Methodology 1. User-oriented drought indicators in California

1. Introduction

The goal of this document is to present the methodology to define user-oriented drought indicators in California's highly-managed water system, focusing on four sectors: cities, small communities, irrigated agriculture and freshwater ecosystems.

Different water users have different water sources, management tools, and needs. Cities and irrigation districts in California have different sources of water such as deliveries from storage, groundwater or imports from other regions, while most small communities are solely reliant on groundwater, and freshwater ecosystems depend on water flowing through rivers and creeks—although some also get deliveries from storage and even imports (Figure 1).

Figure 1. Water sources for different sectors in California

Source: Developed by the authors

The first goal is to define indicators that can provide information about drought conditions for individual sources of water (or users' needs). To do that, in the next section we define the indicators, …

2. Defining parsimonious drought indicators for California water users

We define six indicators oriented for different sources of water—or users' needs—at the hydrologic region scale. These indicators and its main functions are:

- Precipitation deficits: can provide information for users reliant directly on precipitation, like rainfed agriculture.
- Evapotranspiration anomalies: its aim is to show changes in crop water demands in farms and outdoor demands in cities, given changes in temperatures and other factors that affect evapotranspiration.

- Surface water availability: developed to offer indication of water available in storage (including snowpack) for deliveries from local sources.
- Groundwater status: obtained using groundwater elevations to provide information about groundwater pumping, but also about potential impacts of groundwater elevations on wells.
- Streamflow conditions: aimed to link river and stream conditions with potential ecosystem stress
- Imports: as many regions in California depend on surface water imports, this indicator relates surface deliveries in the *importing* basin with the surface water availability of the *exporting* basin

In the following section we define the methods and link to the functions and data used to obtain the indicators for California's hydrologic regions.

3. Obtaining drought indicators for California's hydrologic regions

We obtain monthly indicators for the six indicators defined above for all hydrologic regions.[1] The indicators are based on monthly percentiles—to avoid seasonality—and are calculated using the 30-year period from 1991 to 2020 as a reference period. For the percentiles, we identify 0 as the driest time, and 1 with the wettest, using five categories: *not in drought* (indicator above the 50th percentile), *abnormally dry* (between the 30th and 50th percentile), *moderate drought* (between 20th and 30th percentile), *severe drought* (between 10th and 20th percentile), and *extreme drought* (indicator below the 10th percentile).

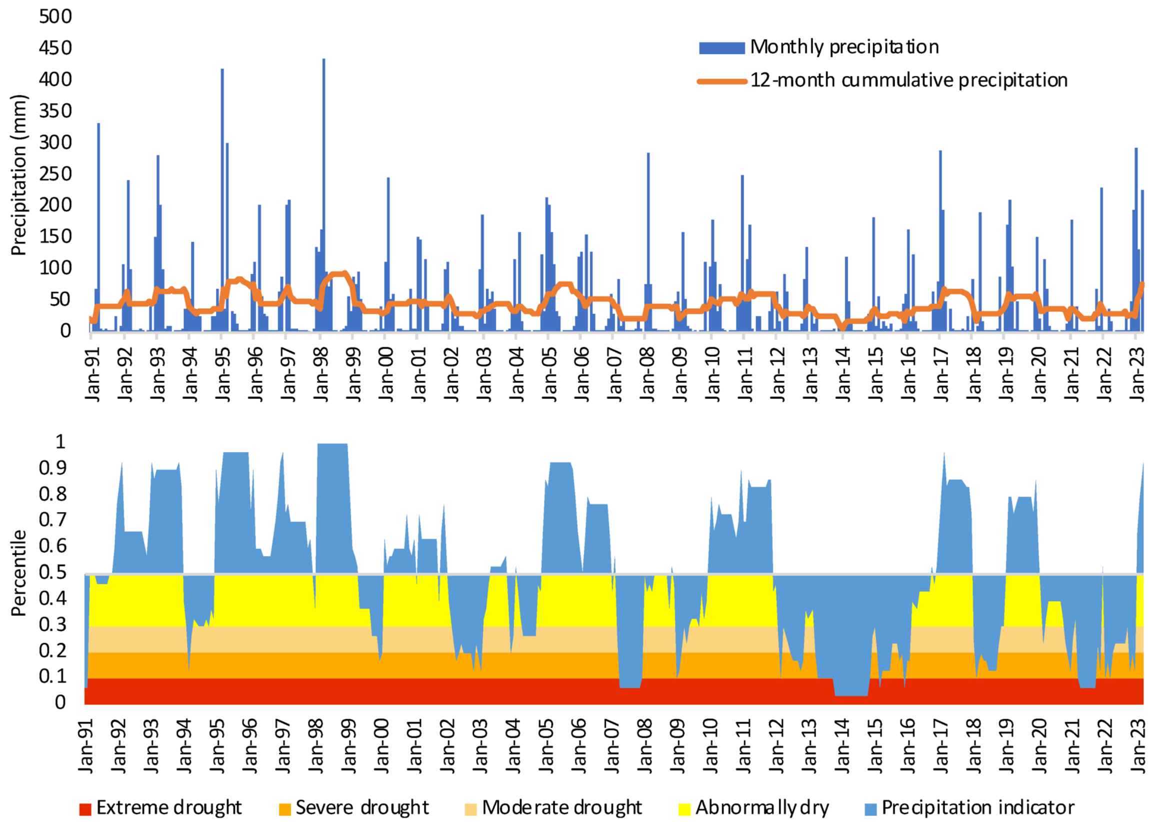
3.1 Precipitation deficits

To obtain the precipitation indicator, we use the following steps:

1. Download daily precipitation data: Daily precipitation data is downloaded from gridMET using the code "download_pr_pet_gridded_data.py" (folder Functions/downloading), and stored as netCDF files in the folder Data/Downloaded/pr.
2. Monthly data at the regional scale: We obtain the monthly mean of the precipitation across each hydrologic region by clipping first the US daily precipitation data with the hydrologic region shapefiles. Then, we obtain the average precipitation for the region, and finally we add up the daily data to obtain the monthly regional average. The code 'pr_pet_obtain_regional_summaries.py" (folder Functions/processing) performs the analyses for all hydrologic regions.
3. Obtain regional indicators (percentiles): Given the high variability of California's monthly and annual precipitation, we decide to obtain the 12-month percentile as an indicator, representing how the past 12 months deviate from the long-term mean (in our case, from the 1991-2020 baseline). Therefore, from the monthly data aggregated at the regional scale, for each month we obtain the precipitation over the latest 12-month period, and finally we obtain the percentile with respect the baseline. The code 'pr_and_et_indicators.py' (folder Functions/processing) performs the calculations for all hydrologic regions.

[1] Except for imports in those regions that don't have significant water imports

Figure 2: Precipitation and precipitation indicator in the Central Coast of California



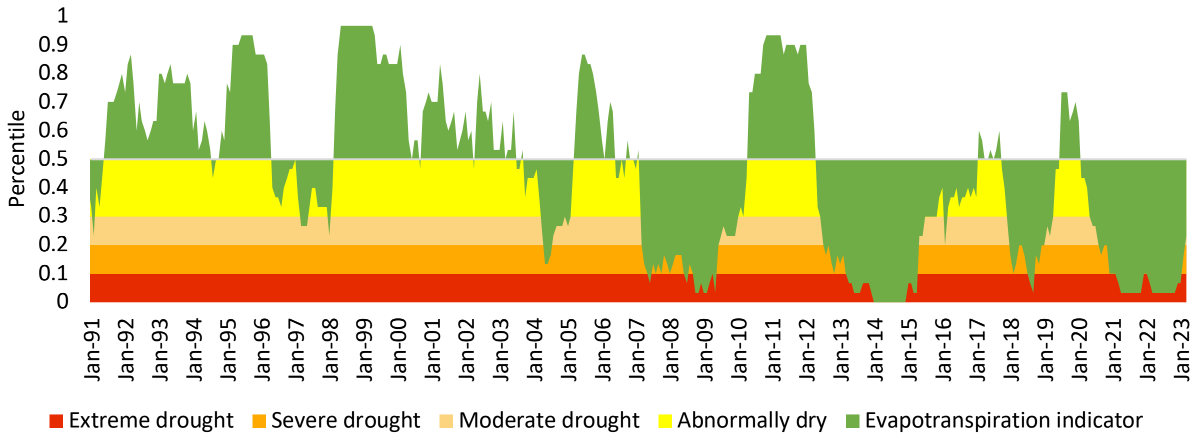
Source: *Developed by the authors using precipitation data from gridMET*
Notes: *The precipitation indicator is obtained as the monthly percentile of the 12-month cumulative precipitation*

3.2 Evapotranspiration anomalies

The process to obtain the evapotranspiration indicator is analogous to the precipitation indicator. First, we download potential evapotranspiration (pet) data from gridMET, then we obtain a dataset with monthly regional means, and finally we calculate the indicator as the percentile of the 12-month cumulative evapotranspiration with respect to the 1991-2020 period.

The code and data are shared with the precipitation indicator, so they are the same indicated in the previous section.

Figure 3: Evapotranspiration indicator in the Central Coast of California



Source: *Developed by the authors using precipitation data from gridMET*
Notes: *The evapotranspiration indicator is obtained as the monthly percentile of the 12-month cumulative precipitation*

3.3 Surface water availability

To characterize water available for surface deliveries, we define an indicator that is a composite of water stored in reservoirs plus water stored in the snowpack. In the following subsections we first show how we obtained data for surface reservoirs, then how we obtained the data for snow, and finally how we obtain the surface water availability indicator combining both sources of data.

3.3.1 Obtaining reservoir data

We download reservoir storage data from the California Data Exchange Center (CDEC) for all reservoirs in California for the 1991-2023 period. We used the code "download_cdec_reservoir.py" (folder Functions/downloading), and stored as a csv file in the folder Data/Downloaded/cdec/reservoir. We added some additional information like the hydrologic region and the total capacity of the reservoirs.

3.3.2 Obtaining snow data

We download snow water equivalent data (SWE) from CDEC for individual stations across California for the 1991-2023 period. Once we have all the data for the individual stations, we obtain the average data for all Sierra Nevada basins, and convert the daily SWE into water volume based on the mean April 1st volume, using data published in (Margulis et al., 2016). Finally, we convert basin data into hydrologic region data.

The code "download_cdec_snow.py" (folder Functions/downloading) downloads the data and performs the analysis and stores two files—one for the individual station data and one for the regional analysis—in the folder Data/Downloaded/cdec/snow.

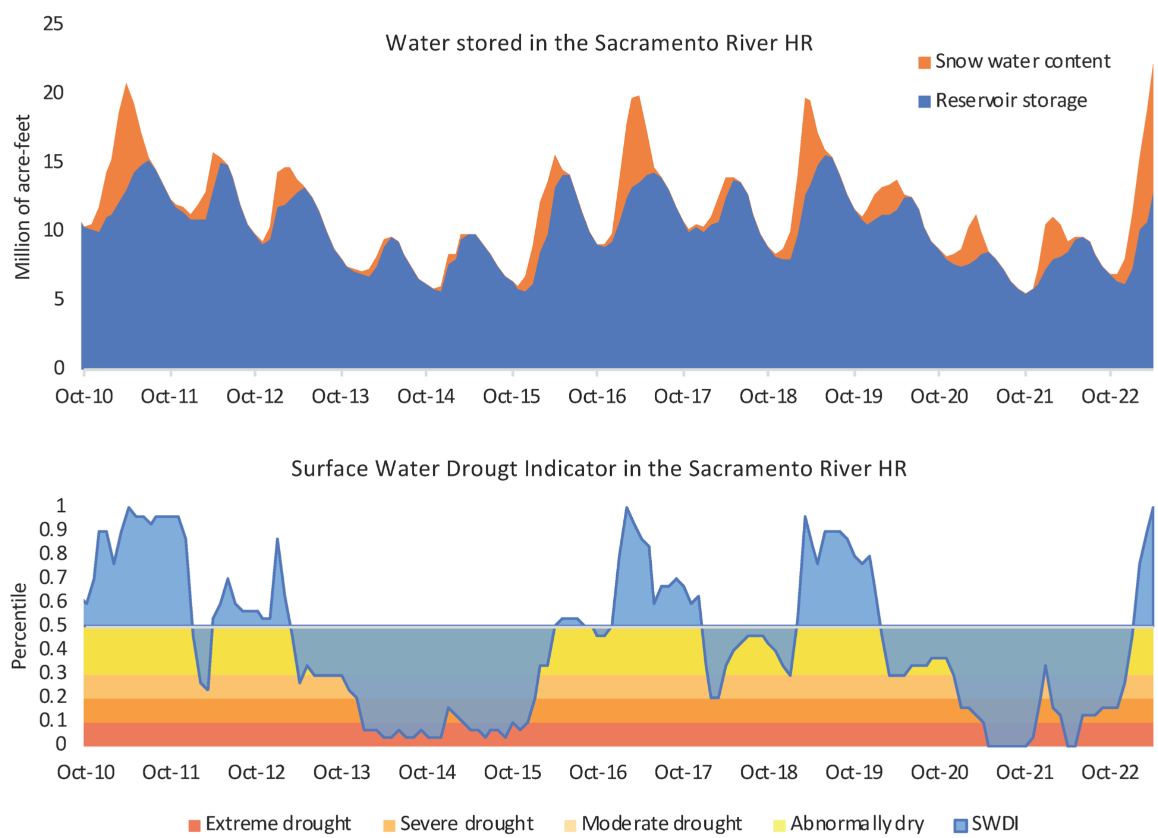
3.3.3 Obtaining the surface water drought indicator (SWDI)

First, we convert the individual reservoir data into aggregated hydrologic level storage. For that we use an auxiliary function ("percentile_average_function" in "func_for_tperiod.py") that aggregates the data at the hydrologic region, correcting for when there is missing data, and also is able to obtain the monthly percentile or the reservoir storage (we call it reservoir drought indicator).

Then, after adding the water stored in the snowpack from the snow data, we sum up both volumes—water stored in reservoirs and water stored in snowpack—and obtain the monthly percentile with respect to the 1991-2020 period. This value is the surface water drought indicator.

The code "surface_water_drought_indicator.py" (folder Functions/processing) performs the analysis and stores the resulting indicator in Data/Processed/surface_water_drought_indicator.

Figure 4: Water stored in reservoirs and snowpack and surface water drought indicator (SWDI) in California's Sacramento River hydrologic region.



Source: *Developed by the authors using data from CDEC*
Notes: *The SWDI is obtained as the monthly percentile of the sum of water stored in reservoirs and snowpack with respect to the 1991-2020 period*

3.4 Groundwater status

We download data from [DWR Periodic Groundwater Levels dataset](), which contains seasonal and long-term groundwater measurements. In most cases, this dataset includes two measurements per year, and it is not consistent over time or space—having many missing data. We store this dataset in the folder Data/Downloaded/groundwater.

Trying to add some consistency to the data, we first clean up the data for each well by only using two measurements per year (spring and fall), filtering out the data with groundwater depths over 300 ft (potentially in confined aquifers), and also removing data that has changes in groundwater elevations for continuous periods over 30 ft—which might be potentially measurement errors. With the remaining data, we perform an analysis of groundwater elevations and the annual change in groundwater elevation for each well—comparing the elevation of fall or spring, with the level for the same season in the previous year. We do this to avoid any seasonality biases, as in California usually in the spring groundwater levels are at the annual maximum—after the wet fall and winter, and before the irrigation season starts—and conversely, groundwater levels are at the annual minimum in the fall.

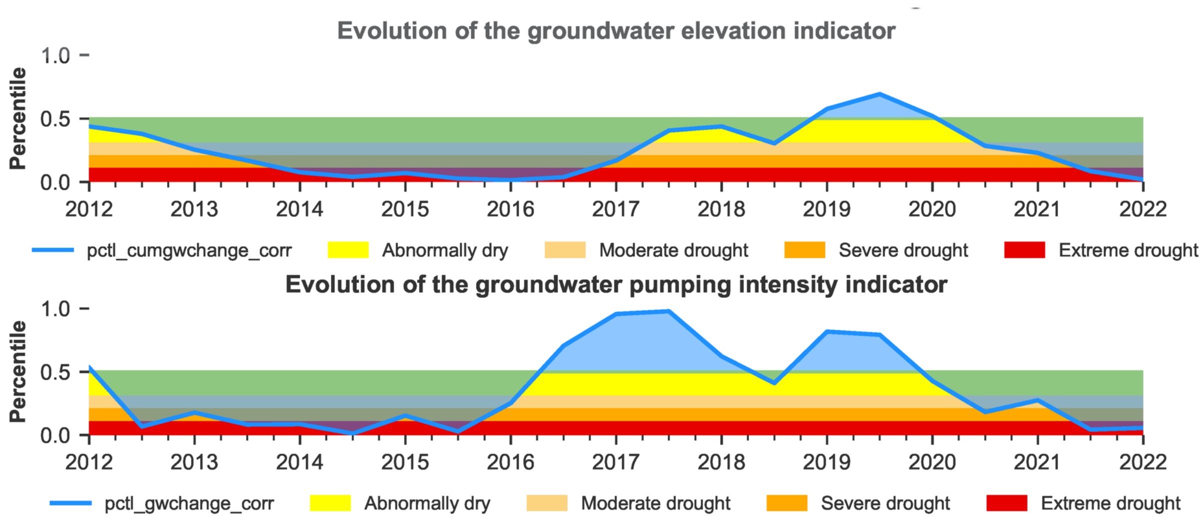
When the data is cleaned, we obtain two different indicators for each well:

- Groundwater elevation indicator: this indicator obtains the percentile of the overall groundwater elevation over the period of analysis. This approach is similar to obtaining the standardized groundwater index (Bloomfield & Marchant, 2013), which gives indicator of the current groundwater level with respect to the historical level. Given that many groundwater basins in California have been overdrafted historically, this tends to overestimate drought conditions later in the historical period (and underestimate drought conditions early in the historical period), but it might be a helpful indicator for wells at risk of going dry.
- Groundwater pumping intensity indicator: to avoid the long-term trends in the data, we obtain also an indicator based on the annual changes in groundwater elevation. In this case, the annual change in groundwater level will be more representative of the intensity of groundwater pumping with respect to the historical conditions. Notice that the median of this indicator will provide the median change in groundwater levels, which for overdrafted basins will approximate the *normal* level of overdraft, while the indicator will show for extreme cases the highest and lowest changes in groundwater levels, no matter if these are positive or negative.

Then, to perform a regional analysis, we will obtain basic statistics across all wells for a region (median, 25th and 75th percentiles). These indicators are finally corrected again by obtaining their percentiles, given that the raw statistics would smooth the distribution. Figure 5 shows the results for one hydrologic region.

The code “groundwater_drought.py” (folder Functions/processing) performs the analysis and stores the resulting indicators in Data/Processed/groundwater.

Figure 5: Groundwater indicators for California's San Joaquin River hydrologic region.



Source: *Developed by the authors using from DWR Periodic Groundwater Levels dataset*
Notes: *The charts show the evolution of the regional analysis of the groundwater indicators for the San Joaquin River hydrologic region from March 2012 to March 2022. These indicators are only calculated using data for spring and fall, so the remaining points are interpolated.*

3.5 Streamflow conditions

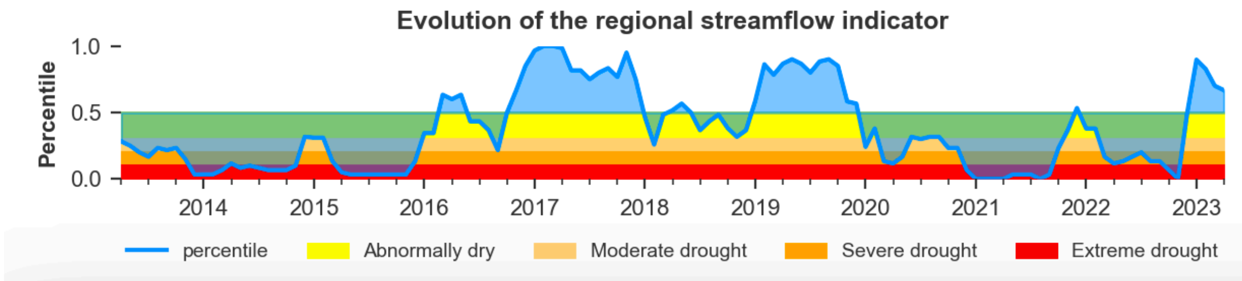
To obtain the streamflow indicator, we first download daily streamflow hydrographs for over 400 gages in California from USGS National Water Information System. We use the code "data_download_usgs.py" (folder Functions/downloading) and store the resulting data as a csv file in the folder Data/Downloaded/usgs.

Then, with the daily data for all the individual gages, we obtain the 3-month average flow (the average over the past 3 months of daily data), and we use these values to perform a monthly percentile analysis to avoid seasonality.

To obtain the regional indicator, we perform an analogous approach than for the groundwater indicators, obtaining first the regional median of the percentiles, and then obtaining the percentile for these values, given that obtaining the median smooths the distribution removing the extreme values. Figure 6 shows an example of the streamflow indicator.

The code "streamflow_indicator.py" (folder Functions/processing) performs the analysis and stores the resulting indicators in Data/Processed/streamflow_indicator.

Figure 6: Streamflow indicator for California's Sacramento River hydrologic region.



Source: *Developed by the authors using from USGS data*
Notes: *The charts show the evolution of the regional analysis of the streamflow indicator for the Sacramento River hydrologic region from April 2013 to April 2023*

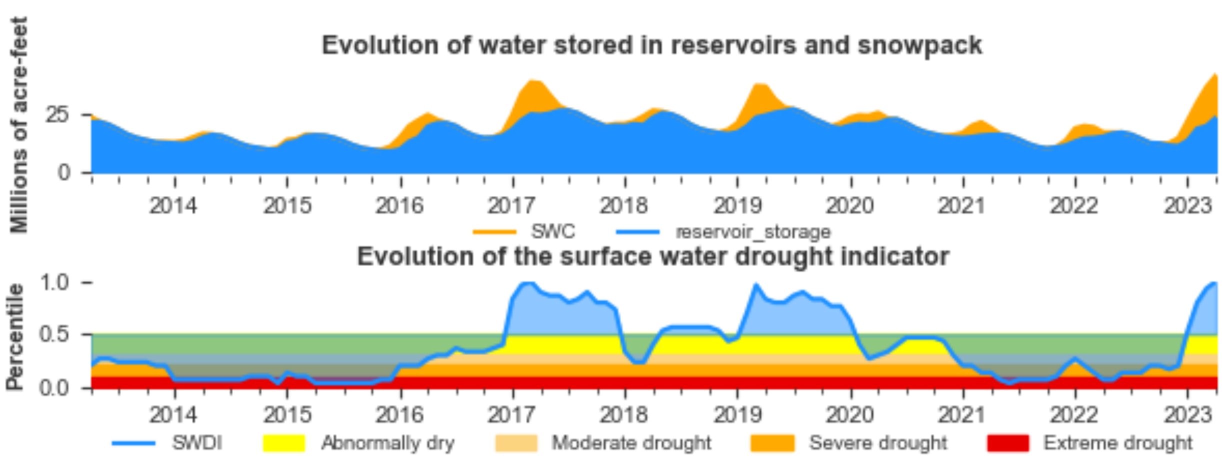
3.6 Imports

For imports we consider imports from the Delta to other regions in California—most importantly the San Joaquin river, the Tulare Basin, and the South Coast, although also the Central Coast.

As imports are made from surface water, the import indicator follows the same methodology that we used for the surface water indicator, but it's based in the combined storage—including reservoir storage and snowpack—of the Sacramento and San Joaquin River hydrologic regions.

The code "imports_indicator.py" (folder Functions/processing) performs the analysis and stores the resulting indicators in Data/Processed/imports/total_storage_percentiles.csv.

Figure 7: Water stored in reservoirs and snowpack and surface water drought indicator (SWDI) in California's Delta exporting basins (include both the Sacramento River and the San Joaquin River hydrologic regions)



Source: *Developed by the authors using data from CDEC*
Notes: *The SWDI is obtained as the monthly percentile of the sum of water stored in reservoirs and snowpack with respect to the 1991-2020 period in the Delta exporting basins (Sacramento River and San Joaquin River hydrologic regions)*

4. Visualizing indicators

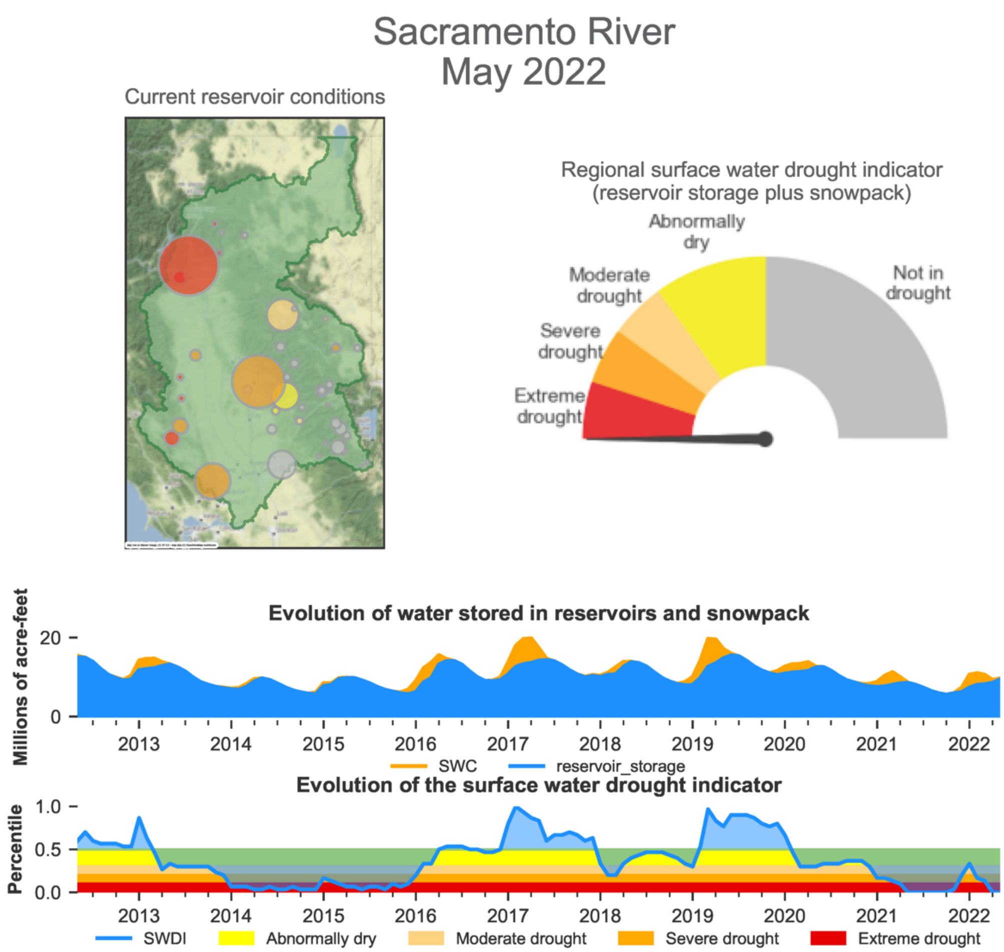
We developed different dashboards to show the indicators at the hydrologic region level using the data obtained in the previous sections. Specifically, we created individual dashboards for the SWDI, groundwater indicators, imports indicator and the streamflow indicator that can be obtained for any date and for any hydrologic region, and then a combined hydrologic region dashboard that includes all six indicators for any date in the database.

4.1 Dashboards for individual indicators

These dashboards (shown in the following figures) present the analysis at the hydrologic region level for the individual indicators and can be obtained for any date in the dataset. They present the conditions of the individual stations and the combined regional drought indicator for the month of analysis, plus the evolution of the previous 10 years of data.

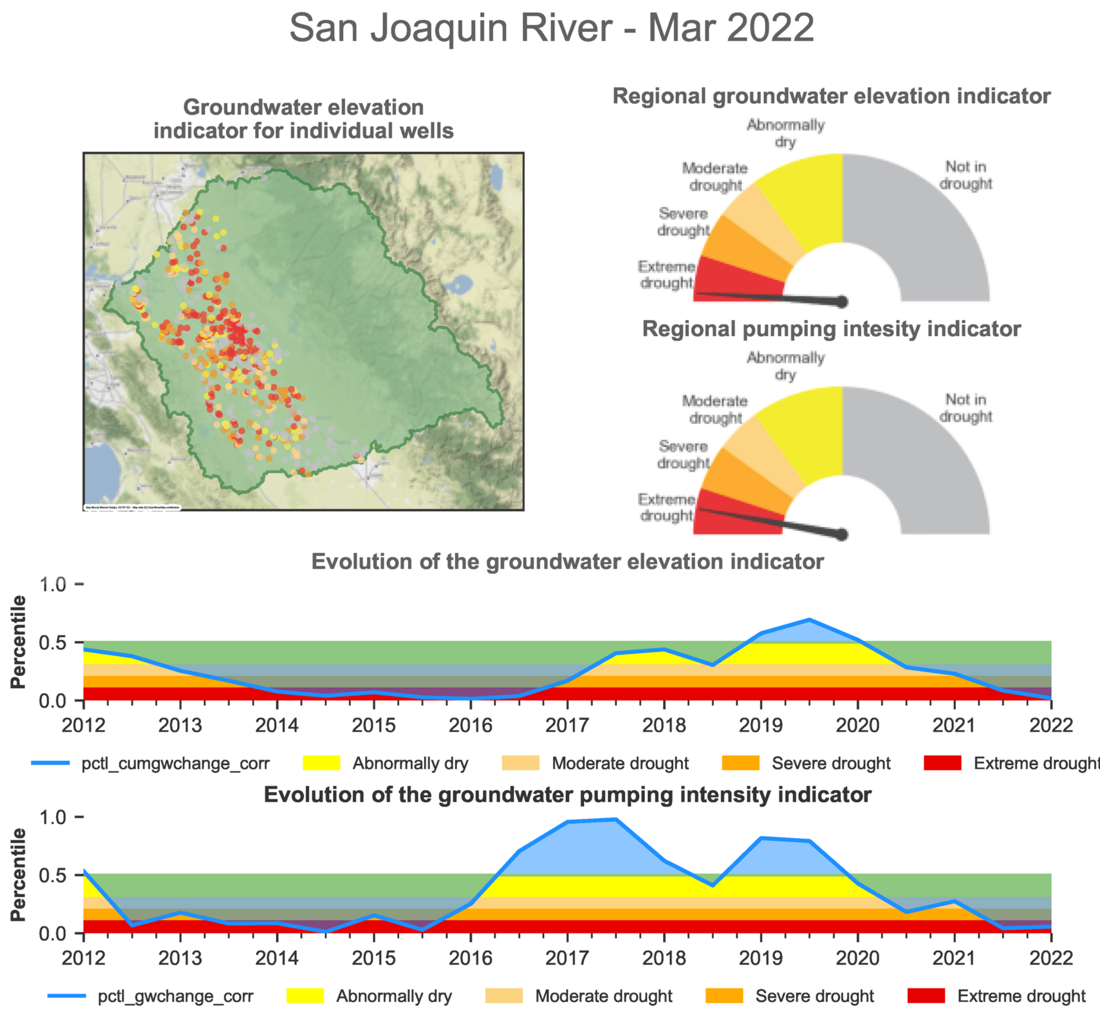
The code “dashboard_sw_gw_imp_strmf_indicators.py” (folder Functions/visualizing) performs the analysis and stores the resulting dashboards in Data/Processed/dashboards

Figure 8: Surface Water Drought Indicator dashboard



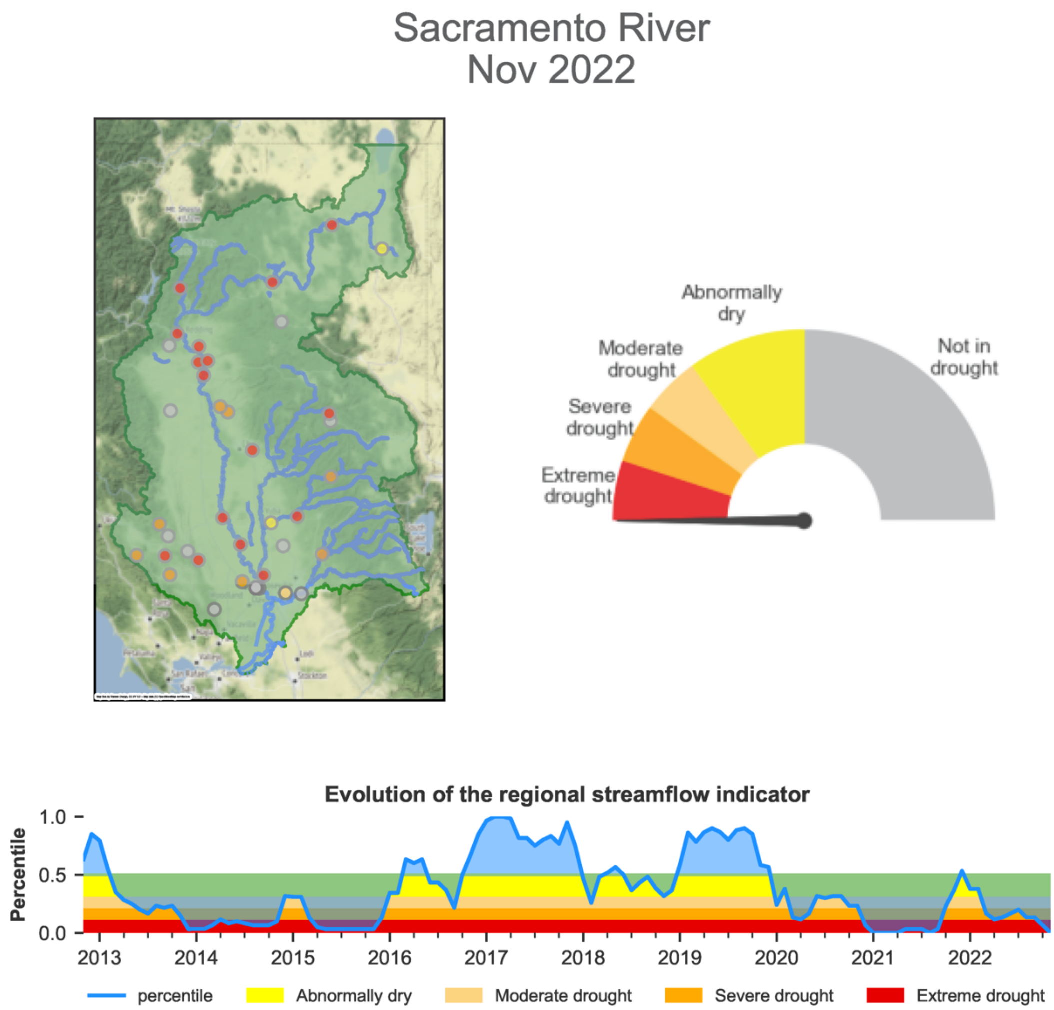
Source: *Developed by the authors*

Figure 9: Groundwater Drought Indicators dashboard



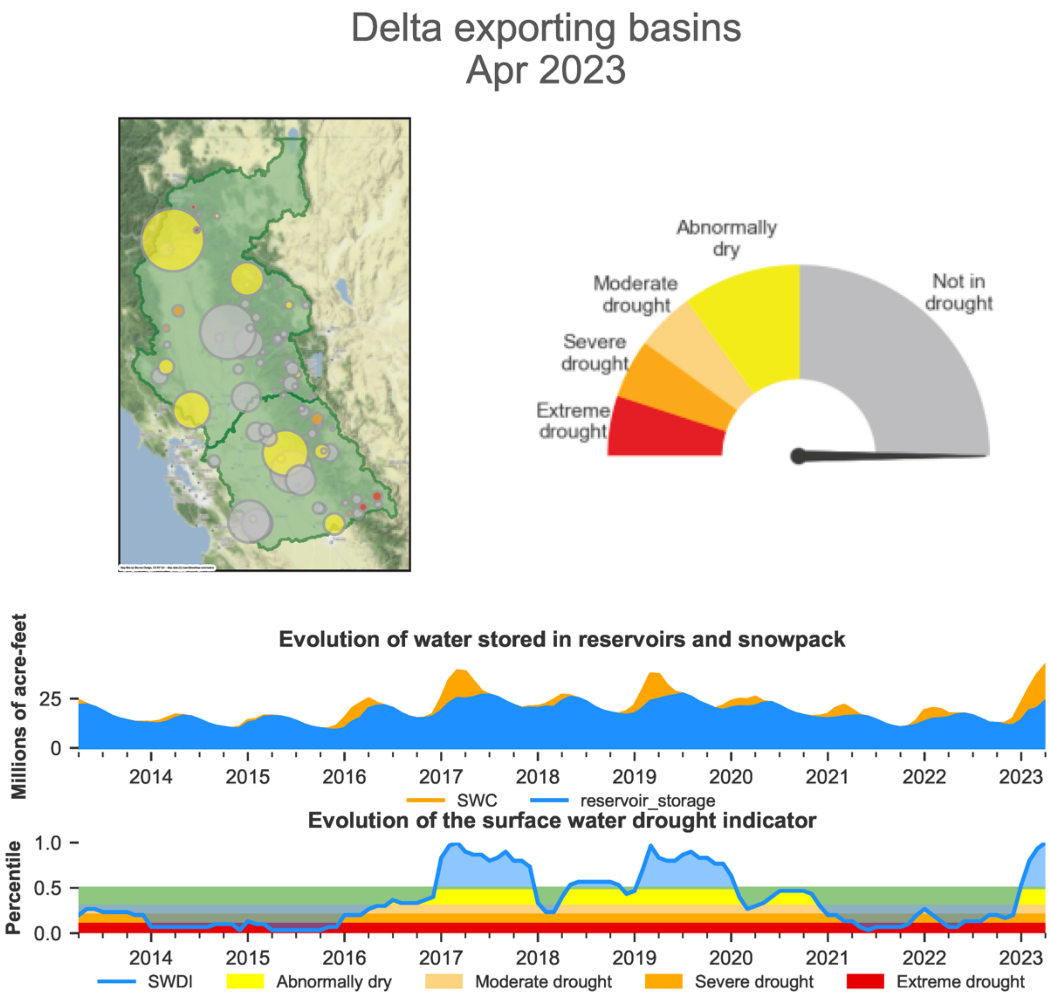
Source: *Developed by the authors*

Figure 10: Streamflow Drought Indicator dashboard



Source: *Developed by the authors*

Figure 11: Imports Drought Indicator dashboard



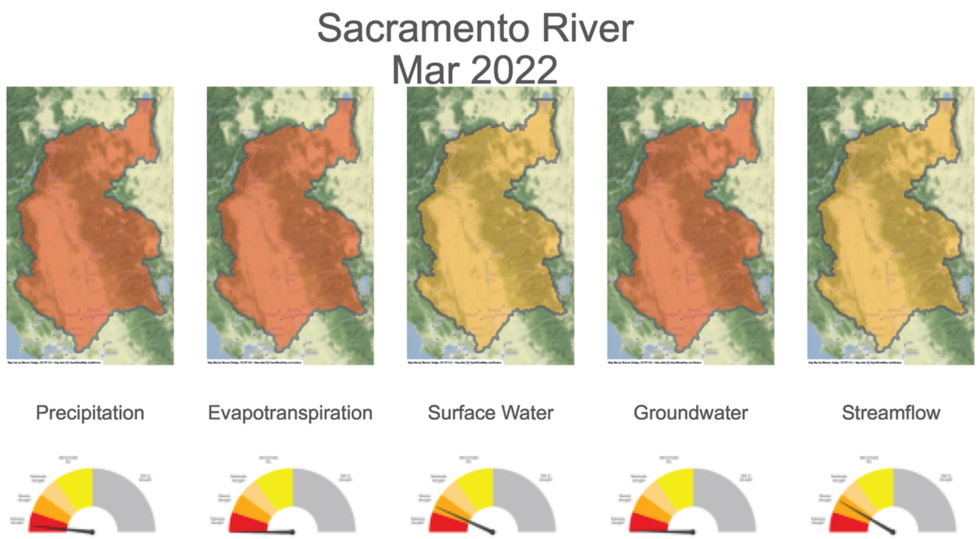
Source: *Developed by the authors*

4.2 Combined drought indicators for an individual hydrologic region

We also developed a code that combines all six indicators for any specific month in the dataset for a specific hydrologic region, so the different drought indicators can be presented together. The code “dashboard_cobined_indicators_hr.py” (folder Functions/visualizing) performs the analysis and stores the resulting dashboards in Data/Processed/dashboards

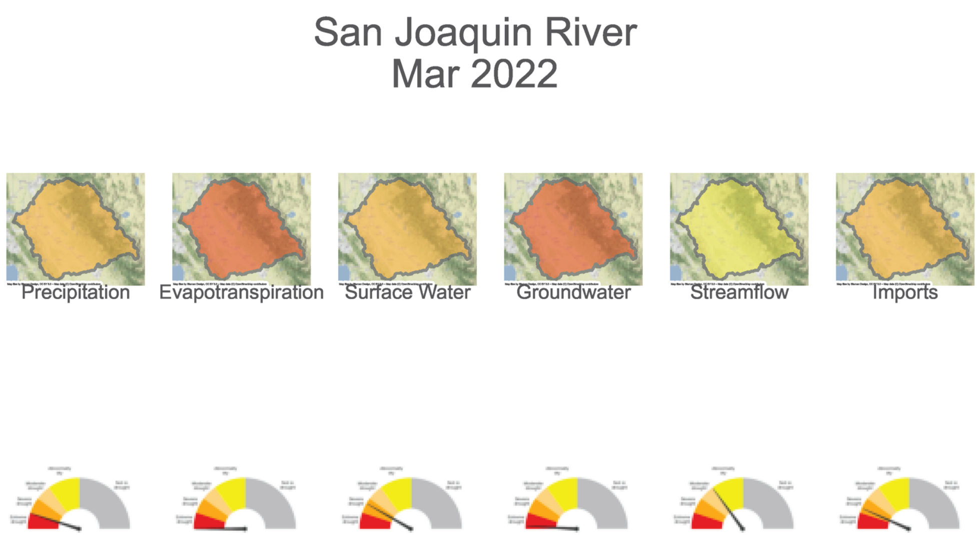
The following figures show a the dashboard for the Sacramento River hydrologic region, where imports are not important, and for the San Joaquin River hydrologic region, where imports are also shown.

__Figure 12: Combined drought indicator dashboard for the Sacramento River hydrologic region__



Source: *Developed by the authors*

__Figure 13: Combined drought indicator dashboard for the San Joaquin River hydrologic region__



Source: *Developed by the authors*

5. References

Bloomfield, J. P., & Marchant, B. P. (2013). Analysis of groundwater drought building on the standardised precipitation index approach. *Hydrology and Earth System Sciences*, *17*(12), 4769–4787. https://doi.org/10.5194/hess-17-4769-2013

Margulis, S. A., Cortés, G., Girotto, M., & Durand, M. (2016). A Landsat-Era Sierra Nevada Snow Reanalysis (1985–2015). *Journal of Hydrometeorology*, *17*(4), 1203–1221. https://doi.org/10.1175/JHM-D-15-0177.1