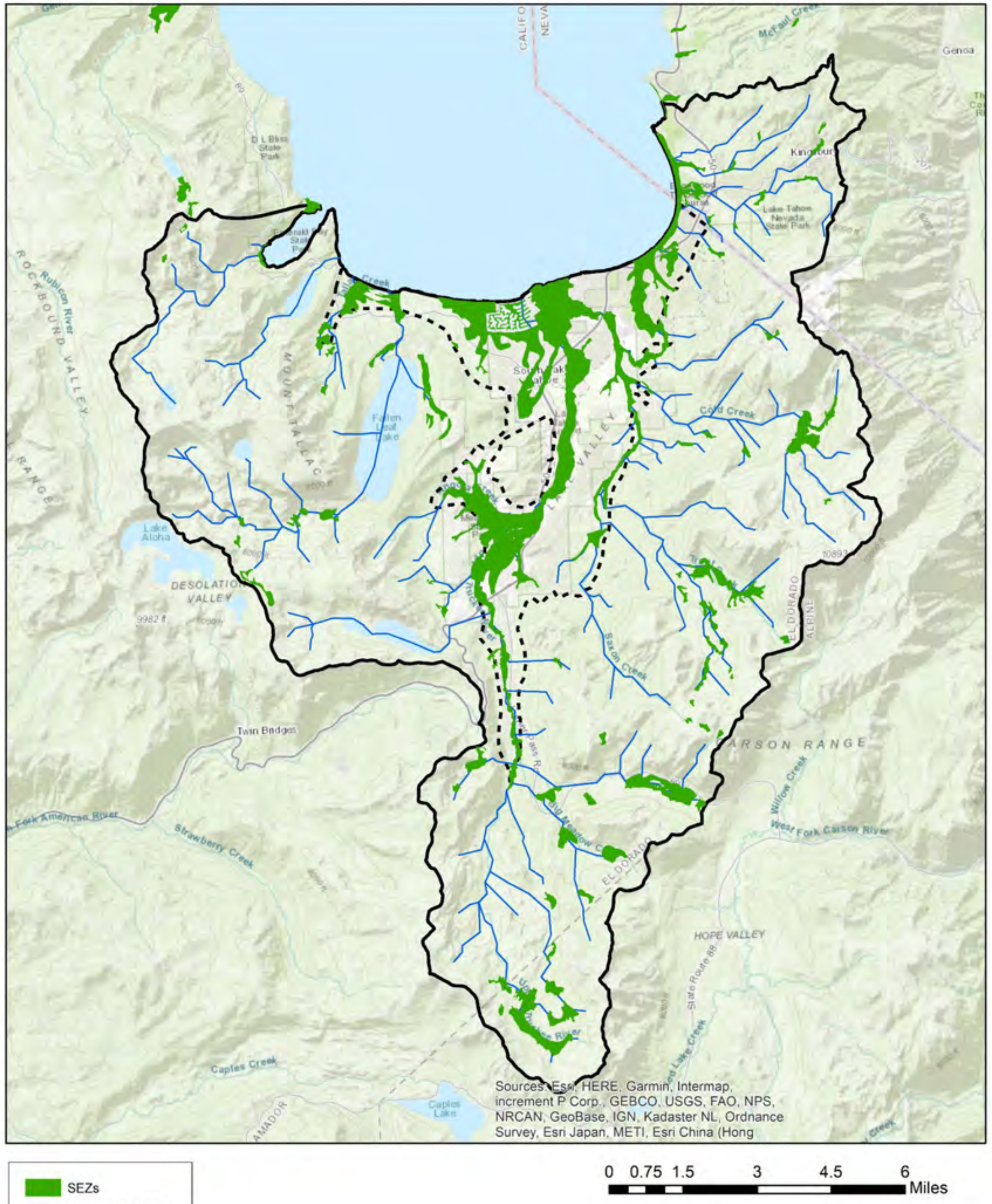
Rybarski et al., 2022a

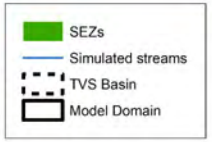


Hausner & Rybarski, Appendix G

Groundwater Dependent Ecosystems

GDEs identified and mapped based on TRPA designated Stream Environment Zones (SEZs)

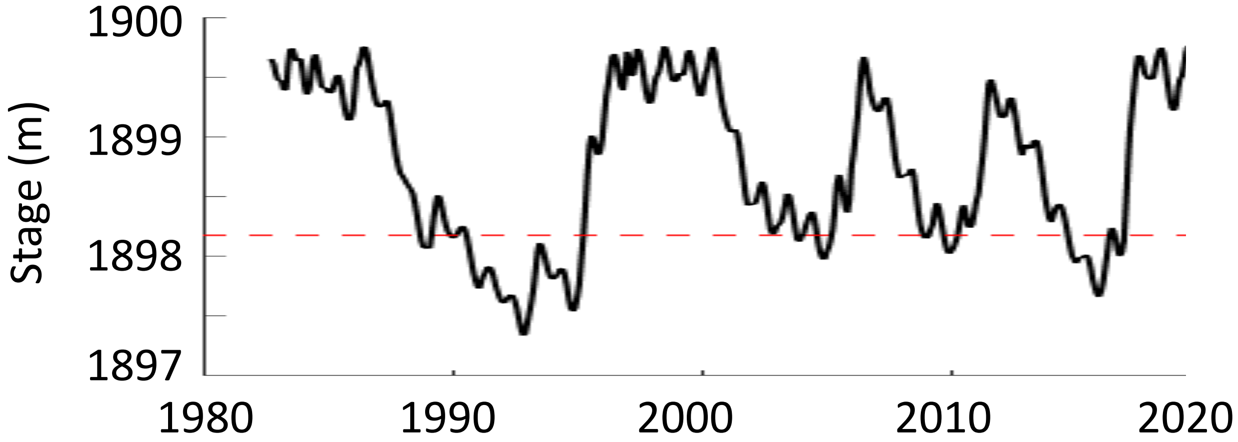




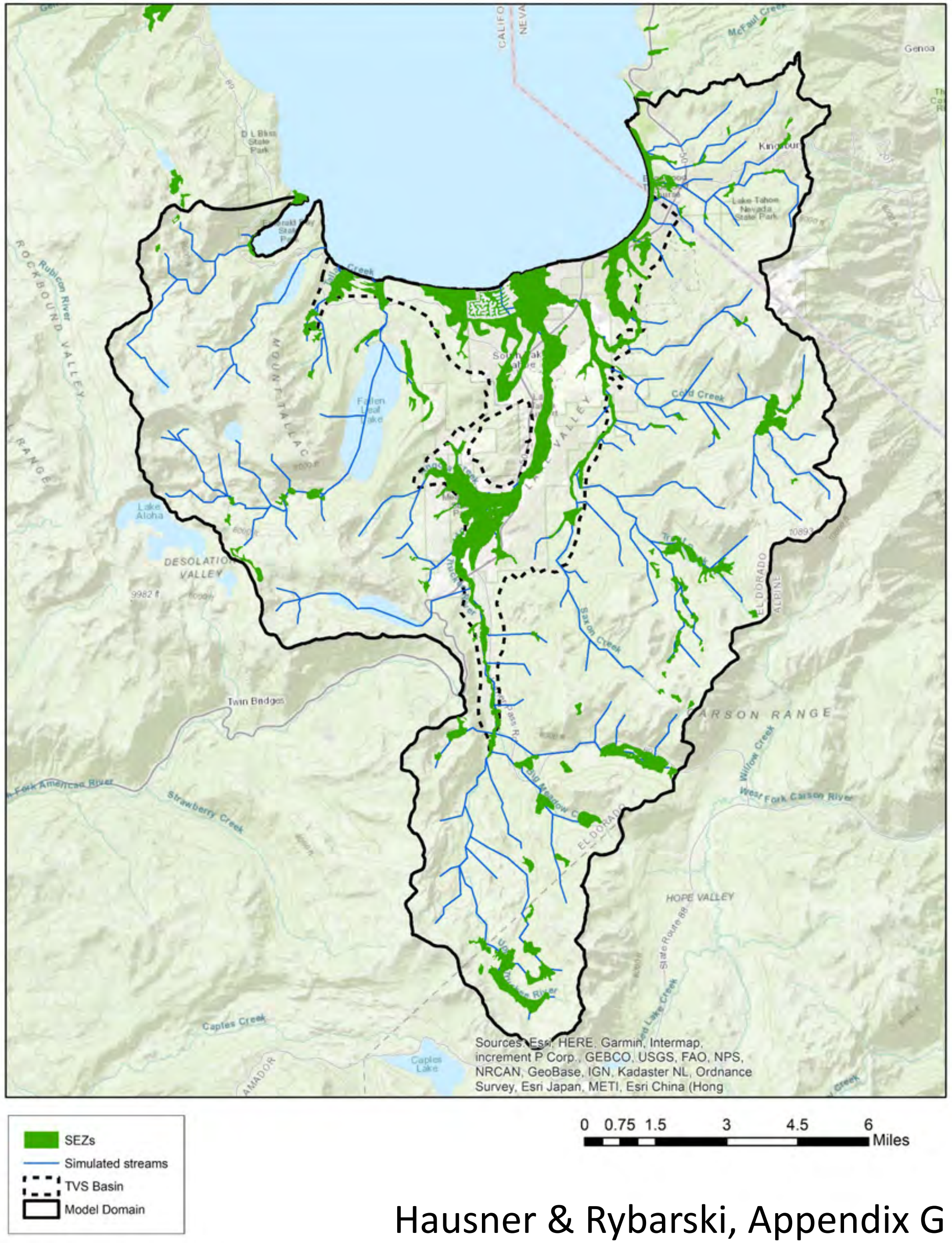
Hausner & Rybarski, Appendix G

Groundwater Dependent Ecosystems

Simulated groundwater levels from historical model were examined for declining water levels and none were found (30-year and 10-year trend tests)



Groundwater Dependent Ecosystems

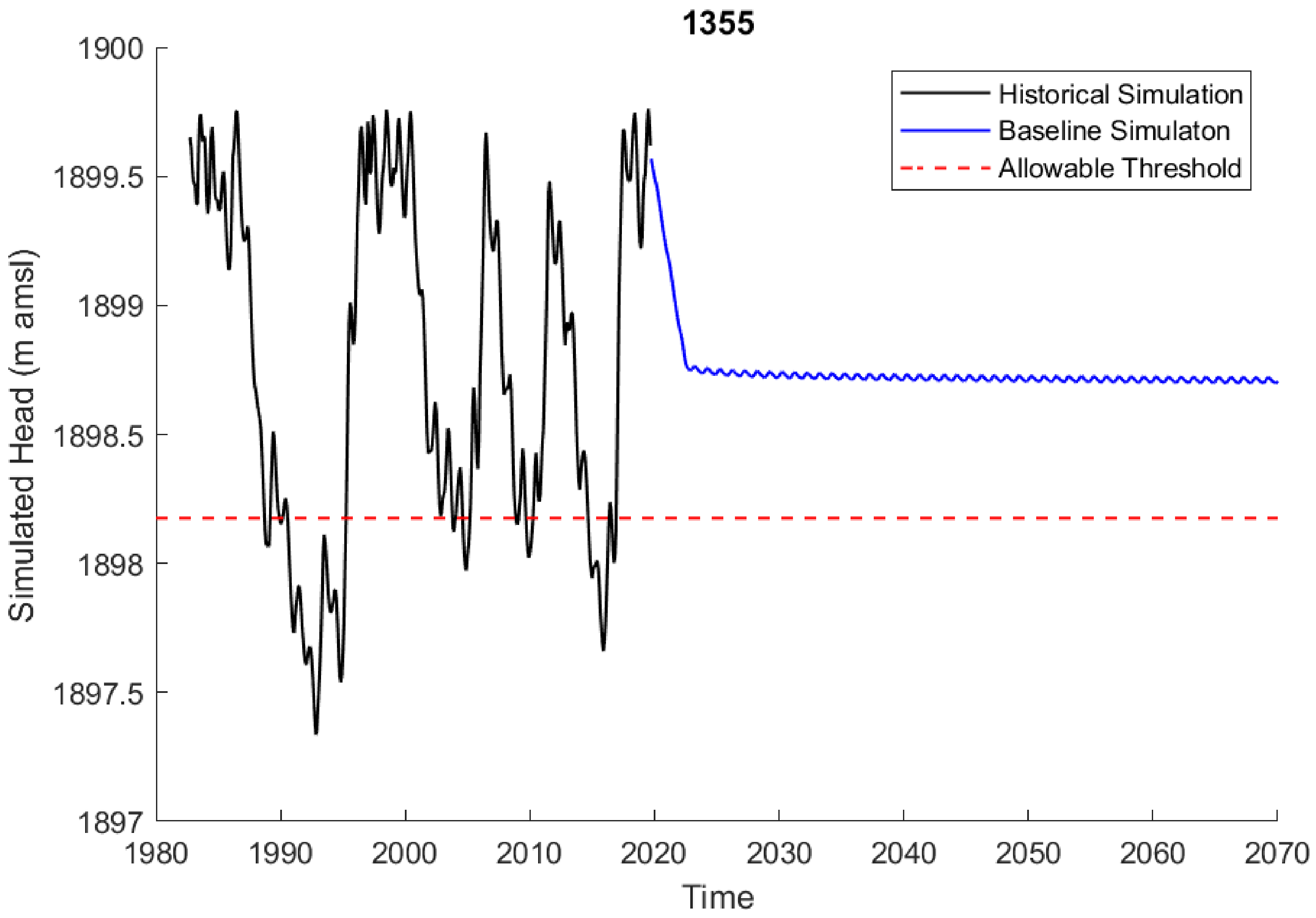


Hausner & Rybarski, Appendix G

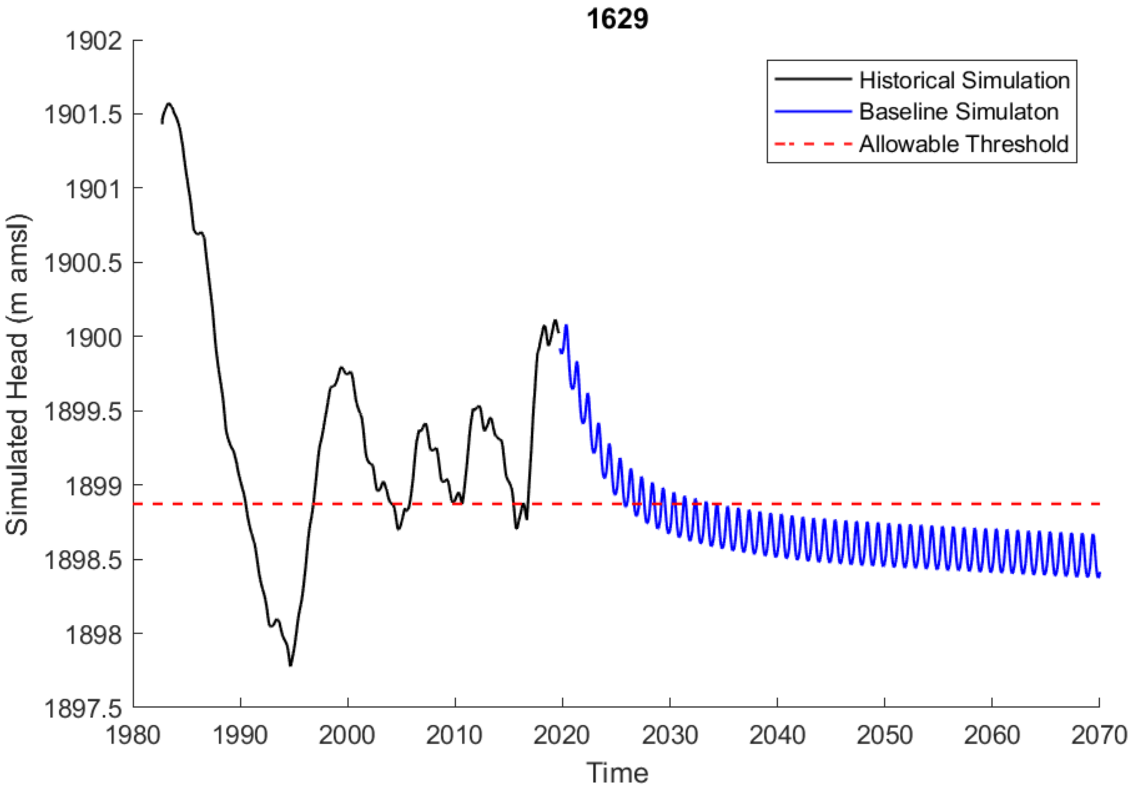
Baseline model simulation was used to identify GDEs that may be vulnerable in the future:

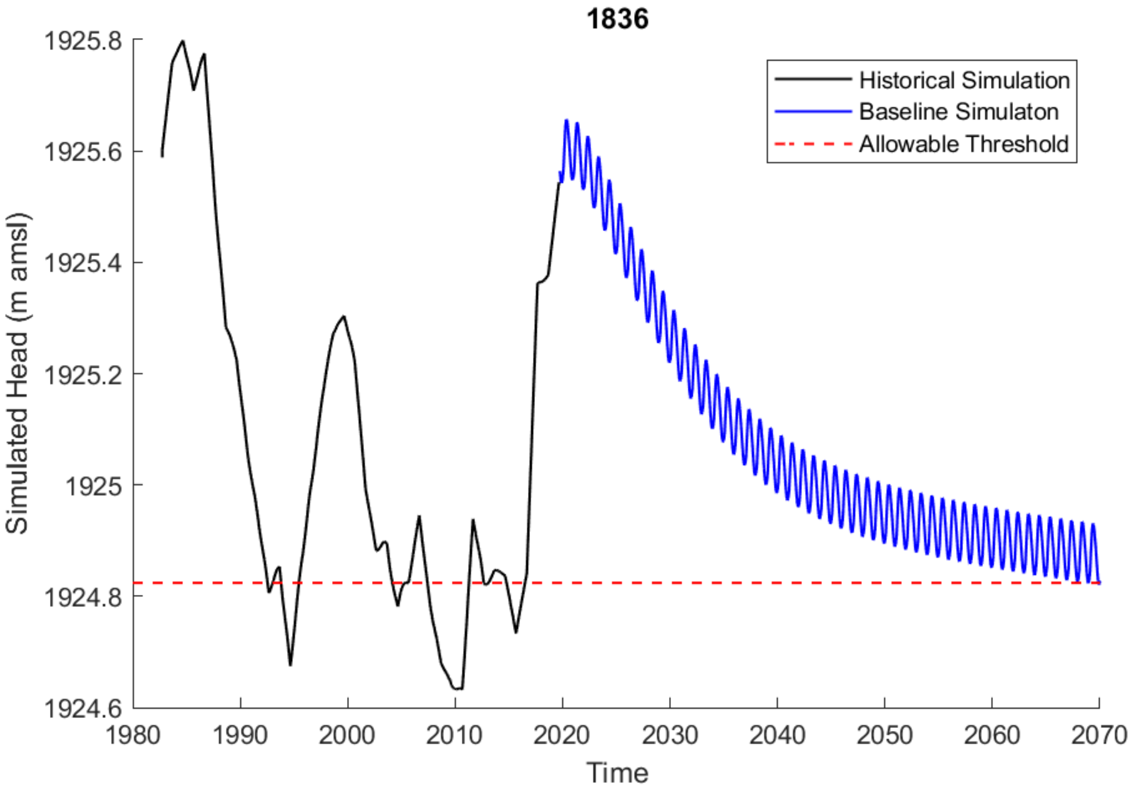
- Vulnerable vs. not vulnerable?
- Timeframe to threshold exceedance?

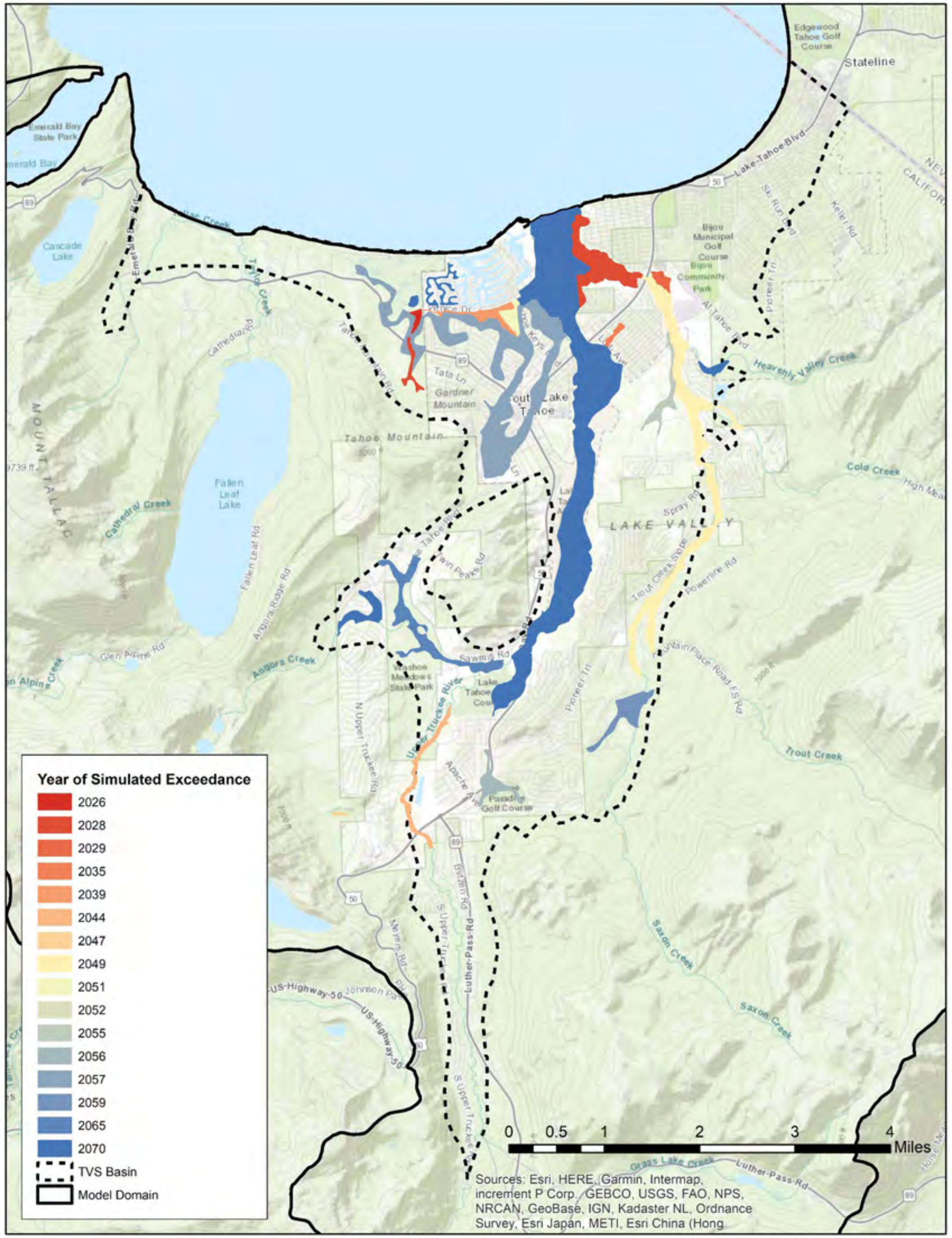
GDE classified as “Not Vulnerable



Vulnerable: Timeframe to Exceedance

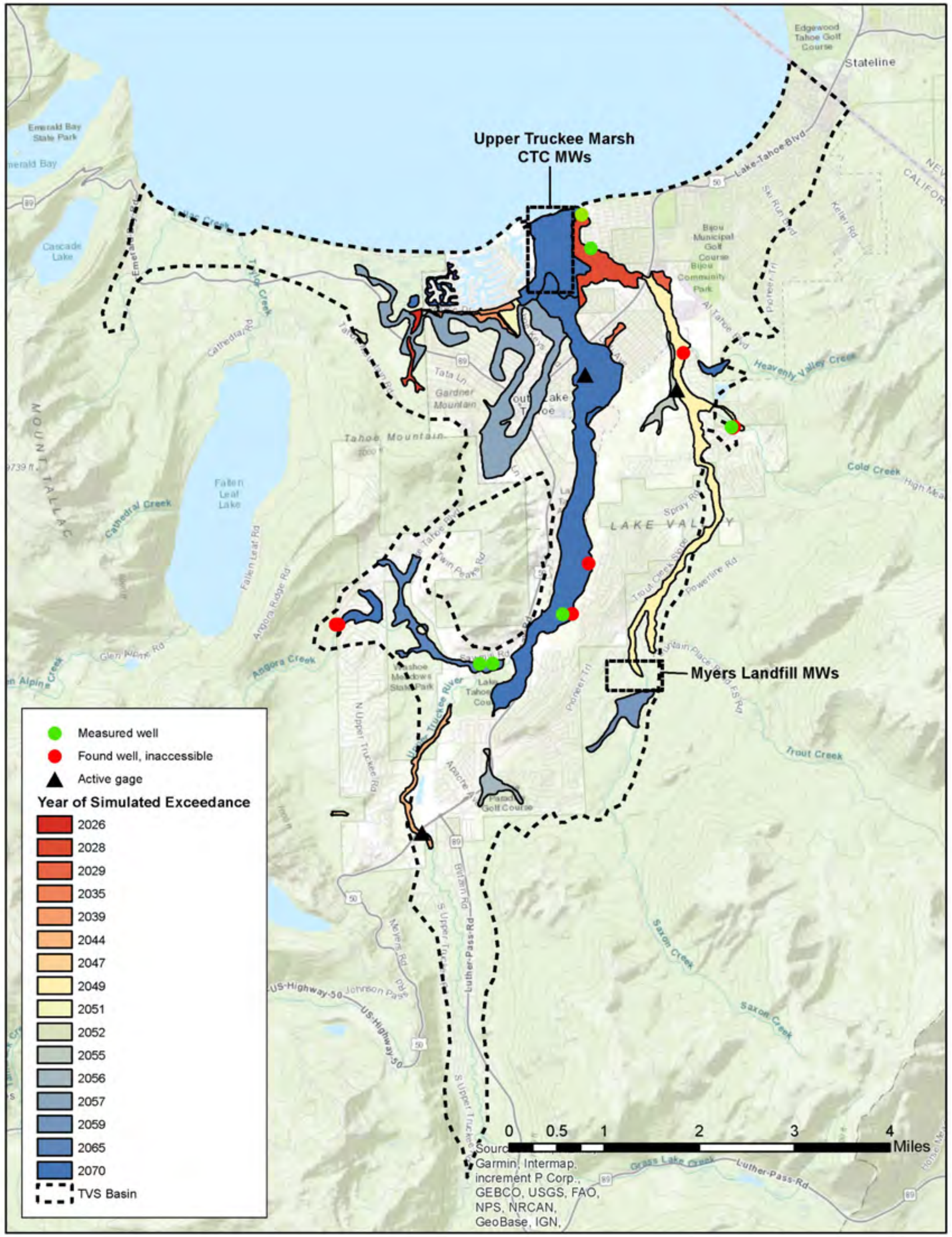






Groundwater Dependent Ecosystems

Prioritized based on simulated date of threshold exceedance, but SGMA monitoring needs to be based on ***measured*** water levels



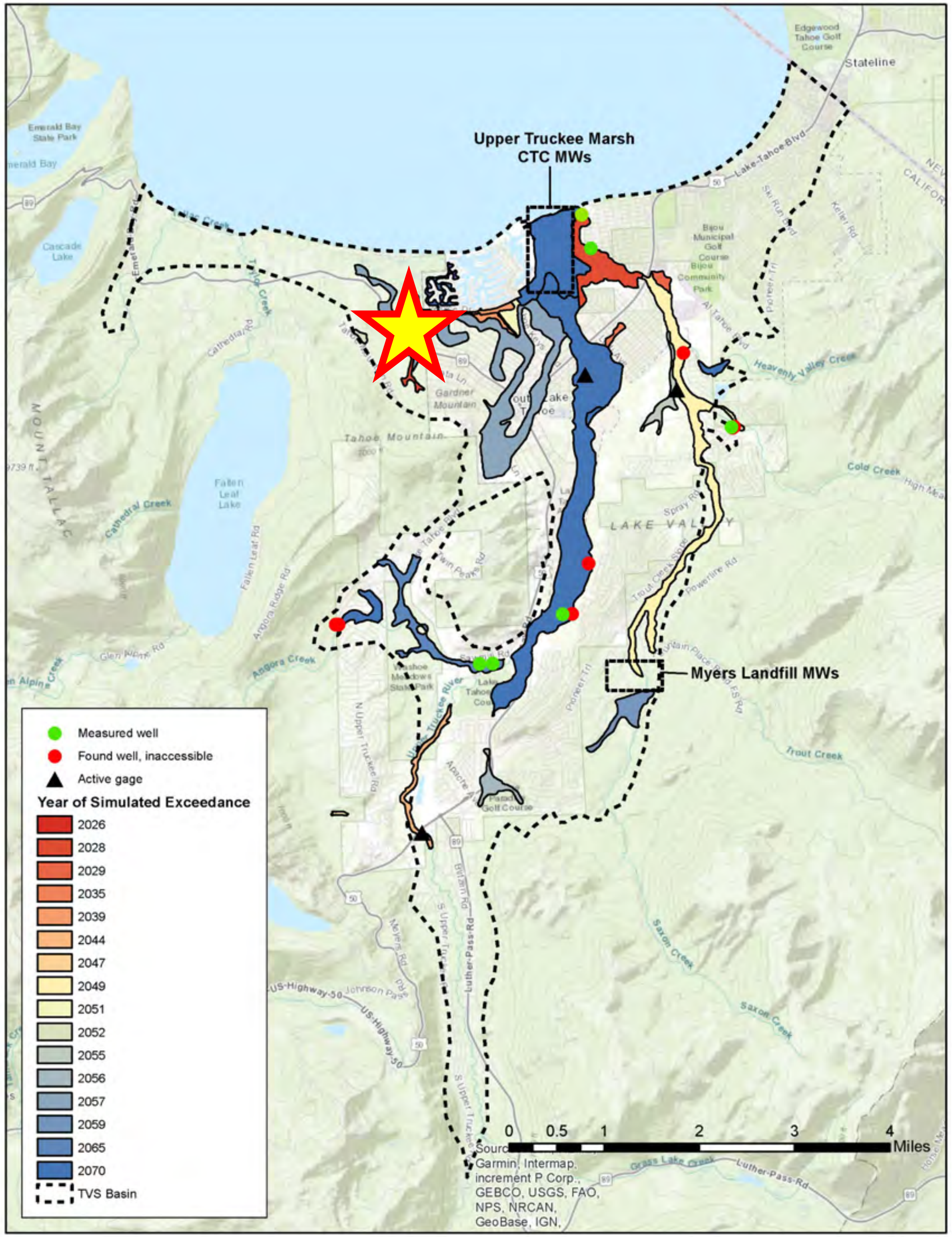
Visited existing monitoring locations in July

Some wells found and accessible to measurements (green dots)

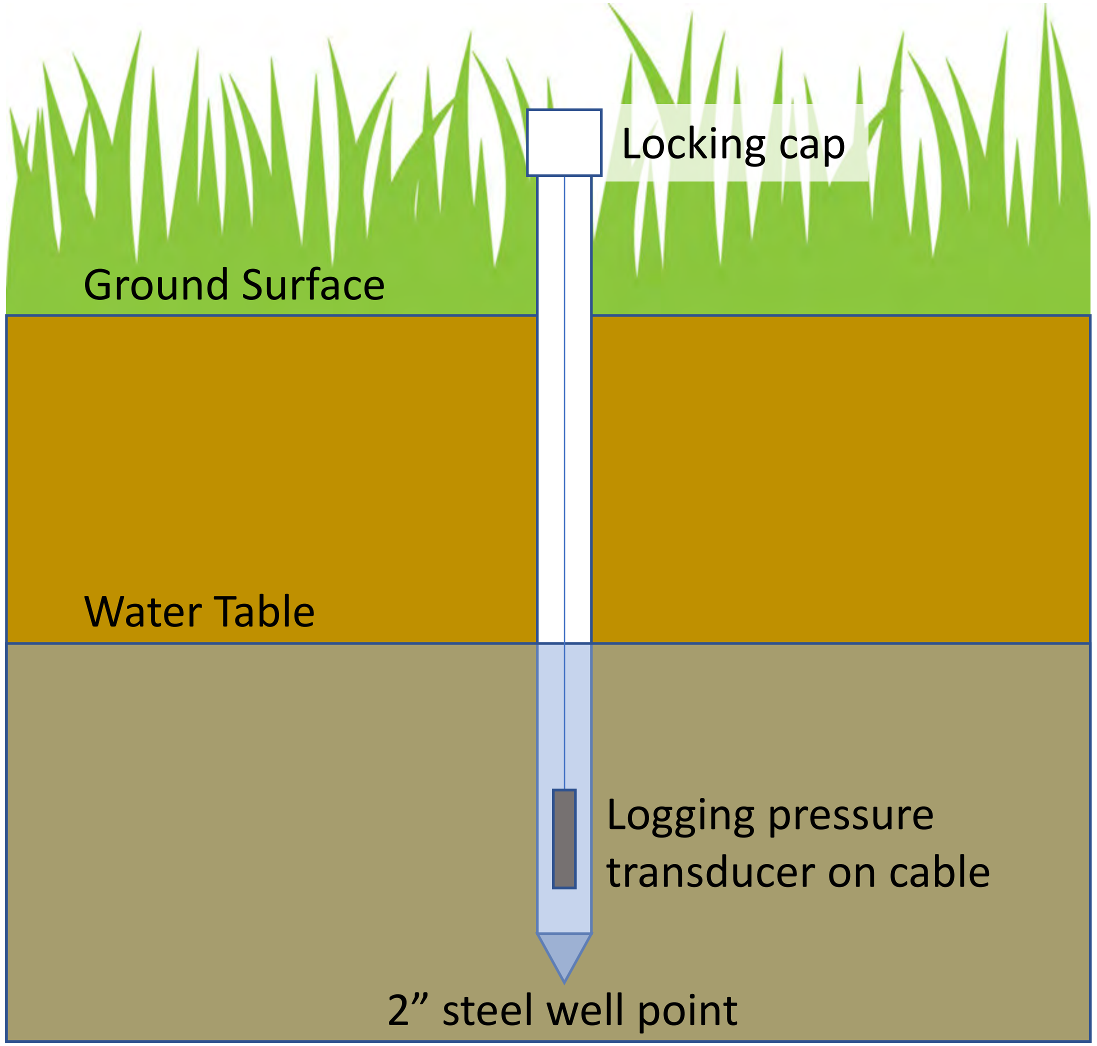
Some wells found but inaccessible (red dots)

Some wells operated by others (e.g. Myers landfill wells)

Proposing new monitoring wells near Pope Marsh



Monitoring Well Construction



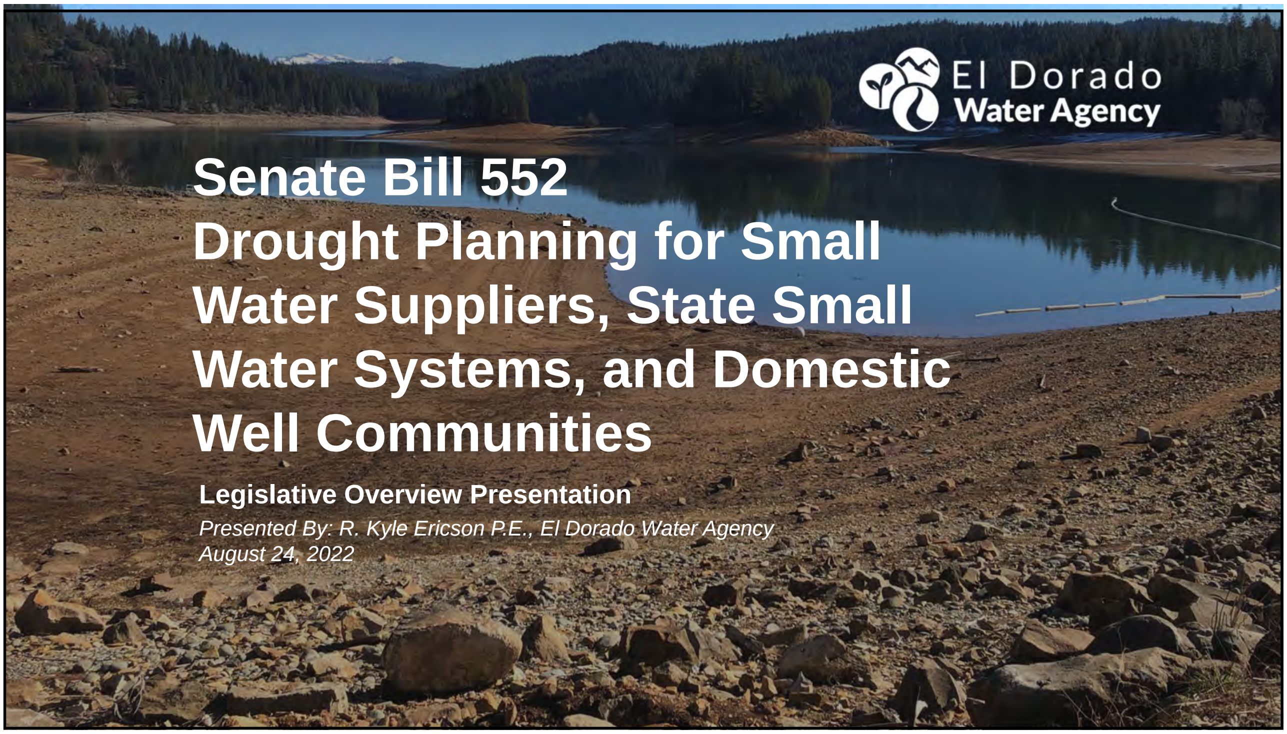
Proposed GDE Monitoring Program

- Instrumentation of existing wells and/or installation of new wells
- 5 years of monitoring
- Quarterly data collection and QA check
- Annual QC and threshold analysis
- Integrate with existing SEZ monitoring programs

Next Steps

- Invite stakeholders with appropriately sited monitoring wells to participate in the GDE monitoring program
- Identify sites and secure permission to install monitoring wells near priority GDEs
- Secure funding for Proposed GDE Monitoring Program

2022 Drought



Senate Bill 552
Drought Planning for Small Water Suppliers, State Small Water Systems, and Domestic Well Communities

Legislative Overview Presentation

Presented By: R. Kyle Ericson P.E., El Dorado Water Agency
August 24, 2022

1

Background

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What is the Role of EDWA

- Created by State Legislation -1959 El Dorado County Water Agency Act
- Principally focused water supply from 1959 – 2018
- 2018 - Refocused as a Countywide Water Resource Planning Agency with the authorities defined in the 1959 El Dorado County Water Agency Act
- New focus is on all aspects of watershed health, long-term water supply planning, climate change adaptation, drought planning, stormwater resources planning, assistance to water purveyors, State and Federal legislative advocacy, etc.
- 2019 Water Resources Development and Management Plan
  - Identifies water resource issues through the county
  - Development of Resource Management Strategies(RMS)
  - Establishes programs too address water resource issues and implement RMS

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Preceding Legislation and Drought Planning

- **Assembly Bill 1668** and **Senate Bill (SB) 606** (passed in June 2018) outlined directives related to urban and agricultural water use efficiency and countywide drought resiliency
- The DWR **County Drought Advisory Group** (formed in November 2018)
  - Included El Dorado Water Agency (EDWA) and other members
  - Identified small water suppliers and rural communities at risk of drought and water shortage
  - Developed recommendations and guidance to address the needs of these communities
  - Informed SB 552

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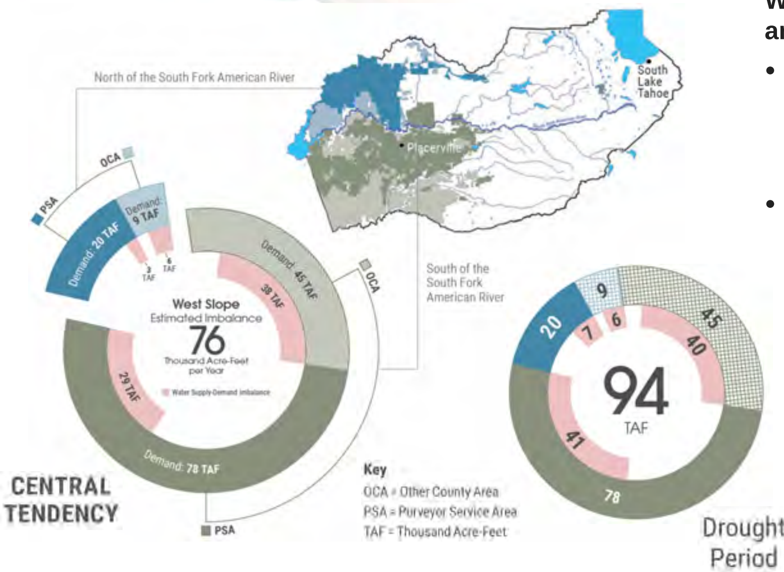
EDWA's Drought Planning Efforts



Water Resources Development and Management Plan (WRDMP)

- Forecasts a water supply-demand imbalance in the future, which will be exacerbated during drought periods
- Resource Management Strategies (RMS) identified water supply-related challenges.
  - *RMS 7*: Improve Drought and Water Shortage Preparedness
  - *RMS 8*: Ensure All Residents Have Water Accessibility and Affordable Water

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EDWA's Drought Planning Efforts

Upper American River Basin Regional Drought Contingency Plan (UARB RDCP)

Developed to increase resiliency of water resources in the face of climate change and droughts.

6

6

Senate Bill 552 Requirements

7

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Definitions

Community water system = public water system that serves at least 15 service connections used by yearlong residents or regularly serves at least 25 yearlong residents of the area

Small water suppliers = community water system serving 15-2,999 service connections and less than 3,000 AF annually

State small water systems = water system serving 5-14 service connections and does not regularly serve drinking water to more than an average of 25 individuals daily for more than 60 days out of the year

Nontransient noncommunity water system = public water system that is not a community water system and that regularly serves at least 25 of the same persons over 6 months per year

Domestic well = groundwater well used to supply water or the domestic needs of an individual residence or a water system that is not a public water system and that has no more than 4 service connections

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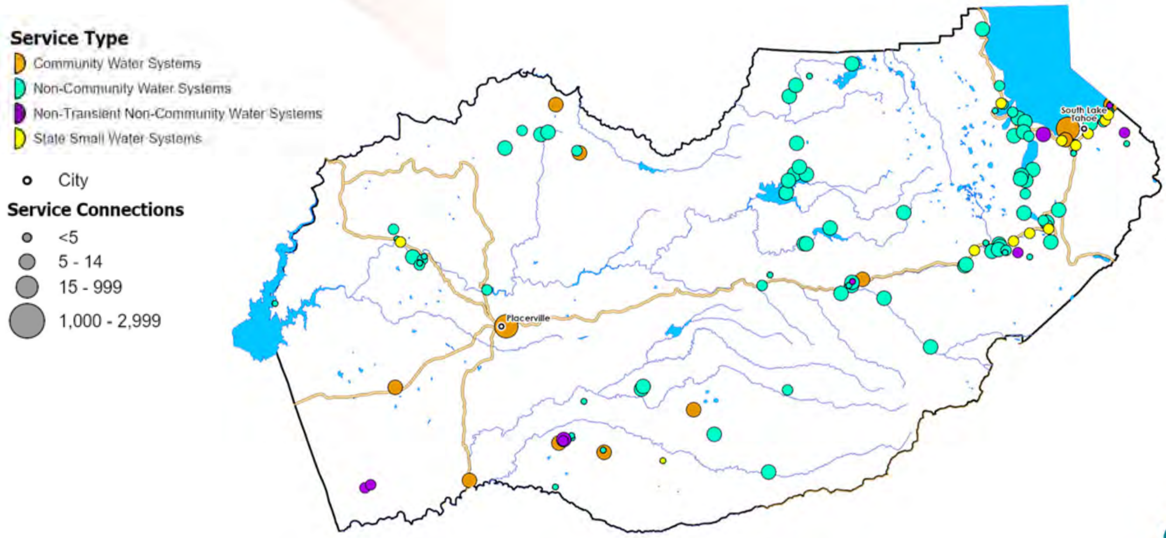
Small Water Systems in El Dorado County



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Small Water Systems in El Dorado County

Connections	Community Water Systems	Noncommunity Water Systems	Nontransient Noncommunity Water Systems	State Small Water System	Total
1,000-2,999 Service Connections	2	0	0	N/A	**2**
15-999 Service Connections	13	46	2	N/A	**61**
5-14 Service Connections	N/A	19	5 (5)	20	**44**
<5 Service Connections	N/A	32	2	N/A	**34**
Total	**15**	**97**	**9**	**20**	**141**

N/A = not applicable per definition

10

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Requirements of SB 552

- Activities required by specific small water systems
- County Drought Task Force Requirements

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1. Community water systems serving 1,000-2,999 service connections and nontransient noncommunity water systems that are schools

- Develop and maintain an abridged Water Shortage Contingency Plan (WSCP) with specific drought planning elements by July 1, 2023
  - Make WSCP available on their website or if no website is available, to persons upon request
  - DWR and State Water Board to provide template by December 31, 2022
- Report annually specified water supply condition information to the State Water Board
- Implement **certain resiliency measures** as early as January 2023

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1. Community water systems serving 1,000-2,999 service connections and nontransient noncommunity water systems that are schools – *Required Resiliency Measures*

- By January 1, 2023, **implement monitoring systems** sufficient to detect production well groundwater levels.
- By January 1, 2023, **maintain membership** in the California Water/Wastewater Agency Response Network (CalWARN) or similar mutual aid organization.
- By January 1, 2024, to ensure continuous operations during power failures, **provide adequate backup electrical supply**.
- By January 1, 2027, **have at least one backup source of water supply, or a water system intertie**, that meets current water quality requirements and is sufficient to meet average daily demand.
- By January 1, 2032, **meter each service connection and monitor** for water loss due to leakages.
- By January 1, 2032, have source system capacity, treatment system capacity if necessary, and distribution system capacity to **meet fire flow requirements**.

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2. Community water systems serving 15-999 service connections

- Add drought planning elements to their Emergency Notification or Response Plans
- Plan should be updated every 5 years or after significant changes
- Report annually specified water supply condition information to the State Water Board

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3. State Small Water Systems and domestic wells within County's jurisdiction

- County to **develop a plan** that includes potential drought and water shortage risk and proposed interim and long-term solutions
  - May be a stand-alone document or included to an existing county plan
- County to establish a **standing county drought and water shortage task force** to facilitate drought and water shortage preparedness

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County Drought Plan Elements

- Plan elements must include:
  - Potential drought and water shortage risk
  - Proposed interim and long-term solutions for state small water systems and domestic wells
- Consider at a minimum:
  - **Consolidations** for existing water systems and domestic wells
  - Domestic well drinking water **mitigation programs**
  - Provision of **emergency and interim drinking water solutions**
  - An analysis of the **steps necessary to implement** the plan
  - An analysis of **funding sources** available to implement the plan

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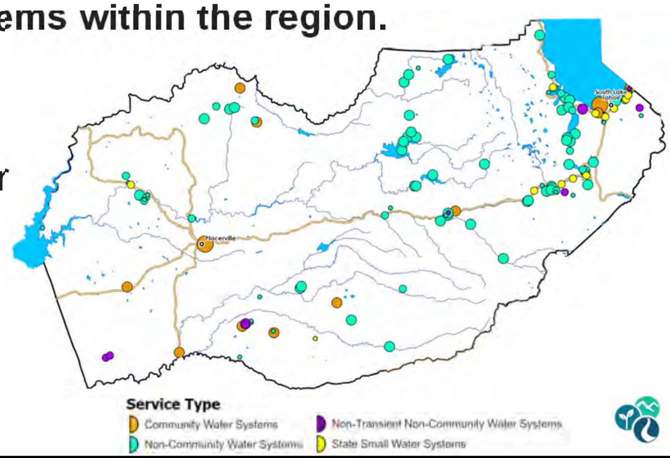
El Dorado County Drought Plan

To address the concerns discussed in the WRDMP and UARB RDCP, **El Dorado County's Drought Plan will address all small water systems within the region.**

This goes beyond what is required by SB 552, which only requires addressing water shortage preparedness for state small water systems and domestic wells.



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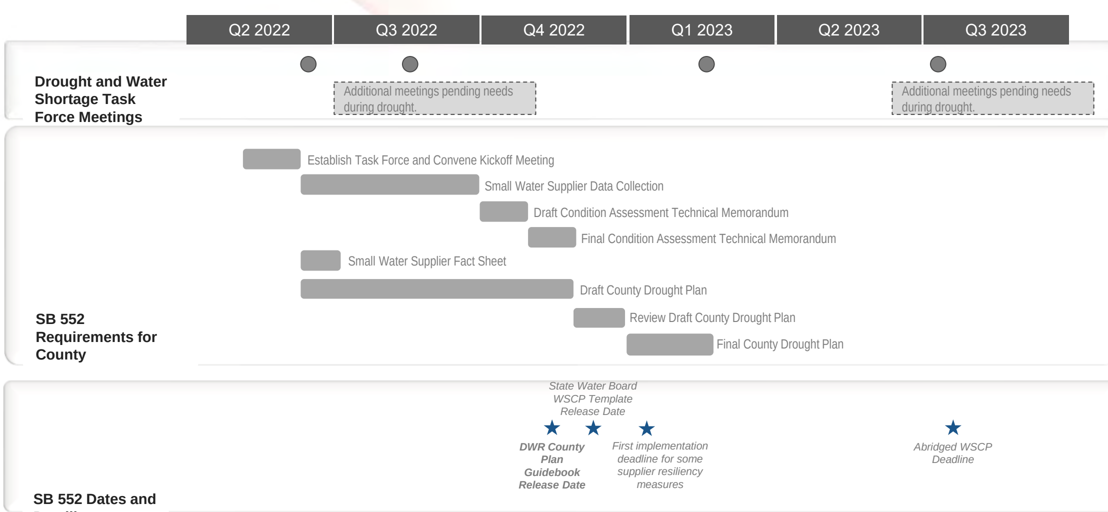
SB 552 Implementation Schedule



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Task Force Roles and Responsibilities

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Drought and Water Shortage Task Force Roles

- Pursuant to Health and Safety Code Part 12, Chapter 4, § 116330, the **Local Primary Agency (i.e., County of El Dorado, Environmental Management Department) is responsible for public water systems.**
- Pursuant to California Code of Regulations Title 22, Chapter 14, § 64211 to 64217, **the local health officer or agency (i.e., County of El Dorado, Public Health Office) is responsible for state small water systems**
  - State small water systems are not public water systems because they have less than 15 service connections

20

20

Drought and Water Shortage Task Force Responsibilities

1. Provide current water supply conditions, data, and feedback
2. Review drought conditions, identify problems, and develop actionable solutions
3. Support SB 552 implementation and County Plan development
4. Disseminate Task Force findings and recommendations

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Drought and Water Shortage Task Force Membership and Schedule

Core Members

El Dorado Water Agency

El Dorado County, California

Supplemental Members

- Small Water Supplier Representatives
- State Small Water System and Domestic Well Representatives
- Public Water Agency Representatives
- Groundwater Sustainability Agency Representative

Meeting Frequency

- 2-3 times a year
- More frequently during drought or other water shortage events as needed

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Moving Forward

23

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Phased Approach to SB 552 Compliance

1. Prioritization and early planning
- Identify gaps & needs
- Identify priorities for grant funding
- Identify actionable next steps

2. Continued planning and information gathering
- Data collection
- Small water systems evaluation
- DWR workshops

3. Implementation of plans and strategies

Currently here

24

24

Questions?

25

TVS SUBBASIN (6-005.01)
2022 SAG Workshop II
August 24, 2022

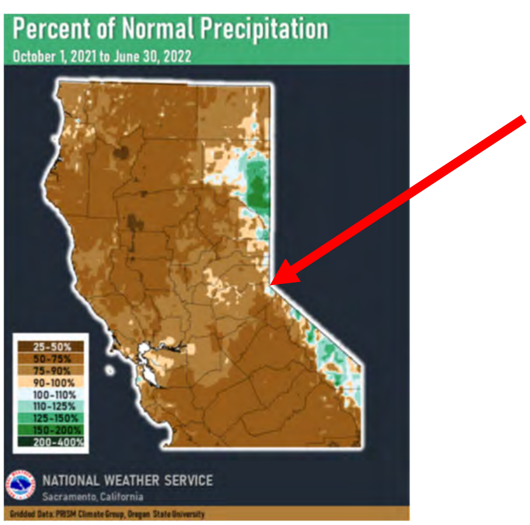
WY 2022

Water Supply and Demand Assessment

I.Bergsohn, PG, CHg

1

NWS Spring 2022 Climate & Drought Summary (NOAA, July 28, 2022)



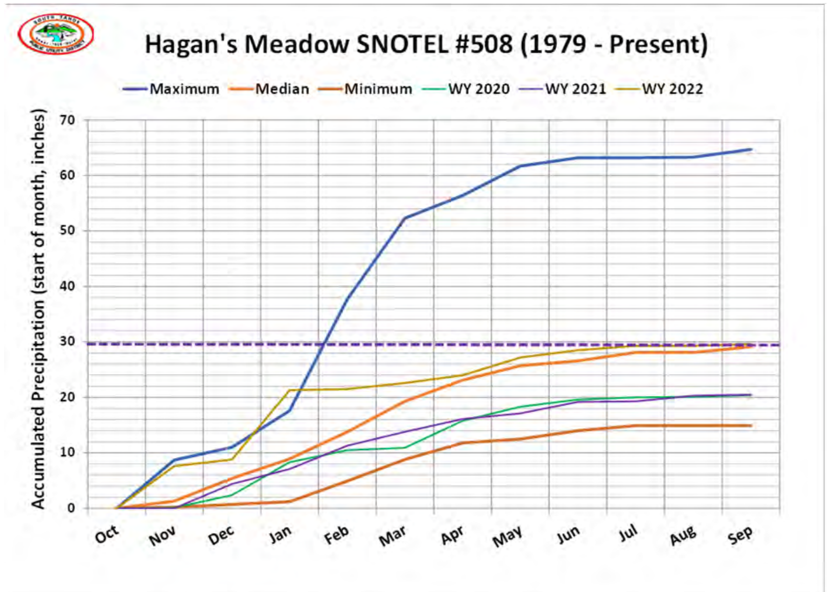
Water Supply and Demand Assessment (CWC § 10632 (a) (2))

- (i) Current year unconstrained demand, considering weather, growth, and other influencing factors, such as policies to manage current supplies to meet demand objectives in future years, as applicable.
- (ii) Current year available supply, considering hydrological and regulatory conditions in the current year and one dry year. The annual supply and demand assessment may consider more than one dry year solely at the discretion of the urban water supplier.
- (iii) Existing infrastructure capabilities and plausible constraints.
- (iv) A defined set of locally applicable evaluation criteria that are consistently relied upon for each annual water supply and demand assessment.
- (v) A description and quantification of each source of water supply

2

Precipitation

- Maximum = 67.5 " (WY 2017)
- Minimum = 14.9" (WY 1987)
- Median = 29.10" (WY 1979 – 2021)
- WY 2020 = 20.4" (Dry)
- WY 2021 = 20.6" (Below Normal)
- WY 2022 = 29.6" (Normal, Projected thru Aug 18, 2022)



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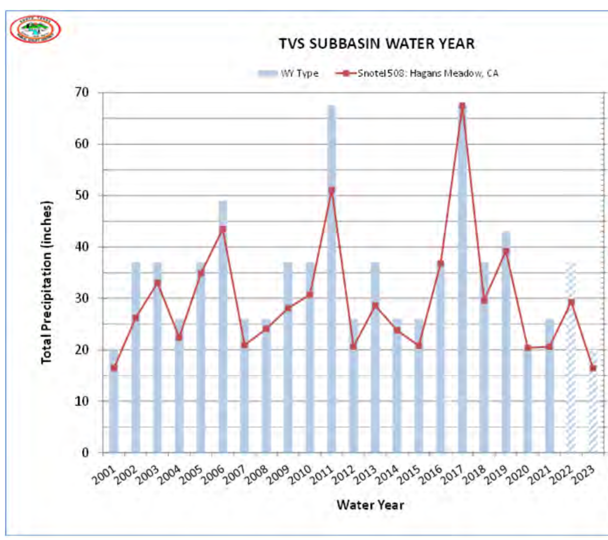
Water Year Type

- WY 2021 = 20.6" (Below Normal)
- WY 2022 = 29.3" (Normal, Projected thru June 20, 2022)
- WY 2023 = 16.4" (Dry, WY 2001)

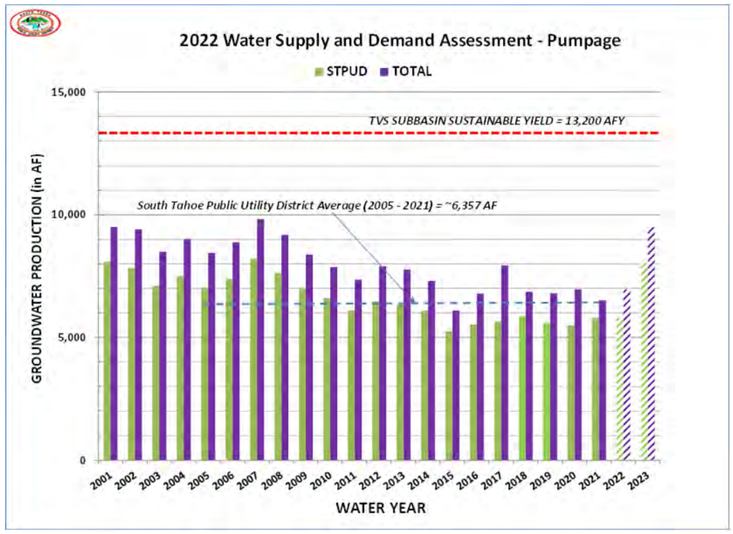


WY Type	PPT (in) >	PPT (in) ≤
Critical		14
Dry	14	20
Below Normal	20	26
Normal	26	37
Above Normal	37	43
Wet	43	48
Very Wet	48	

4

Water Demand

- Water Demand (AF):
  - STPUD: TOTAL
- WY 2021 (AF):
  - 5802: 6516
- WY 2022 (AF)
  - Projected, 5796: 6955
- WY 2023(AF)
  - 8037: 9500 (WY 2001)



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Water Supply

Storage Threshold [(-55,687 AF) – (GW in Storage AF)]

- WY 2021 = 41,082 AF
- WY 2022 = 40,627 AF (projected)
- WY 2023 = 35,368 AF (projected)

6

South "Y" PCE Plume

Tahoe Valley South Subbasin Groundwater Management Plan Stakeholder Advisory Group Workshop August 24, 2022

Site Cleanup Subaccount Program (SCAP) Regional PCE Plume Investigation Update

Ed Tarter, PE
AECOM

Agenda

- Overview of Site Cleanup Subaccount Program (SCAP) Regional PCE Plume Investigation Task Objectives
- Key Observations from Regional PCE Plume Groundwater Investigation
- Summary of Current and Future SCAP Activities
- Recommended Future Actions

Regional PCE Plume Investigation Tasks

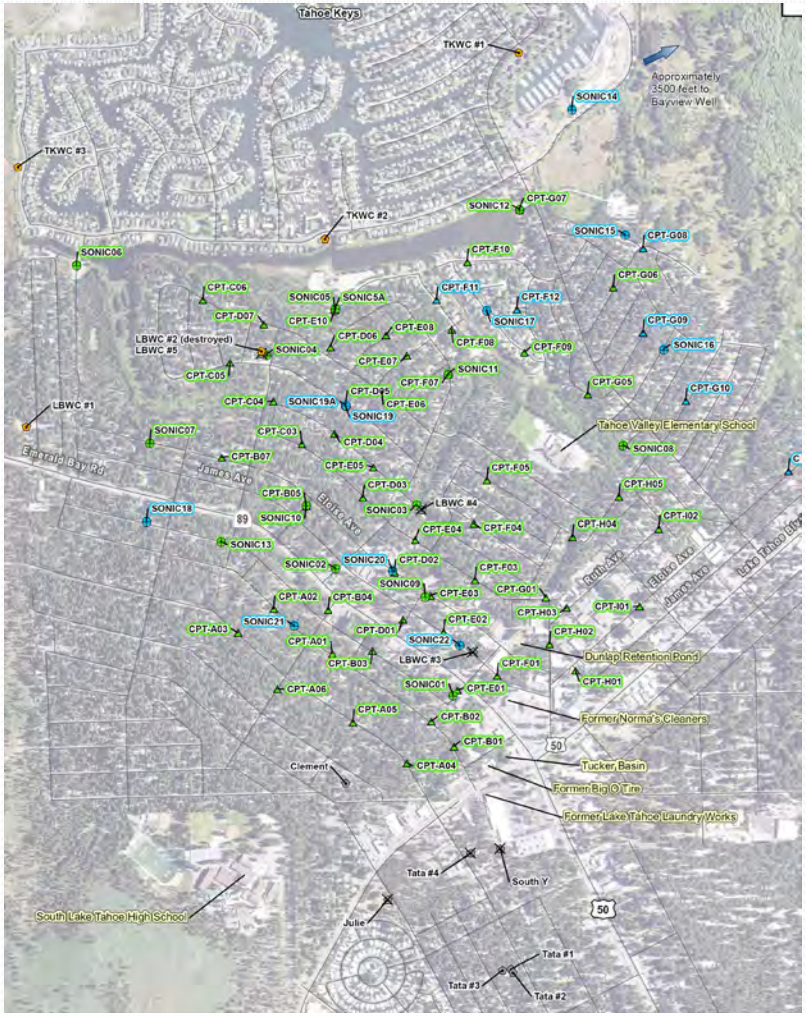
- Records Review and Inventory Development
- Regional PCE Plume Investigation
- Vertical Conduit Evaluation and Destruction
- Non-Municipal Water Supply Well Sampling
- Soil Gas Sampling
- Sentry Well Network Installation and Monitoring

Regional PCE Plume Investigation Objectives

- Define lateral and vertical extent of Regional PCE Plume
- Develop understanding of regional subsurface lithology
- Estimate horizontal and vertical groundwater gradients
- Monitor plume migration upgradient from key municipal supply wells
- Identify preferential pathways contributing to contaminant transport of PCE
- Evaluate potential threat to human health from vapor intrusion
- Evaluate feasibility of potential remedial and receptor protection options

Summary of Regional PCE Plume Investigation

- Fieldwork performed in 2019 and 2020
- 22 Sonic borings advanced to 300 feet bgs
- 57 Cone Penetration Test (CPT) borings advanced to 100 feet
- 6 - 8 groundwater samples collected per location



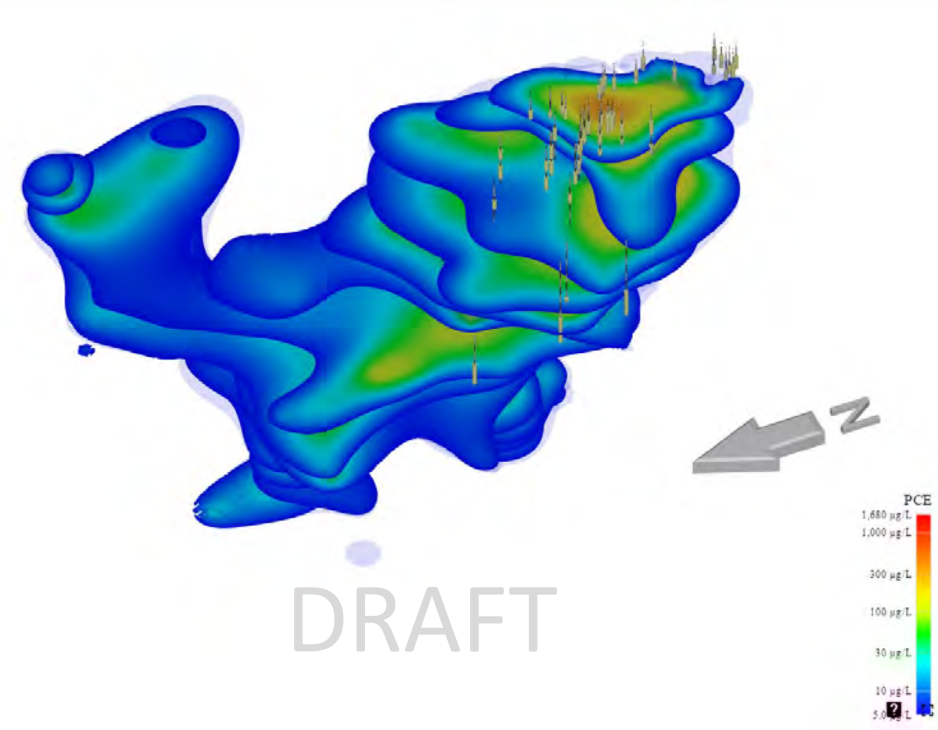
Key Observations from Regional PCE Plume Groundwater Investigation

Improved Understanding of the Conceptual Site Model

- Nature and Extent
- Regional Geology/Lithology
- Fate and Transport

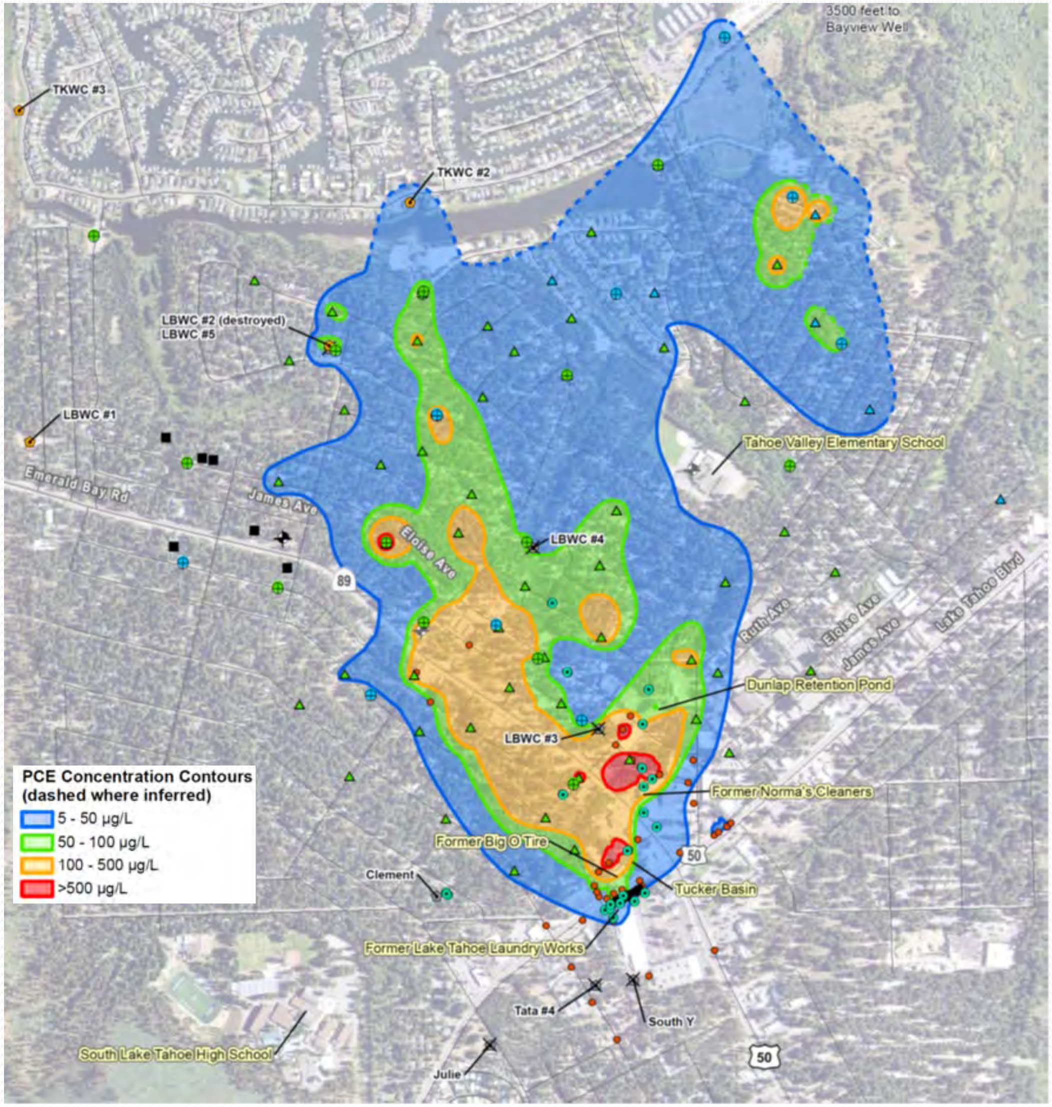
Earth Volumetric Studio™ (EVS) 3-D Model

- Developed Site specific model to estimate nature and extent of plume
- Model inputs:
  - PCE groundwater data collected by AECOM and various parties (LTLW, water purveyors, etc.)
  - Lithologic data during CPT sounding and Sonic drilling
- Model outputs:
  - Isocontour maps
  - 2D cross sections
  - 3D visualization tool



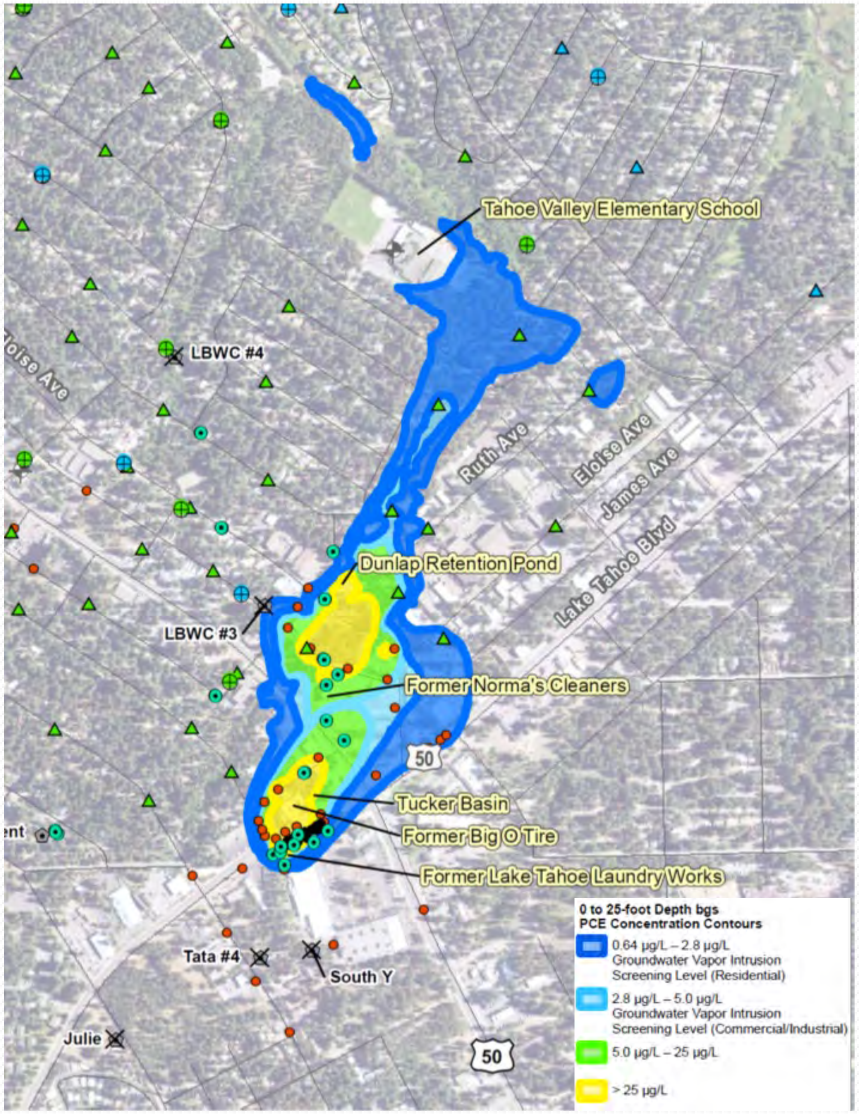
*EVS – Earth Volumetric Studio. EVS uses geostatistical mathematical methods (kriging), also known as gaussian process regression, to predict geological and PCE concentrations from sparse data samples spatially across a set model domain

Lateral Extent of PCE in Groundwater



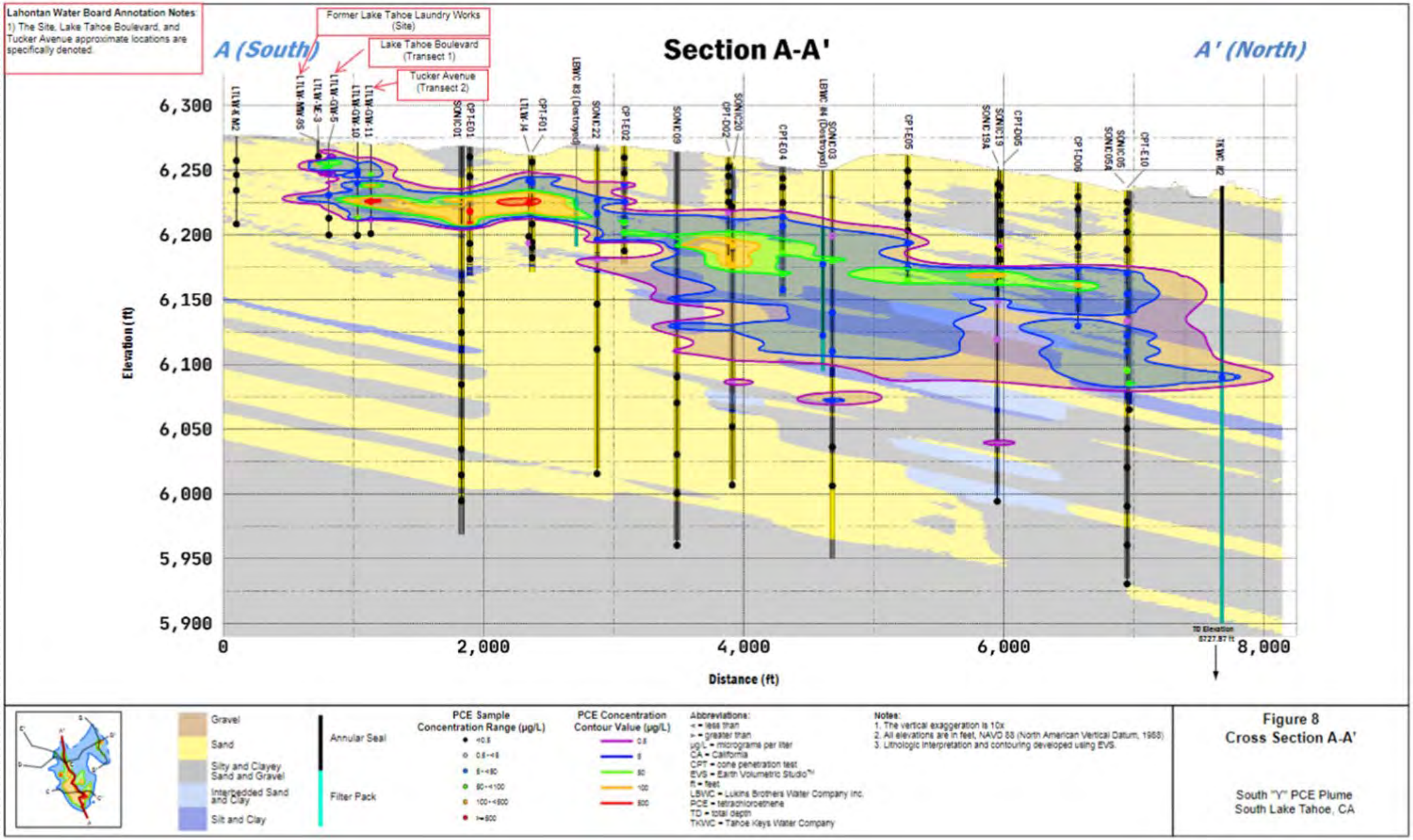
- PCE plume extends 8,000 feet longitudinally (south to north) towards Lake Tahoe.
- PCE plume extends 5,000 feet in the (east to west)
- Vertically down 50 feet to over 150 feet in depth.
- PCE detected above 5 µg/L from depths down to 185 feet bgs
  - 34 µg/L at Sonic 2 at a depth of 183-185 feet, bgs.
- PCE ranged from below the detection limit of 0.5 µg/L to 570 µg/L.

Lateral Extent of PCE in Shallow Groundwater



- PCE exceeds residential and commercial/industrial vapor intrusion Environmental Screening Levels (ESLs)
- PCE in shallow groundwater exceeds the residential vapor intrusion ESL (**0.64 µg/L**) from the South "Y" Area to the northeast towards Tahoe Valley Elementary School along the City of South Lake Tahoe's stormwater conveyance, then towards Tahoe Keys
- Max PCE detected 170 µg/L at location LTLW-MW-9S (screened from 10 to 25 feet bgs).

Vertical Extent of PCE in Groundwater and Regional Lithology



Vertical Extent of PCE in Groundwater and Regional Lithology - Notes

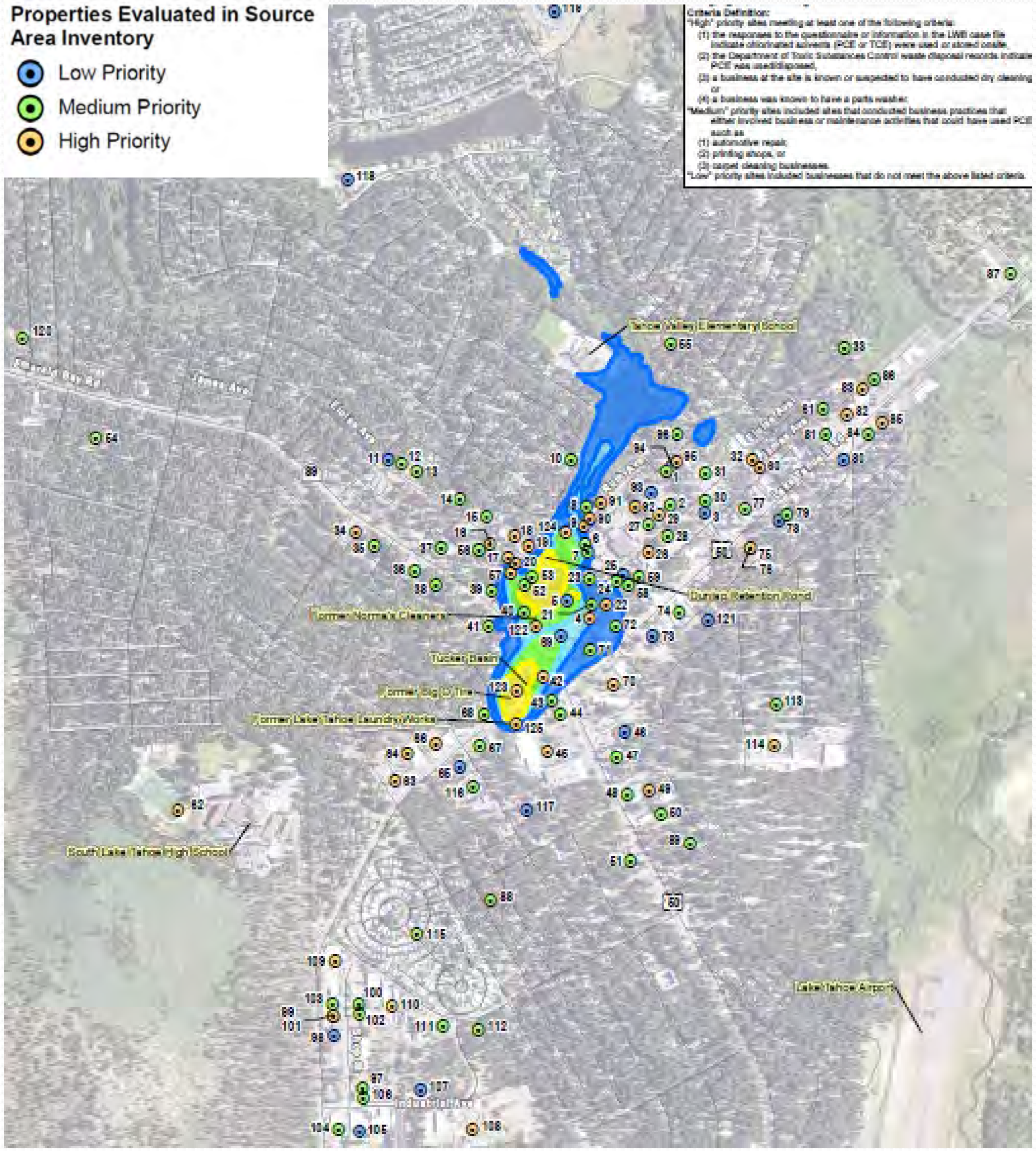
Nature and Extent

- Estimated extent PCE plume across the South "Y" Area from the south (A) near the former LTLW Site at historical multi-depth sampling location LTLW-KM2 to the north (A') near municipal supply well TKWC #2.
- From the far south near the former LTLW Site, historical multi-depth sampling locations with maximum concentrations near 50 feet bgs include LTLW-GW-12 (42 to 46 feet bgs) at a concentration of 10.9 µg/L, LTLW-J4 (35 to 39 feet bgs) at a concentration of 718 µg/L, and LTLW-GW-11 (42 to 46 feet bgs) at a concentration of 1,680 µg/L.
- In general, PCE concentrations are greater than 500 µg/L at a depth of approximately 50 feet bgs or 6,225 feet elevation above mean sea level (MSL).

Lithology

- In the southern portion of the regional PCE plume, cross section A-A' shows deposits of predominantly fine-grained sand underlain by silty and clayey sand and gravel.
- Progressing north, cross section A-A' shows interlayered silty/clayey coarser-grained sand and gravel deposits with lenses of ML and CL deposits becoming more common.
- These silt and clay deposits generally form aquitards or low permeability units that impede the vertical flux of groundwater and PCE.
- The general fining of sediments lakeward (north) is consistent with lower-energy deltaic and lake sedimentation near the lake versus higher energy glacial outwash and alluvial sedimentation near the uplands/mountains.

Potential Source Area Inventory



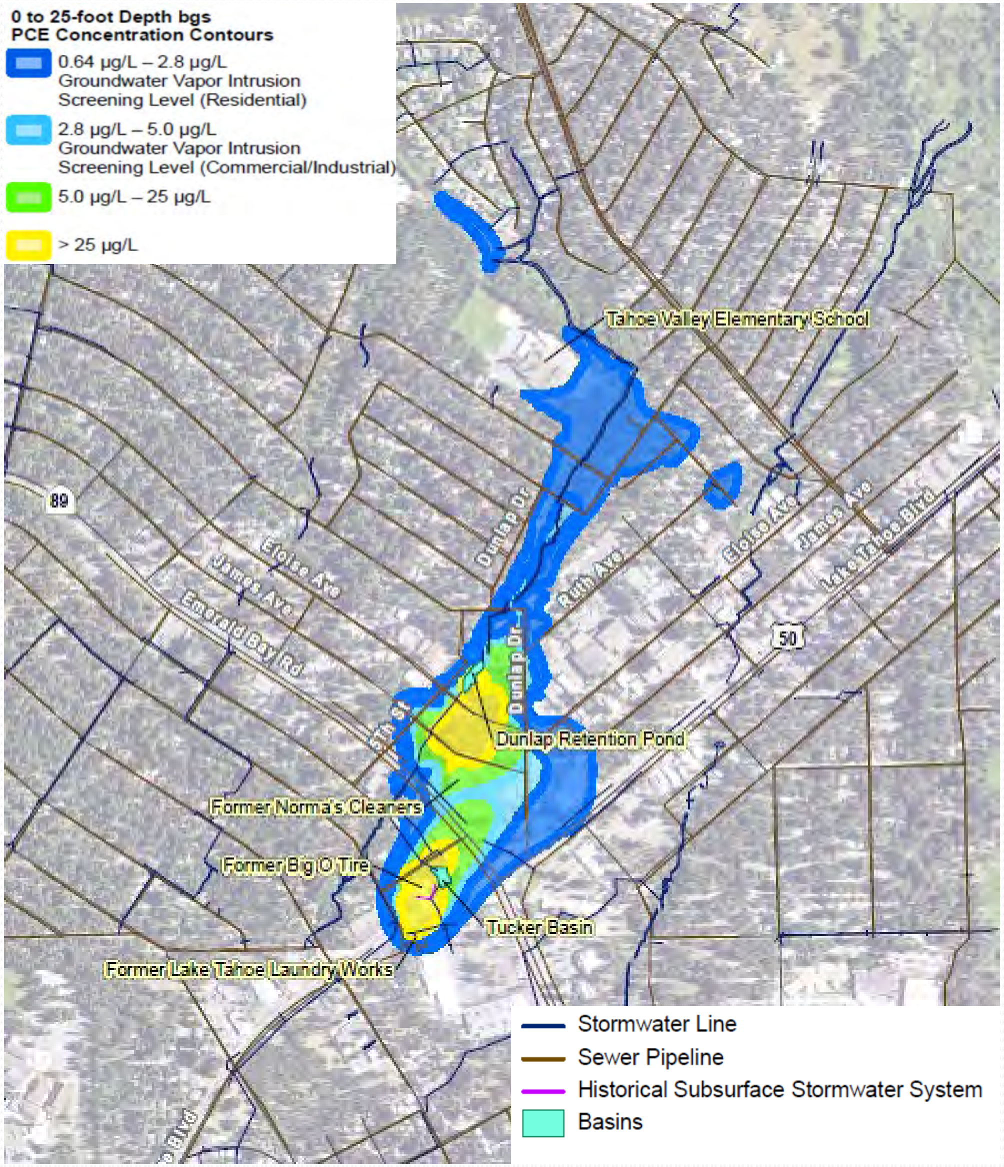
Identified Properties

- Properties with known or suspected use, storage, or disposal of PCE

Priorities

- “High” meet at least one of the following conditions:
  1) Records indicate that PCE or TCE onsite,
  2) DTSC records indicate PCE was used/disposed,
  3) Business at the site is known or suspected to have conducted dry cleaning, or
  4) Business was known to have a parts washer.
- “Medium” conducted business practices that either involved business or maintenance activities that could have used PCE, such as (1) automotive repair, (2) printing shops, or (3) carpet cleaning businesses.
- “Low” priority sites included businesses that did not fit into any of the criteria.

Preferential Pathway Inventory

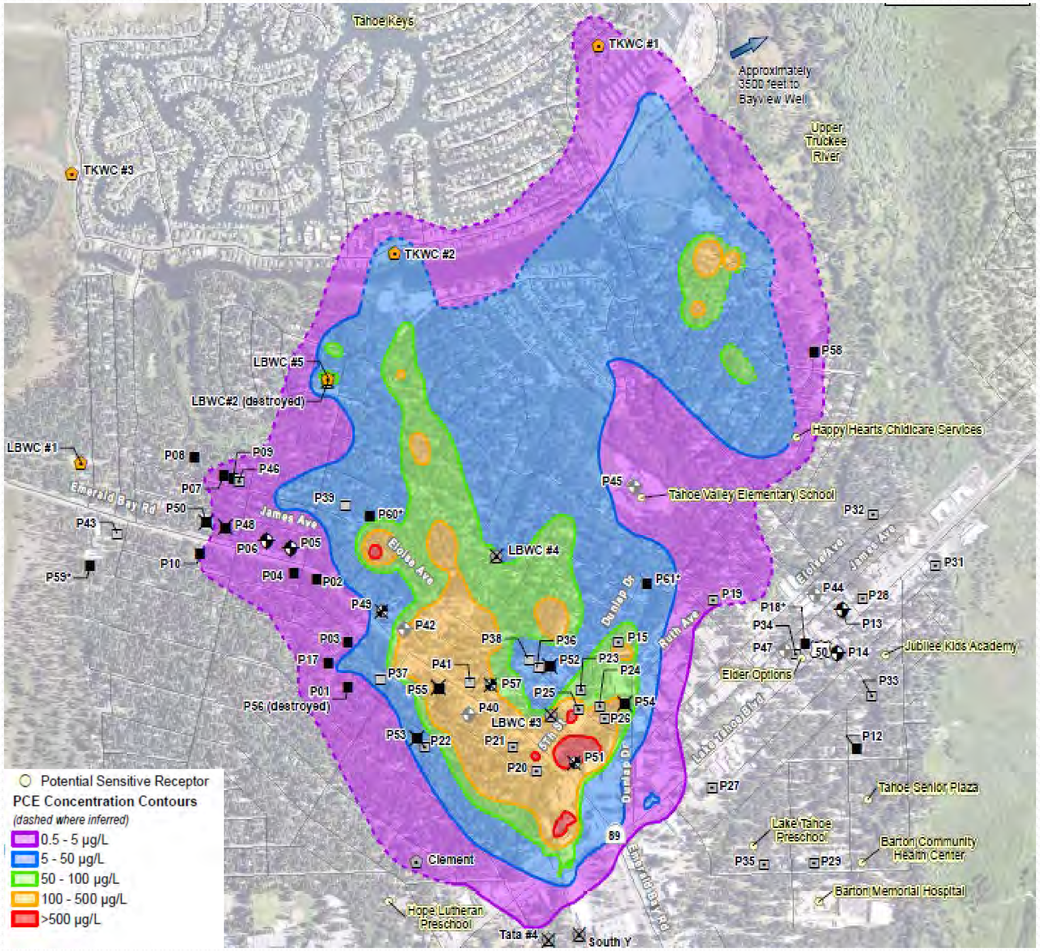


Inventory includes:

- stormwater conveyance systems,
- sewer conveyance systems,
- associated subsurface utility trench backfill materials

- Evaluate the potential role of potential pathways played in the distribution of contamination

Receptor Inventory

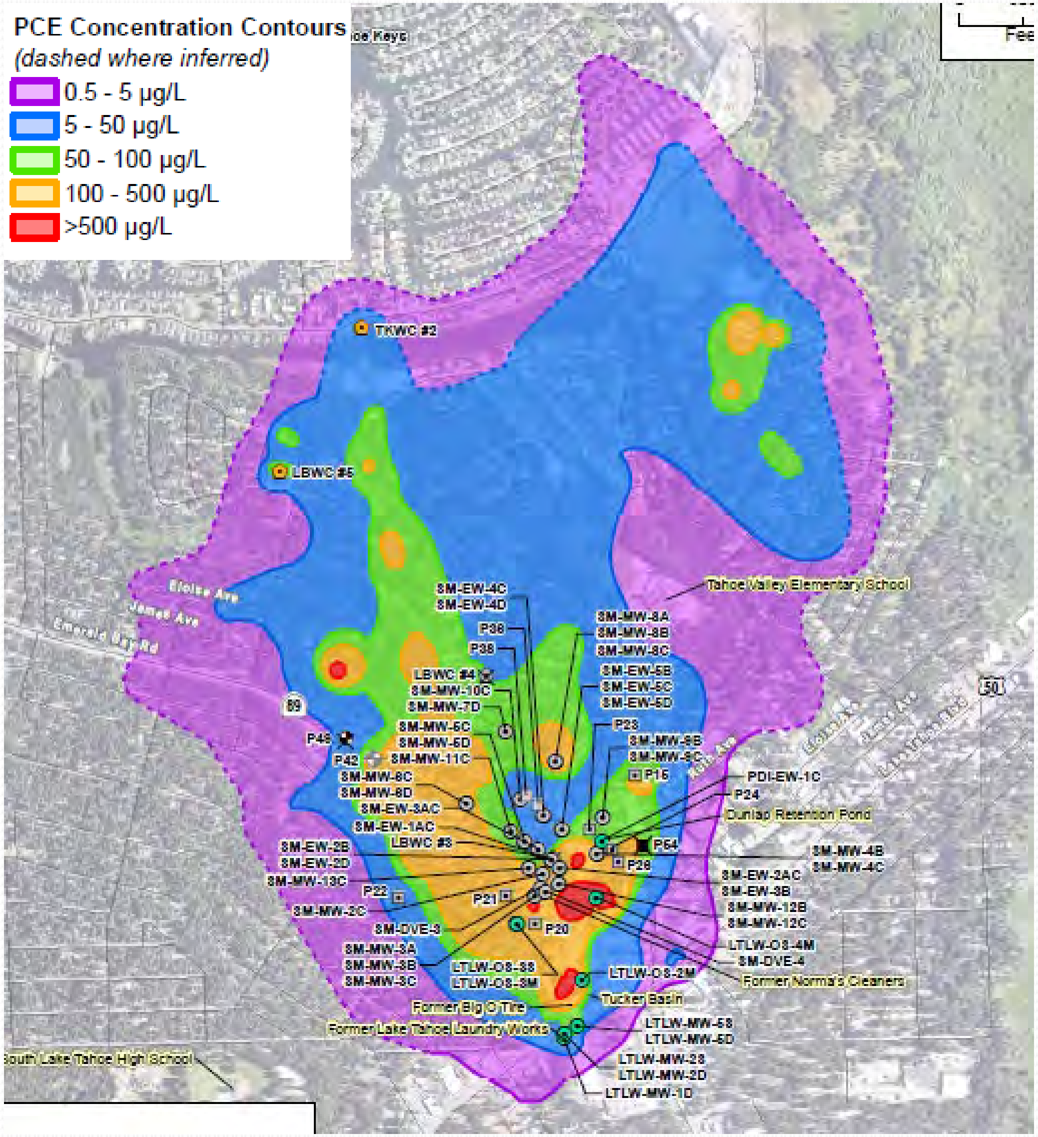


Types of Receptors

- Municipal wells
- Private Supply Wells
- Small Community Wells

Further evaluation and monitoring of wells described later.

Vertical Conduit Inventory



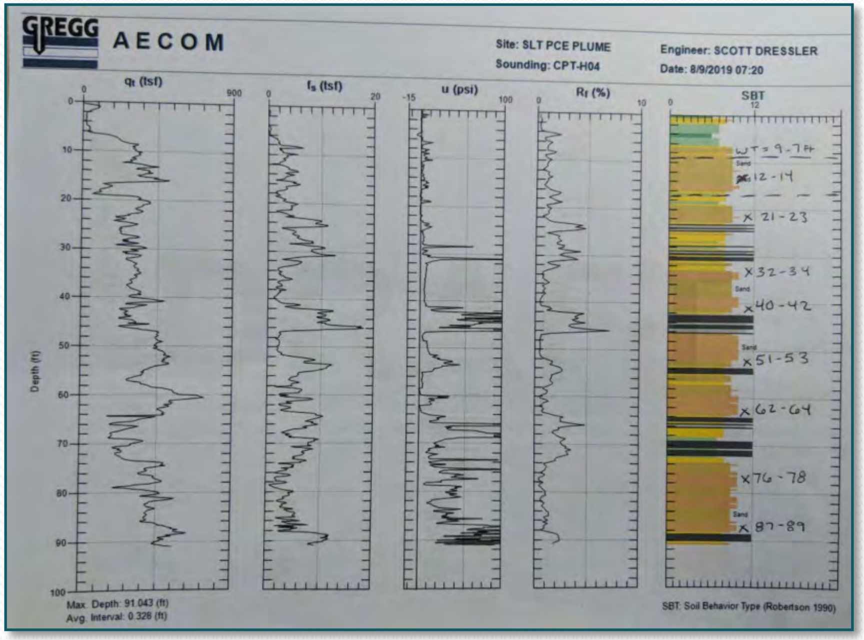
- Wells that act as a conduit for downward migration of PCE
- Further evaluation is currently ongoing

Nature and Extent Conclusions

- Improved understanding of lithology and lateral/vertical extents of Regional PCE Plume
- Plume appears to originate in the vicinity of the former LTLW Site
  - No PCE detected upgradient during previous sampling activities
- EVS model suggests an eastern lobe may be present east of Tahoe Valley Elementary School
- PCE in shallow groundwater appears to coincide with the alignment of portions of stormwater conveyance system
- PCE in shallow groundwater exceeds the residential vapor intrusion ESL (potential threat to human health)

Fate and Transport Conclusions – How PCE has migrated

- Regional and local lithology variability
- Physiochemical and geochemical conditions of the aquifer
- Regional groundwater flow direction towards Lake Tahoe



Fate and Transport Conclusions – (cont'd)

- Expected migration pathways
  - Infiltration of surface run-off containing dissolved PCE through the vadose zone
  - DNAPL migrated directly to the vadose zone and into the saturated zone/water table
  - Vapor-phase contamination/migration through the unsaturated zone via vapor transport

Fate and Transport Conclusions – (cont'd)

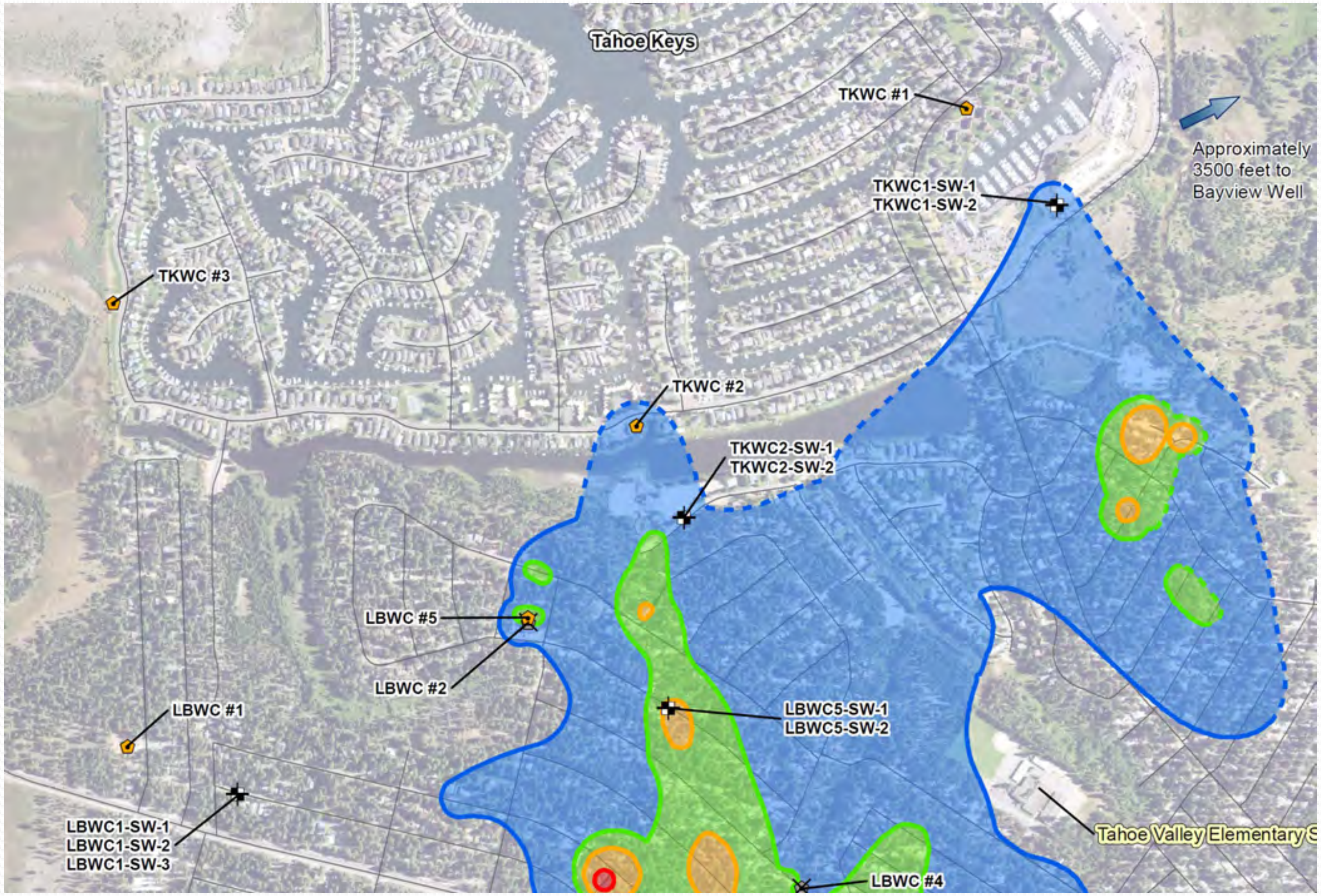
- Along preferential pathways (i.e., stormwater, sanitary sewer, and/or other subsurface utility corridors)
- Natural vertical recharge gradients along with intersecting capture zones from pumping wells (sinks)
- Potential vertical conduits (wells)

Summary of Current and Future SCAP Activities

- **Sentry Well Sampling**
  - 2 sample events completed (Oct 2021 and Apr 2022)
  - 2 more event scheduled (4Q22 and 2Q23)
- **Soil Gas Sampling –** July/August 2022
- **Non-Municipal Well Sampling –** July 2022
- **Vertical Conduit Evaluation and Destruction** - Summer/Fall 2022

Sentry Well Monitoring - Update

- Task Objective: Install and monitor sentry wells upgradient from threatened/impacted receptors



Results from Sentry Well Monitoring

PCE Concentrations for Event 1 (Oct 2021) and Event 2 (Apr 2022)			
Sentry Well ID	Sample Depth (feet bgs)	Sample Date	PCE (mg/L)
LBWC1-SW-1	106.1-108.9	4/26/2022	< 0.30
LBWC1-SW-1	106.1-108.9	10/19/2021	< 0.30
LBWC1-SW-2	141.6-144.4	4/26/2022	< 0.30
LBWC1-SW-2	141.6-144.4	10/19/2021	< 0.30
LBWC1-SW-3	163.6-166.4	4/26/2022	0.41 J
LBWC1-SW-3	163.6-166.4	10/19/2021	< 0.30
LBWC5-SW-1	76.1-78.9	4/27/2022	< 0.30
LBWC5-SW-1	76.1-78.9	10/19/2021	< 0.30
LBWC5-SW-2	148.6-151.4	4/27/2022	**160**
LBWC5-SW-2	148.6-151.4	10/19/2021	**130**
TKWC1-SW-1	115.6-118.4	4/26/2022	**120**
TKWC1-SW-1	115.6-118.4	10/20/2021	**99**
TKWC1-SW-2	157.6-160.4	4/26/2022	< 0.30
TKWC1-SW-2	157.6-160.4	10/20/2021	< 0.30
TKWC2-SW-1	145.6-148.4	4/26/2022	**40**
TKWC2-SW-1	145.6-148.4	10/19/2021	**43 J**
TKWC2-SW-2	175.6-178.4	4/26/2022	**34**
TKWC2-SW-2	175.6-178.4	10/20/2021	**21**

Note: TKWC1-SW-1 PCE detected greater than during the investigation

Calculated Vertical Flow Gradients (4Q21 and 2Q22)			
Location	Sentry Well	Vertical Gradients	
		Oct-21	Apr-22
Venice Drive	TKWC1-SW-1	0.0219	0.0060
	TKWC1-SW-2		
Texas Avenue	TKWC2-SW-1	0.0122	-0.0073
	TKWC2-SW-2		
James Avenue	LBWC1-SW-1	0.0341	0.1116
	LBWC1-SW-2		
	LBWC1-SW-3	0.0208	-0.1146
Anita Drive	LBWC5-SW-1	0.0097	0.0122
	LBWC5-SW-2		

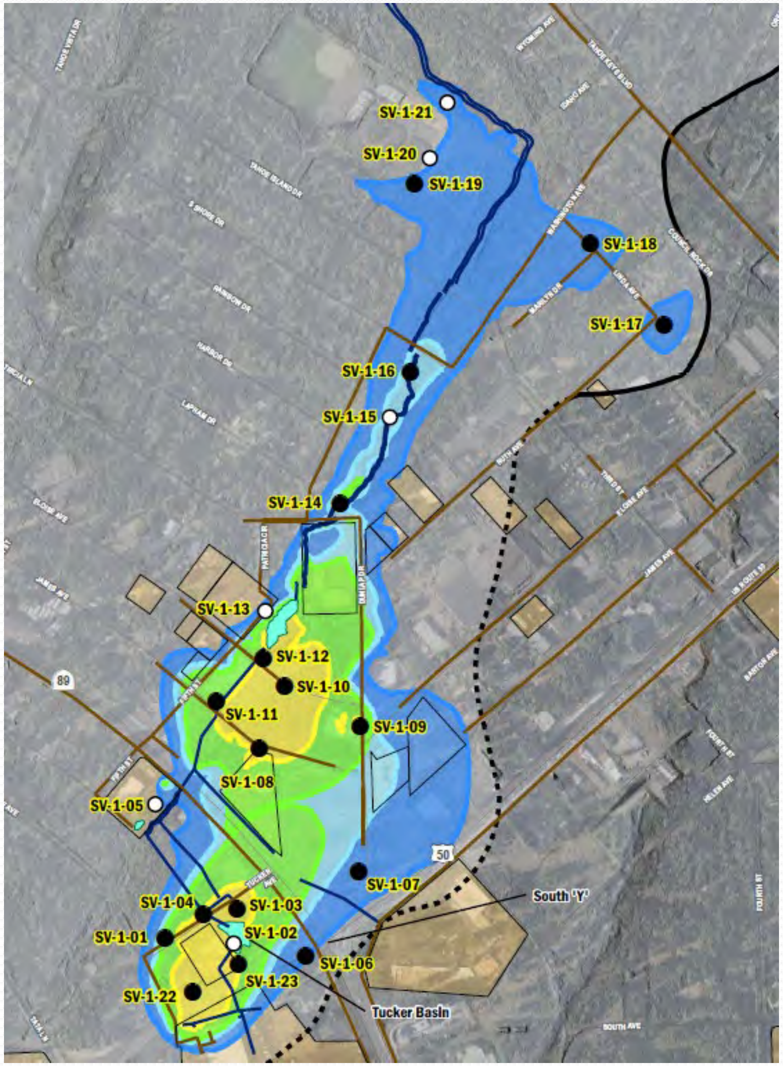
Note: Negative value show upward gradient

Groundwater vertical gradients can vary spatially due to:

- Permeability differences
- Fluctuate due to seasonal conditions
- Highly influenced by pumping wells

Soil Gas Sampling

- Task Objective: Evaluate potential threat to human health from vapor intrusion
- Completed soil gas sampling
  - Installed samplers at 25 locations (7/19 – 7/21)
  - Only shallow soil gas intervals sampled (~ 5 ft bgs)
    - Water encountered at 5 ft bgs
  - Retrieved samplers 8/4 - 8/5
  - Results will be presented in an investigation summary report (end of Sept)



Non-Municipal Water Supply Well Sampling

- Task Objective: Evaluate potential PCE exposure risk from well water consumption
- Completed well sampling
  - Wells that met the following criteria were sampled
    - Active wells
    - Have access from property owners
  - Sampled 7 non-municipal wells in July 2022

Recommended Future Actions

- Conduct investigations of utility-related preferential pathways
- Evaluate vertical gradients (install nested wells)
- Install perimeter wells to monitor plume stability
- Routinely sample active non-municipal supply wells
- Conduct GW investigations to address data gaps
  - Near Tahoe Valley Elementary (limited boring coverage)
  - Eastern lobe's connectivity to the main portion of the plume originating near the South "Y" Area

Recommended Future Actions (cont'd)

- Continue investigations of known and potential PCE source area(s)
- Conduct investigation(s) along the stormwater conveyance system
- Determine if shallow PCE plume poses a threat to human health
- Properly destroy identified potential vertical conduits
- Conduct a groundwater source protection analysis
  - Capture zone modeling or ROI determinations
- Evaluate feasibility of potential alternatives to protect receptors

Questions?

Tahoe Valley South Subbasin Groundwater Management Plan Stakeholder Advisory Group August 24, 2022

Proposed Cleanup and Abatement Orders

Lake Tahoe Laundry Works

Former Norma's Cleaners

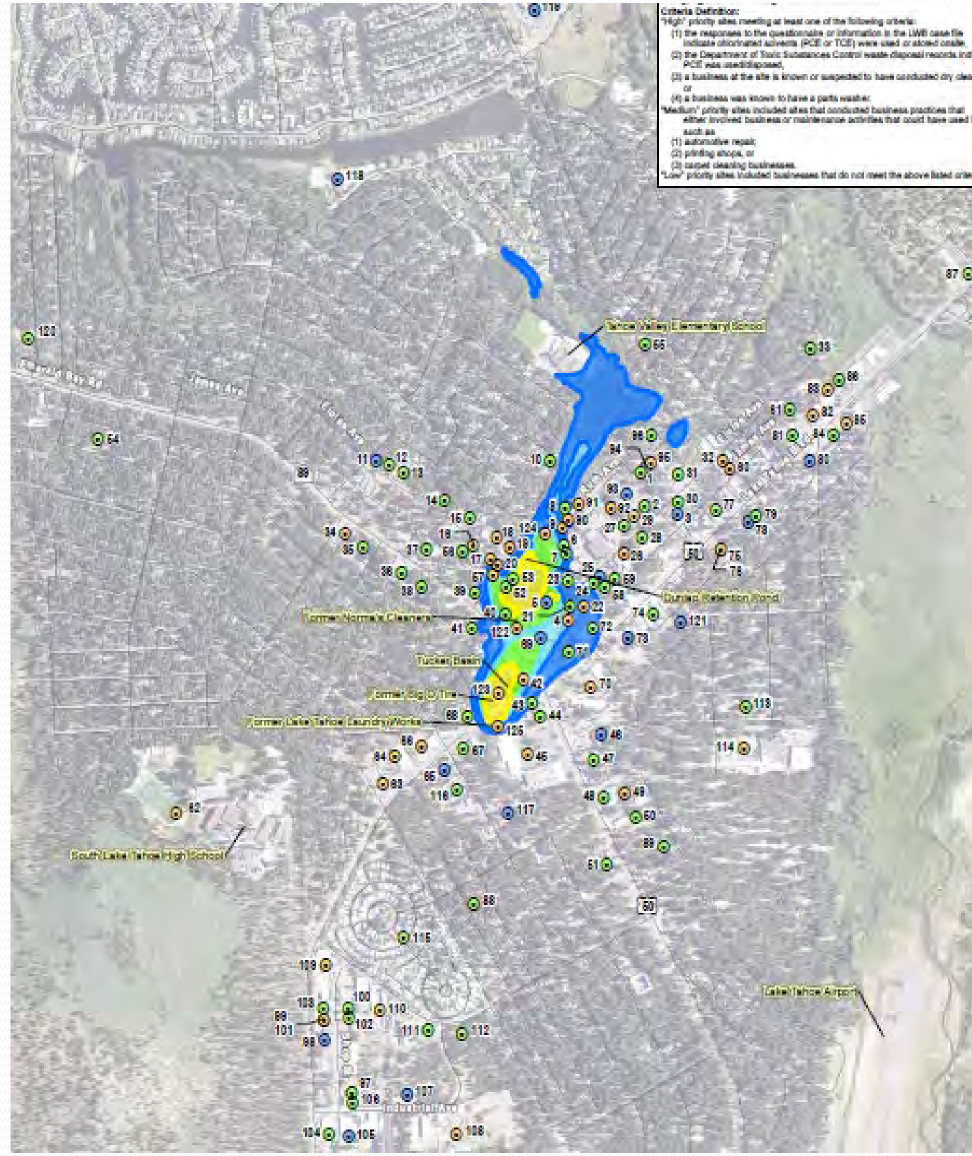
Big O Tires

Brian Grey, PG
Lahontan Water Board

Introduction

Proposed CAOs

- Lake Tahoe Laundry Works
- Former Norma's Cleaners
- Big O Tires



Proposed Cleanup and Abatement Orders– Lake Tahoe Laundry Works

Brief Background

Discharge source: Coin operated dry cleaning unit (1972-1979)

Municipal Supply Well Impacts Discovered: 1989

Case Opened: 2003

Investigations: 2003, 2004, 2005, 2008, 2015, 2017, 2018, 2019

Remediation: Soil vapor extraction/air sparge (2010-present)

Quarterly monitoring and reporting: (2009-present)

Current Enforcement Directive: CAO R6T-2017-0022

Property Ownership: No change

Proposed Cleanup and Abatement Orders–Lake Tahoe Laundry Works

Slice of Enforcement History

2014 Municipal Supply Well Impairment: Lukins #2 and #5

2015 Proposed CAO: Included requirements associated with regional PCE plume

- Public comments received: Connection to receptors is uncertain.
- Never issued.

Cleanup and Abatement Order R6T-2017-0022: Required delineation of lateral and vertical extent of contamination originating from the Site (i.e., evaluate potential contribution to regional PCE plume) and cleanup and abate of its effects.

Proposed Cleanup and Abatement Orders – Lake Tahoe Laundry Works

CAO R6T-2017-0022 Petitions

State Water Board

State Water Board did not hear petitions; dismissed

EL Dorado County Superior Court

El Dorado County Superior Court 2020 rulings:

Fox (June 2020): Petition granted. Vacated 2017 CAO as it relates to Fox and remanded it to Lahontan Water Board to apply the law provided by United Artists vs. Regional WQCB (2019)

Seven Springs (November 2020): Petition granted in part and denied in part. The Lahontan Water Board must set forth findings to bridge the analytical gap between the raw evidence and ultimate decision that the burden including costs, bear a reasonable relationship to the need for the reports. All other parts of the petition were denied.

Proposed Cleanup and Abatement Orders – Lake Tahoe Laundry Works

2022 Proposed CAO

- Considers data collected since 2017 CAO
  - Discharger
  - SCAP Investigation
- Requires delineation and cleanup of regional PCE plume
- Includes provisions for replacement water
- Addresses El Dorado County Superior Court rulings
  - Applies law provided in United Artist decision
  - Contains findings to support the Water Code section 13267 cost burden analysis

Proposed Cleanup and Abatement Orders – Big O Tires

Brief Background

Discharge source: Automotive Repair (1975-2006)

Municipal Supply Well Impacts Discovered: 1989

Case Opened: 2001

Investigations: 2001, 2006, 2020

Remediation: None

Quarterly monitoring and reporting: None

Current Enforcement Directive: Water Code Section 13267 letter (May 2019)

Property Ownership: No change

Proposed Cleanup and Abatement Orders – Big O Tires

2022 Proposed CAO Contents

- Like May 2019 Water Code 13267 directive
- Considers data collected since 2019
  - Discharger
  - SCAP Investigation
- Requires delineation and cleanup of known unauthorized releases originating from property
- SCAP Application

Proposed Cleanup and Abatement Orders – Former Norma's Cleaners

Brief Background

Discharge source: Coin operated dry cleaning unit (1969-1977)

Municipal Supply Well Impacts Discovered: 1989

Case Opened: 2001; Closed 2009; Re-opened 2019

Investigations: 2001, 2003, 2007, 2020

Remediation: Excavation (2008)

Quarterly Monitoring and Reporting: None

Current Enforcement Directive: Water Code Section 13267 letter (May 2019)

Property Ownership: 2014 (new)

Proposed Cleanup and Abatement Orders – Former Norma's Cleaners

2022 Proposed CAO Contents

- Like May 2019 Water Code 13267 directive
- Considers data collected since 2019
  - Discharger
  - SCAP Investigation
- Requires delineation and cleanup of known unauthorized releases originating from property
- SCAP Application

What's Next?

Public Comment Review and Response

- Comment Period Extended to September 19
- Review and Respond to Comments Received:
  - Seven Springs
  - Fox Capital
  - South Tahoe Public Utility District
  - Lukin Brothers Water Company
  - Tahoe Keys Water Company
  - Other interested parties
- Modify CAO(s) as needed
- Provide Opportunity for Additional Public Comment (if necessary)

Questions?

SGM Grant Program

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
2022-1	1	Expand TVS Subbasin Monitoring Network	Monitor groundwater levels for a five-year period in selected sentinel wells north of the South Y within the South Lake Tahoe subarea and in selected monitoring wells associated with the Meyers Landfill within the Meyers subarea.	Two (2) areas of the TVS Subbasin have been identified as needing additional groundwater monitoring. Monitoring north of the South Y would provide data on vertical gradients and localized drawdown effects. Monitoring within the Meyers subarea would improve regional water level and groundwater flow definition; and help identify potential groundwater level changes due to climate change.	Groundwater Levels	DRI, 2018	Data Gap	
2022-2	2	Targeted Groundwater Quality Monitoring	Identify existing wells that could be used for limited monitoring of	The South Y PCE contaminant plume impairs groundwater and threatens drinking	Water Quality	Kennedy Jenks, 2019; DRI, 2019; Rybarski et al, 2022	Data Gap	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
			groundwater quality for specific contaminants of concern.	water wells within the TVS Subbasin. New sentry wells were installed in 2021 to provide water purveyors advanced warning of potential PCE migration upgradient from water supply wells. Funding for monitoring of these wells will end in 2023 (?). Targeted Groundwater Quality Monitoring would be used to extended monitoring in selected sentry wells. Many active community water supply wells within the TVS Subbasin are located near dry wells and detention basins used to infiltrate				

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				stormwater. Dry wells and detention basins are susceptible to contamination from illicit discharges or dissolved contaminates in stormwater. Targeted Groundwater Quality Monitoring could also be used to assess the local occurrence of PFAS in stormwater.				
2022-3	2	TVS Subbasin WQ Database	Develop and maintain a comprehensive surface water and groundwater quality database for the TVS Subbasin.	Groundwater quality is evaluated based on available data. Land and water management agencies within the TVS Subbasin collect water quality data which is not regularly reported. A dedicated	Water Quality	Rybarski et al, 2022	Annual Reporting	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				database used to manage this data would improve future evaluation of groundwater conditions, data sharing and collaboration on water quality issues within the subbasin.				
2022-4	3	GSA Webpage Development	Use information from the Alternative Plan to improve public outreach through the District and EDWA websites.	Development of the first five-year update of the Alternative Plan has produced a plethora of new local groundwater information. Review and update of existing webpages would allow for improved understanding and engagement of well owners through dissemination of this information related to groundwater		Rybarski et al, 2022	Engagement and Outreach	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				management, private well ownership, contaminated groundwater, wellhead protection and local changes in groundwater levels.				
2022-5	3	Survey of Private Well Owners – Phase III	Complete the survey of private well owners in a safe, efficient, and cost-effective manner.	The District received 509 responses from private well owners during surveys of private well owners in 2017 (PWOS-I) and 2020 (PWOS-II). These surveys were successful in initiating contact with private well owners; notifying private well owners of the GSA; providing information to confirm the locations and use of private wells;			Engagement and Outreach	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				and inform the GSA on private well owner groundwater quality and groundwater supply concerns. Approximately 100 well owners remain to be contacted. A Phase III survey would endeavor to complete these surveys.				
2022-6	5	GDE/SEZ Monitoring	Develop and implement plans to monitor the potential impact of groundwater withdrawals on interconnected surface waters (ISWs).	Addresses the need for shallow groundwater monitoring within or near GDEs. Establishes groundwater level record to define a minimum threshold for GDEs in potentially vulnerable SEZs. Provides data to consider the need for establishment of a provisional	GDEs; Groundwater Levels	Rybarski et al, 2022	Data Gap	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				groundwater management area. Allows for evaluating measurable benefit to groundwater recharge from stream restoration EIPs.				
2202-7	2	Update South Y PCE Model	Incorporate new lithologic and groundwater quality data to update the South Y PCE Model	The South Y PCE Model is a three-dimensional fate and transport model used to evaluate various remedial alternatives for management of the South Y Regional PCE Contaminant Plume. The South Y PCE Model was developed in 2018 prior to the Regional Plume Characterization Investigation of the South Y Plume	Water Quality	DRI, 2019;	Technical assistance; Evaluation of groundwater management needs; groundwater contamination remediation.	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				(RPC). The RPC included the collection of lithologic and groundwater quality data from a total of 57 cone penetrometer test (CPT) and 31 sonic borings. In corporation of these data into the South Y PCE Model would improve the utility of this model as a tool for evaluating remedial alternatives and clean-up of this plume for impacted water purveyors, private well owners and enforcement agencies.				
2022-8	8	South Tahoe Groundwater Model (STGM)	Support inter-agency efforts to develop a revised GSFLOW model for the Lake	The STGM is the primary tool used to simulate future groundwater conditions in the	Groundwater Levels; Groundwater Storage;	Rybarski et al, 2022	Data Gap	

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
			Tahoe Hydrologic Basin including applying updated climate models to refine recharge estimates for the STGMl.	TVS Subbasin. This model relies on an existing GSFLOW model that uses boundary conditions from climate projections using best available global climate models (CMIP5). Since inception of the STGM, updated climate models (CMIP6) and emission scenarios have been developed which are being used to update climate-change projections for the Lake Tahoe Hydrologic Basin. A revised GSFLOW model of the Lake Tahoe Hydrologic basin would allow for the reassessment of groundwater	Interconnected Surface Waters			

ID	BMO	Project/Management Action (PMA)	Description	Benefit(s)	Indicator(s)	Reference(s)	SGM Project Type	RANK
				recharge based on the latest climate science using improved climate scenarios.				