Methodology 3. Linking drought indicators with impacts in highly-managed water systems

1. Introduction

Although drought are natural-occurring events, the risk of a drought impact is determined not only by the climatic hazard, but also by the exposure and vulnerability to these hazards (Cardona et al., 2012). In other words, drought impacts are not only a function of a natural event, but also a function of how humans manage and adapt to these events.

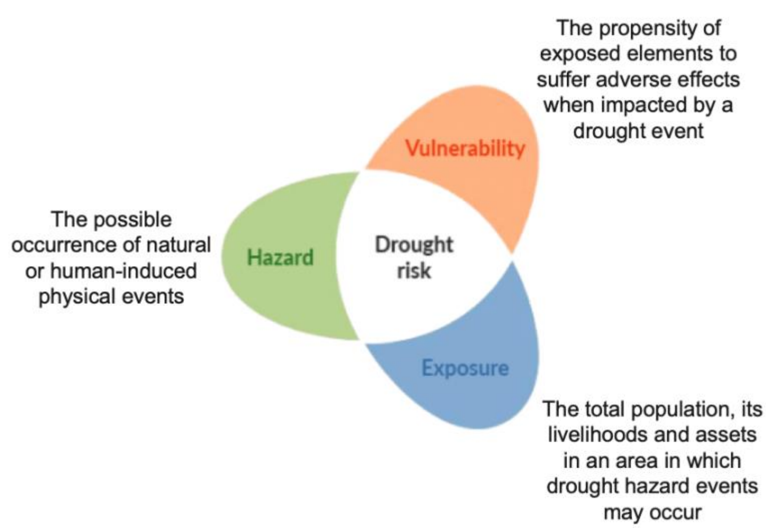
The goal of this document is to present a methodology to link drought hazards with expected drought impacts in highly-managed water systems, using some examples in California as case studies.

In the next sections we first… TBD

2. Overview of the methodology

In the recent decades, a new paradigm has emerged to assess climatic risks from higher understanding of both the natural features of a climatic hazard and the factors that influence social and economic vulnerability (Cardona et al., 2012; IPCC, 2014; Peduzzi et al., 2009). Following this paradigm shift, (Carrão et al., 2016) defines drought risk as the probability of harmful consequences or likelihood of losses resulting from interactions between drought hazard (i.e. the possible future occurrence of drought events), drought exposure (i.e. the total population, its livelihoods and assets in an area in which drought events may occur), and drought vulnerability (i.e. the propensity of exposed elements to suffer adverse effects when impacted by a drought event).

Figure 1. Determinants of drought impact risk



Notes: *Figure adapted from (IPCC, 2014) and definitions adapted from (Carrão et al., 2016).*

In this document, we followed this methodology to show how to link drought hazards with potential drought impacts, using case studies in California. But given that most of the publications worked at larger regional, national or global (Birkmann, 2007; Carrão et al., 2016; Naumann et al., 2021; Peduzzi et al., 2009; Wilhite et al., 2014), we had to adapt the methodology to the sub-regional scale to include management considerations—given our interests in linking drought indicators and impacts for California. Similarly, given our interest in multi-sectoral drought impacts, we defined indicators for different sectors that were more nuanced to California's reality (Table 1).

Table 1. Examples of different indicators of the determinants of drought impact risks for different sectors

	Agriculture	**Cities**	**Small communities**	**Environment**
Hazard	• Hydro-climatic hazard considering the built infrastructure (supply portfolio), its regulations (water rights, environmental regulations, etc.) and its management decisions			
Exposure	• Acreage • Agricultural value (crop revenues) • Investments (perennial crops) • Dependent communities	• Service population • Industries and businesses	• Population on domestic wells or small supply systems • Industries and businesses on domestic wells or small supply system	• Freshwater species • Ecosystem habitat
Vulnerability	• Demand flexibility (perennials vs annual crops) • Crop insurance • Access to water markets • Financial health of farmers/irrigation districts	• Demand flexibility (outdoor vs indoor water use) • Access to water markets • Financial health of suppliers • Socio-economic status of population		• Ecosystem vulnerability (alteration with respect pristine conditions) • Endangered species

Notes: *Developed by the authors*

For the quantification of drought impacts, we just included an example for the assessment of drought impacts in the agricultural sector, but we argue later that qualitative approaches might be needed for the difficulty of assessing quantitatively drought impacts in some sectors.

3. Determinants of drought impact risk

In the following sub-sections, we show some examples on drought indicators for hazard, exposure and vulnerability that can be used to determine drought impacts in California.

3.1 Drought hazard

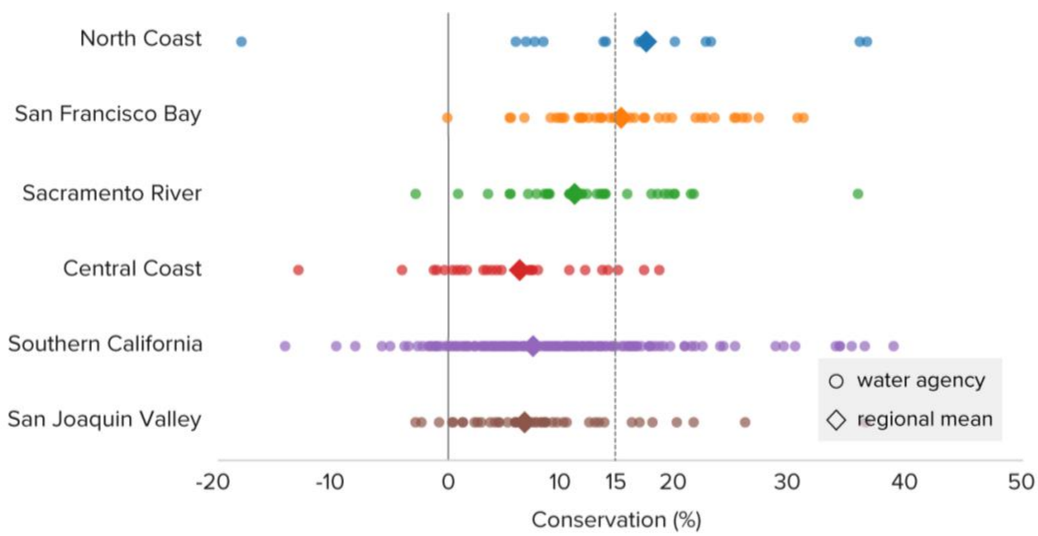
In the previous documents we have developed user-oriented drought hazard indicators (*Methodology 1: User-oriented drought indicators in California*) and proposed a methodology to develop drought hazard indicators for users with complex supply portfolios (*Methodology 2: System drought indicator for users with complex supply portfolios*) using California as our case study. An important difference with respect to previous definitions of drought hazard is that we consider built infrastructure, regulations and management as an implicit characteristic. Beyond what we have already shown in the previous documents, we want to highlight here how water infrastructure (and access to an enhanced supply portfolio), water regulations, or water management can impact drought hazard.

3.1.1 The role of water infrastructure in drought hazard

Humans have developed water infrastructure to minimize their drought risks. Access to supply infrastructure is linked to improved water services (Beuhler, 2006; Leroux & Martin, 2016; Mukherjee & Schwabe, 2015), although some have also noticed that this over-reliance can also aggravate impacts (Di Baldassarre et al., 2018; Loon et al., 2022).

When infrastructure can't ensure enough supplies to meet water demands, water managers turn into demand management practices, including urban conservation, but also agricultural curtailments (Lord et al., 2018; Maggioni, 2015). During the 2020-22 drought, and to avoid larger supply shortages, California's governor asked to voluntarily reduce their water use by 15 percent from their 2020 levels (see Executive Order N-10-21). The results, as Figure 2 shows, were quite heterogeneous in the state. Agencies in the North Coast and San Francisco Bay were affected earlier by the drought (Escriva-Bou et al., 2021), so they responded most prominently—although even in these regions there are differences across agencies.

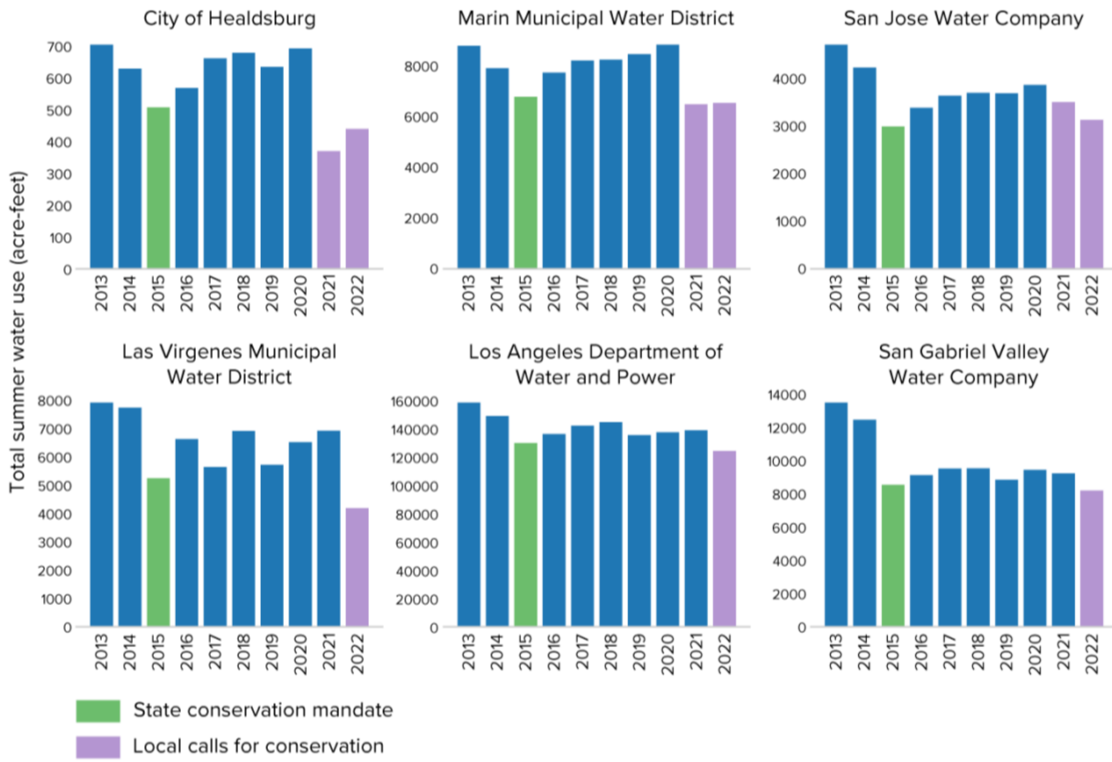
Figure 2. Water conservation for California water agencies in Summer 2022 with respect to 2020



***Source**: (Escriva-Bou et al., 2022) **Notes:** This chart shows how much urban agencies have conserved between June and August 2022 compared to the same period in 2020. The regional mean is weighted by service area population.*

Some of the differences in conservation might be explained by the vulnerability of their supply portfolio: i.e. agencies that had lower confidence on future supplies given their supply sources enacted stricter conservation rules. Figure 3 shows an example of how drought response changes according to the supply portfolio: the top row show agencies in the North Coast and Bay Area strongly affected by the drought in 2021 (and with constrained supply portfolios), while the bottom row shows Southern California communities that rely heavily on the drought-challenged State Water Project with limited access to other supplies.

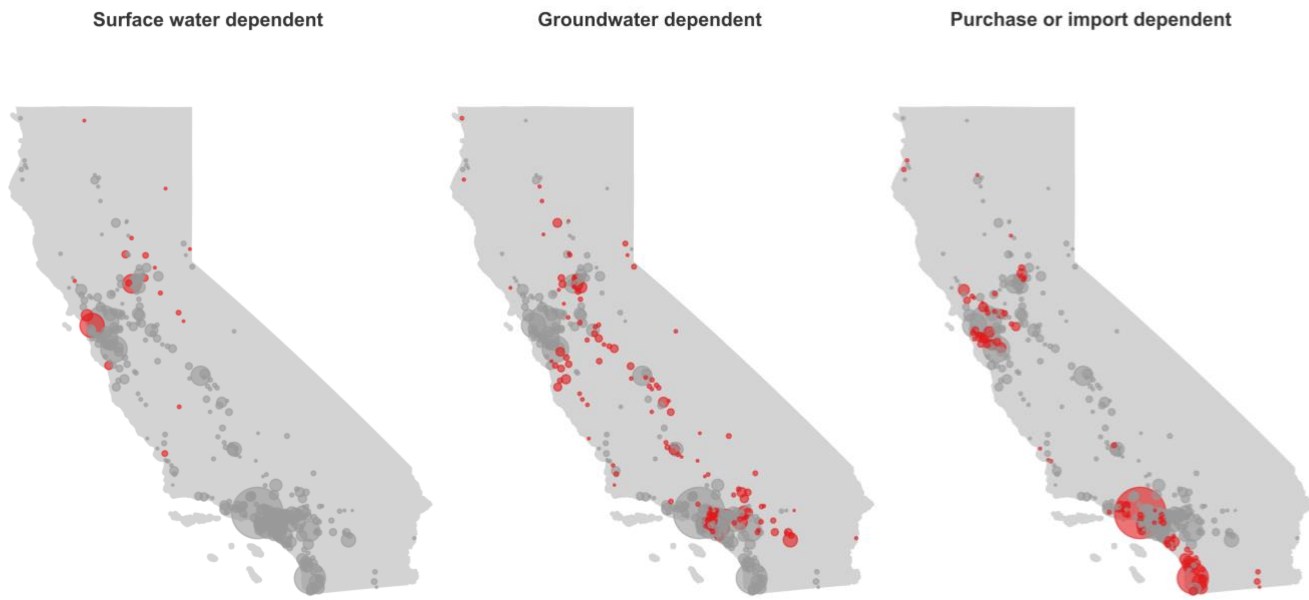
Figure 3. Individual agencies with vulnerable supply portfolios saved water significantly



***Source**: (Escriva-Bou et al., 2022) **Notes:** These bar charts illustrate the total water use of each urban agency during summer months (June through August) from 2013 to 2020.*

Following these insights, we could link the methodologies developed in the previous documents to get to actual shortages by water agency. For that, we need to define the water supply portfolio at finer detail. But also, individual characteristics of the supply could be used as drought hazard indicators. Figure 4 shows the water agencies that are highly reliant on one supply source (agencies with >75% of total supplies coming from one source). The code 'visualizing_hazard_supply_portfolio.py' (folder Functions/visualizing) contains the data to obtain the following maps.

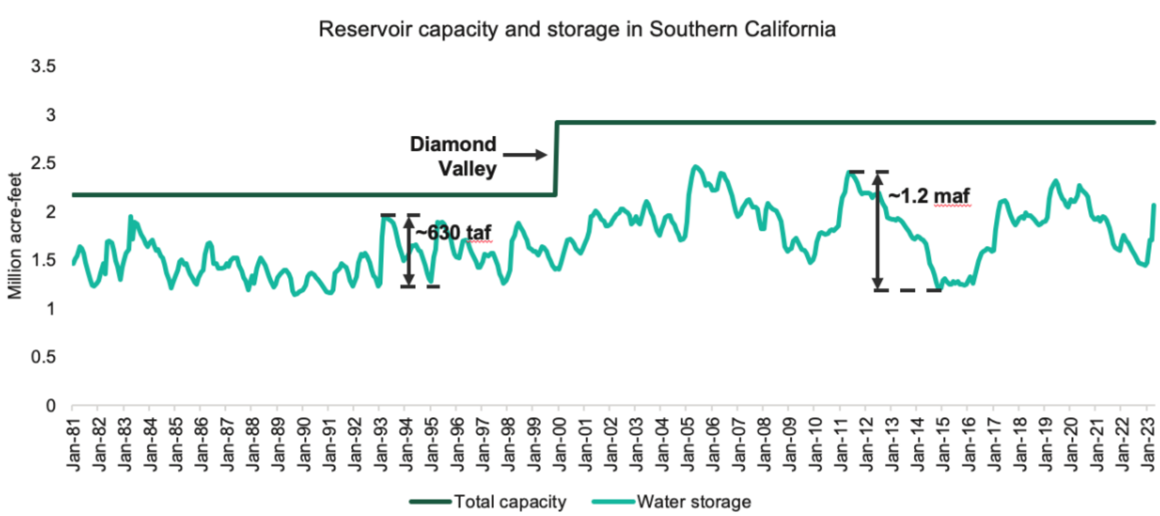
Figure 4. Water agencies largely reliant on a supply source



Notes: This figure shows the 400+ large water suppliers (cities). The highlighted suppliers have more than 75% of their supplies from source indicated in the top. The size of the bubble is proportional to the population served.

Another way to see how infrastructure can help reducing hazard is looking at the role of new infrastructure in reducing supply shortages. Figure 5 shows how the construction of a sizable reservoir in Southern California—Diamond Valley, a reservoir with a capacity to store 800 taf, built in the late 1990s—increased the ability to store water, reducing the hazard of supply shortages during droughts. Similarly, the construction of water reuse or desalination plants, the connection of groundwater-dependent communities to larger surface supply networks, and the increase in water efficiency to reduce water use, lessens water supply hazard.

Figure 5. The construction of a new reservoir in Southern California increased drought reserves significantly

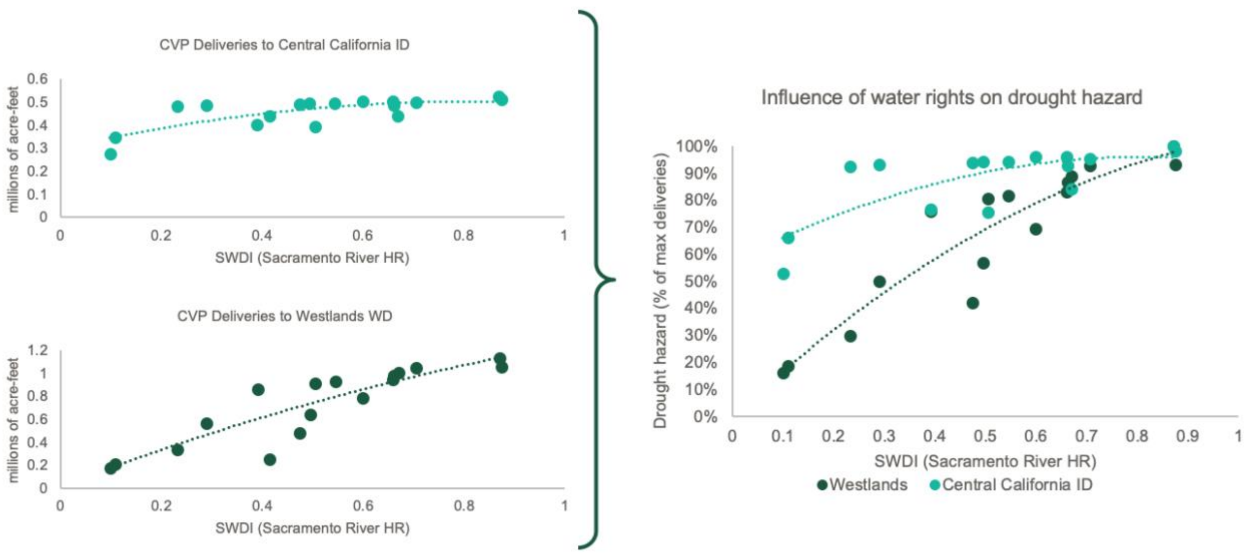


Notes: *Water storage includes all reservoirs used for water supply in the Southern California. Taf stands for thousand acre-feet, and maf is million acre-feet.*

3.1.2 The role of regulations in drought hazard

California, as many other western states, uses appropriative rights to determine the priority of water allocations—which are determined by the seniority of the water right. Therefore, suppliers with the same source of water can have different drought hazards based on their different seniority. In Figure 6 we show this effect using the water allocations to two irrigation districts in the San Joaquin Valley from the same sources of water—the Central Valley Project—as a function of the Surface Water Drought Index (SWDI). The chart shows how water allocations to the Central California ID, a senior water right-holder, are much less variable than water allocations to Westlands ID (a junior water right-holder), which are much curtailed significantly during drier years.

Figure 6. Influence of water right priority on drought hazard



Source*: Central Valley Project historical allocations for water allocations, and own calculations for the SWDI.*
Notes: *The left charts show the annual water allocations (in millions of acre-feet) from the Central Valley Project to two different irrigation districts in California as a function of the Surface Water Drought Indicator (SWDI) of the Delta Exporting Basins (see Methodology 1 for more information on this). The chart in the right shows the percentage of the annual allocation with respect to the system maximum as a function of the SWDI for the two irrigation districts.*

3.1.3 The role of management in drought hazard

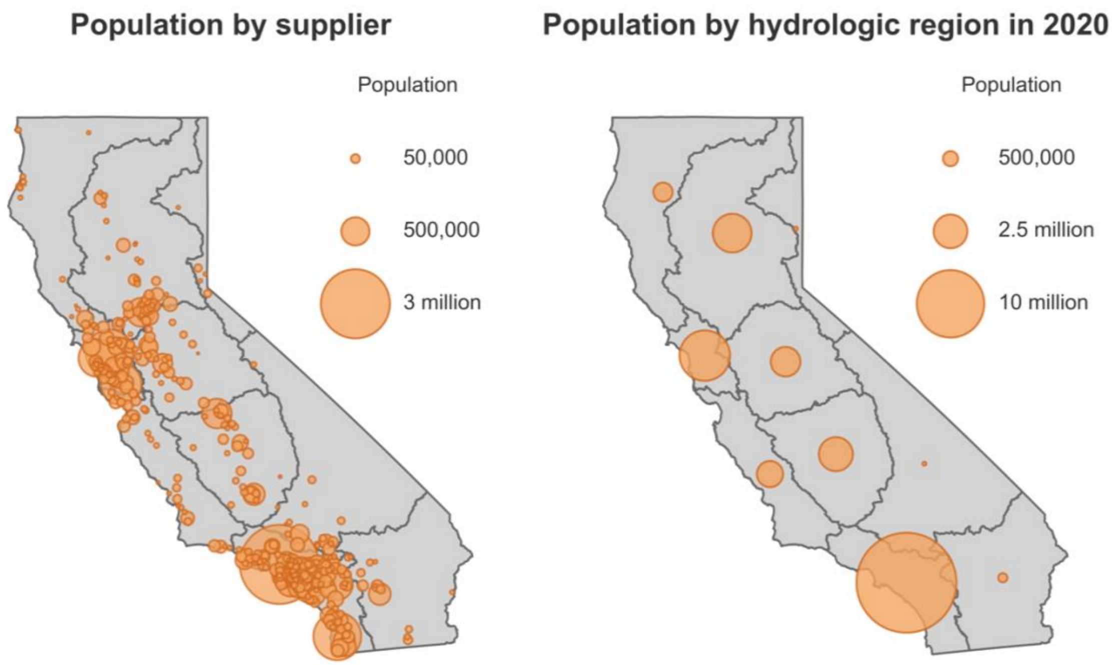
In *Methodology 2: System drought indicator for users with complex supply portfolios* we have shown how users with complex supply portfolios use first surface water, and then during drier years, they try to mitigate surface water shortages by increasing groundwater pumping. This is a clear example of the role of water management in reducing drought hazard.

3.2 Drought exposure

Following (Carrão et al., 2016), we define exposure as the total population, its livelihoods and assets in an area in which drought events may occur. There are many ways in which exposure could be defined for the different sectors we are considering—cities, small communities, agriculture and the environment—so in this section we are show some indicators that could help assessing exposure in California.

For cities, an option is to consider population at risk of suffering drought events. In this case we use the data from the California Department of Finance and from the State Water Board Conservation Reporting to calculate population exposed in large suppliers. Figure 7 shows important concentrations of urban population in the Southern Coast and in the Bay Area, while other places of the state are less exposed.

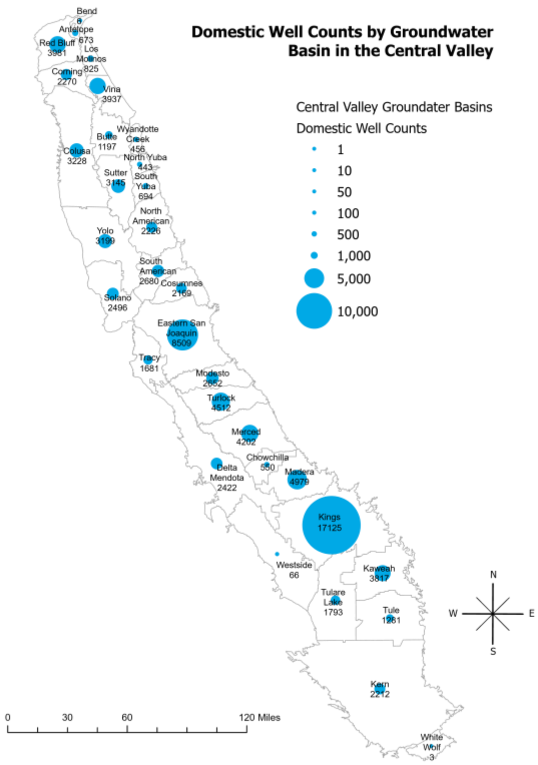
Figure 7. Human population exposed to droughts in California cities



***Source**: California Department of Finance and SWRCB. **Notes:** The map in the left shows the population for the 400+ large suppliers in California, while the map in the right shows population by hydrologic region.*

For small communities we show exposure using domestic wells in the Central Valley basins—where concentration of small communities is larger. Figure 8 shows that the Kings basin (where the city of Fresno is located) and the Eastern San Joaquin (around the city of Stockton) concentrate a large proportion of domestic wells. Looking at these maps can help identifying drought hot spots for small communities.

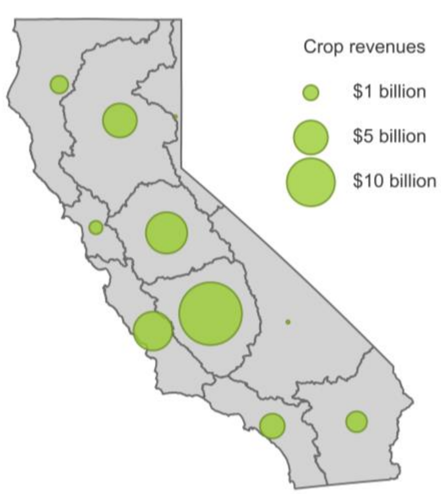
Figure 8. Population in small communities exposed to drought in the Central Valley, using well count as a proxy



***Source**: California Department of Water Resources.*

Farm acreage, crops, revenues or profits, or the value of investments are different type of indicators for agriculture. Figure 9 shows how the regions Central Valley (Tulare Lake, San Joaquin and Sacramento hydrologic regions) and the Central Coast concentrate most of the state's agricultural economic output, but other regions are also exposed to droughts.

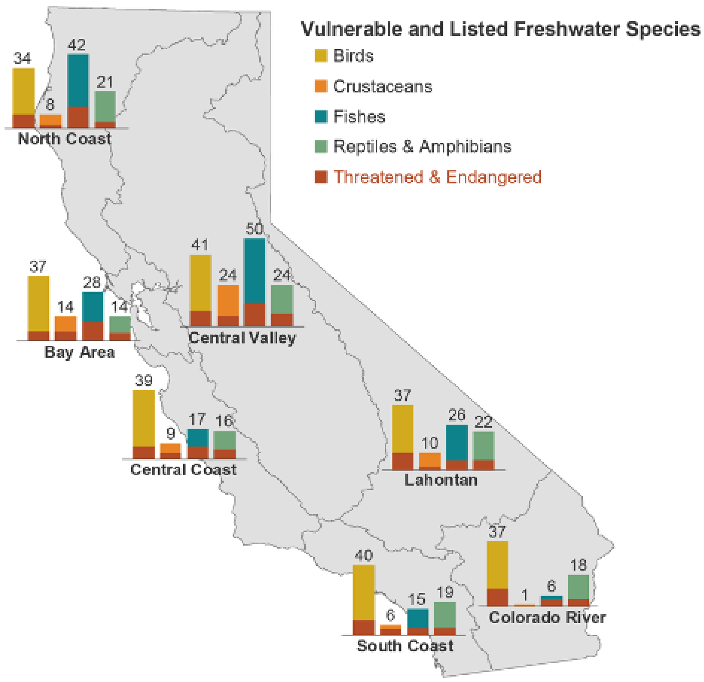
Figure 9. Crop revenues by hydrologic region



***Source**: California County Commissioners' Reports.*

Finally, environmental exposure can be defined in many different ways. Figure 10 shows vulnerable and listed freshwater species for different hydrologic regions in California obtained from XXX. Other indicators could also be useful depending on the final drought impact assessment.

Figure 10. Freshwater species can indicate the exposure of the environment to drought conditions



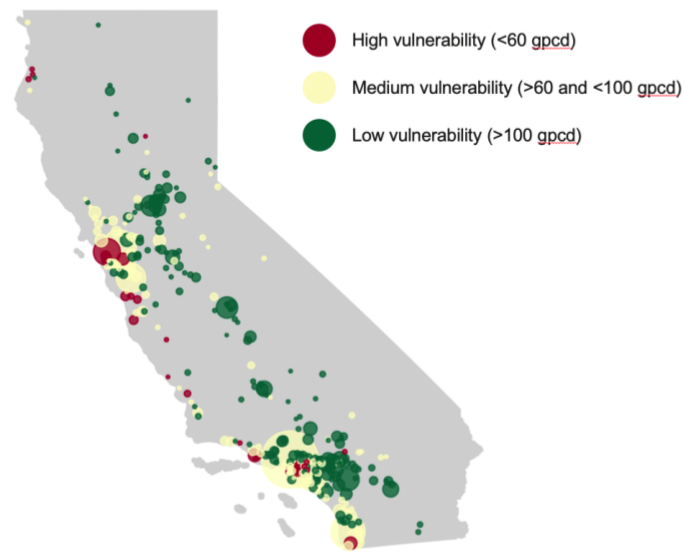
***Source**: TBD.*

3.3 Drought vulnerability

Drought vulnerability is the propensity of exposed elements to suffer adverse effects when impacted by a drought event. Therefore, vulnerability indicators need to identify the flexibility to adjust to reduced supplies—the costs incurred in reducing consumption in conservation campaigns for urban and small community users or deficit irrigation or land fallowing costs for agricultural uses—, the ability to get alternative supplies by participating in water markets for suppliers or being able to use other sources (digging new wells or buying bottled water for urban users), and finally options to mitigate costs by participating in insurance policies.

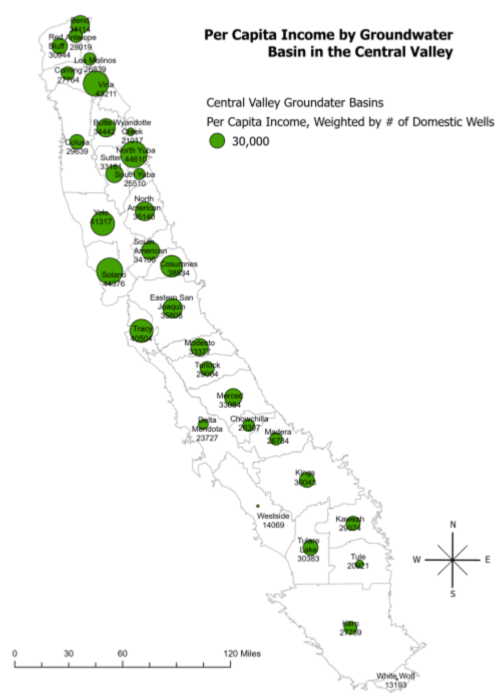
The following figures show different type of vulnerability indicators for California cities, small communities and agriculture. Cities with lower per capita water use are expected to have higher costs to reduce water use, because might be forced to reduce indoor and industrial use that has a higher value than outdoor uses (Figure 11). For users on domestic wells or small communities, socioeconomic status (Figure 12) might be used as an indicator to represent the vulnerability of these users to look for alternative supply sources (digging new wells) or being able to buy bottled water. Other potential vulnerabilities—like health vulnerabilities for reduced water supplies during droughts—might also be related with socioeconomic status. Finally, for farms, the share of perennials (Figure 13) might represent an indicator of vulnerability, as perennial represent long term investments that could be lost during droughts. Obviously, the cost of fallowing lands are also a good indicator, so the flexibility to reduce less valuable acreage first is a good adaptation option, that can be achieved through water trading or other reallocation mechanisms.

Figure 11. Demand vulnerability is greater in cities when there is less outdoor use



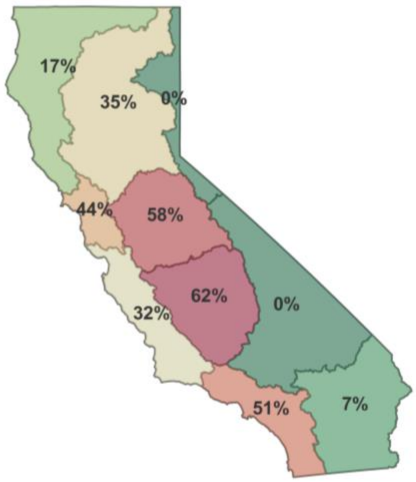
***Source**: State Water Resources Control Board.*

Figure 12. Per capita income for water users on domestic wells by groundwater basin in the Central Valley



***Source**: California Department of Water Resources.*

Figure 13. Share of perennials by hydrologic region



***Source**: California County Commissioners' Reports.*

4. Example of a drought impact assessment

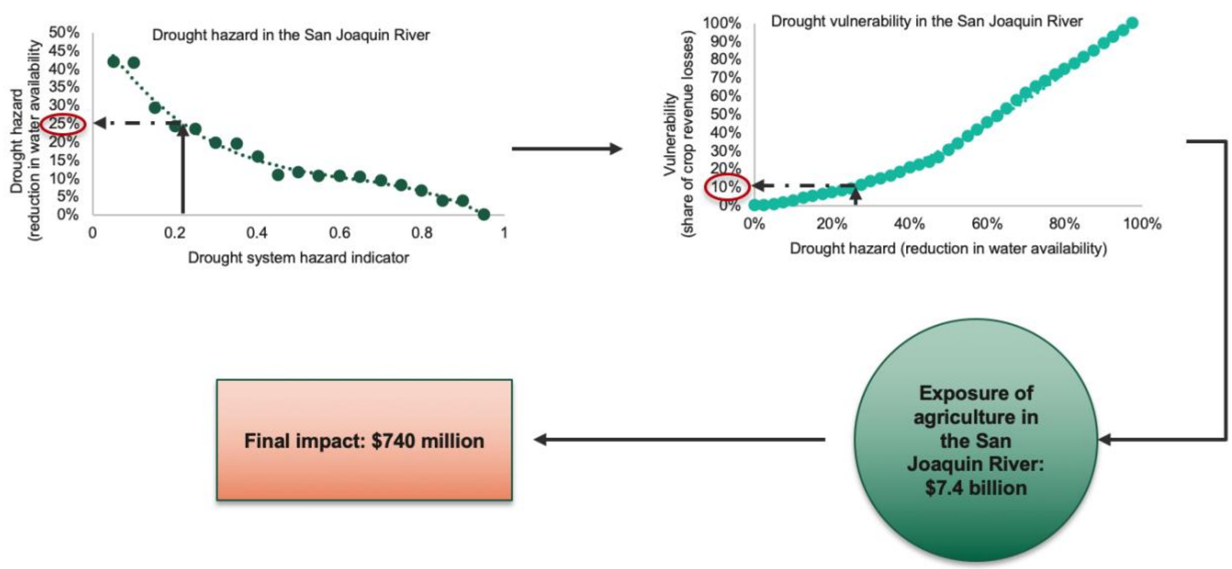
In this section we show and example of a drought impact assessment for agricultural regions, but the idea is to show how this methodology could be applied to other sectors if the proper data is available.

In this example, shown in Figure 14, we used the drought system hazard indicator (DSHI) for the San Joaquin Valley developed in the *Methodology 2: System drought indicator for users with complex supply portfolios*. Assuming that *"a specific drought year"* has a DHSI of 0.22, following the top left chart that would represent a 25% reduction in water availability in the region.

Then, using data from (Medellín-Azuara et al., 2022) we calculate the revenue losses as a function of the reduction in water availability, which is a measure of vulnerability—or the cost of agriculture given drought events. As the top right chart shows, a decrease in 25% of available supplies would reduce crop revenues in 10% (assuming that water trading would help reallocating water to the most profitable uses).

Finally, multiplying this 10% reduction in crop revenue by the exposed crop revenues in the San Joaquin River HR ($7.4 billion), we obtain that the impact in crop revenues of a drought of that magnitude in agriculture in this region would amount $740 million.

Figure 14. Drought impacts can be assessed as a combination of drought hazard, exposure and vulnerability



Source: *Developed by the authors.*

It is worth noting that data for drought impact assessment are not available in most of the cases, so the calculations are not straightforward. Furthermore, in many cases the drought impacts can't be monetized, so it might be more appropriate to use qualitative approaches for drought impact evaluation.

5. References

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