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# Piloting Drought Management Participatory Modeling-Based Approaches in Chile

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# ABSTRACT

Chile's unique geography and climatic zones, including the arid Atacama Desert in the north and the cold, humid Patagonian zone in the south, represent a challenge for water resource management. Droughts, and particularly mega-droughts, have become more frequent and intense, affecting not only the north but also central regions like the Maipo Basin, located in the Metropolitan Region. To address these issues, this project aims to develop a Drought Management Plan (DMP) for the Maipo Basin, and to support an analysis of drought conditions, including characterization of spatial coverage, intensity, and duration, a Drought Management module has been implemented in WaterALLOC, combining the Hydro-BID and MODSIM modeling systems. This module enables the analysis of drought conditions, including spatial coverage, intensity, and duration, while Hydro-BID utilizes the Analytical Hydrography Dataset (AHD) and a hydrologic model to simulate runoff and baseflow. This case study focuses on the Maipo River Basin in Chile, using the Drought Management module in WaterALLOC to simulate response stages for mitigating drought impacts. Existing drought monitoring tools, such as the Chilean Drought Observatory and the Meteorological Drought Bulletin, provide national-level information using the Standardized Precipitation Index (SPI). The model setup in the Maipo Basin, part of a water security project, integrates Hydro-BID and WaterALLOC to evaluate water efficiency, assess climate impacts, and develop water security plans. The study highlights the importance of integrated tools and modeling systems for enhanced water resources planning and decision-making in drought-prone regions. Finally, a capacity training program was implemented, aimed at strengthening technical capacities of local stakeholders in water resources management. The program focused on using these analytical tools to enhance water resource planning and assessment. Multiple stakeholders, including CEA, UDD, UDEC, and Fundación Chile, participated in the program. Additionally, a session was conducted to introduce the Drought Management Module in WaterALLOC, presenting the theory, development, and a case study in the Maipo Basin.

# ABBREVIATIONS

| | |
|---|---|
| AHD | Analytical Hydrography Dataset |
| ASI | Agricultural Stress Index |
| CDIT | Climate Data Interpolation Tool |
| CEA | Centro de Ecología Aplicada (Applied Ecology Center, in English) |
| CN | Curve Number |
| DMP | Drought Management Plan |
| ET | Evapotranspiration |
| FAO | Food and Agriculture Organization |
| GIS | Geographical Information System |
| GUI | Graphical User Interface |
| GWLF | Generalized Watershed Loading Function |
| IDB | Interamerican Development Bank |
| IRI | International Research Institute for Climate and Society |
| NDVI | Normalized Difference Vegetation Index |
| SPI | Standardized Precipitation Index |
| PDSI | Palmer Drought Severity index |
| VCI | Vegetation Condition Index |
| WMO | World Meteorological Organization |

# 1. INTRODUCTION

## 1.1. BACKGROUND INFORMATION

Chile is a peculiar country. It has a length of 4,270 km, while its maximum width is only 445 km. In addition, its proximity to the sea results in a great diversity of climatic zones: the arid and dry Atacama Desert in the north; the southern Patagonian zone in the south, whose climate is much colder and more humid; and intermediate climates, such as the Mediterranean or the oceanic, or even the tundra of the Andes Mountains.

These climatic differences make proper management of water resources somewhat complicated to carry out. The existence of a desert in the country can also imply marked seasons of drought in its vicinity, a situation that occurs in Chile on a regular basis. In recent decades, data on various droughts has been collected, generally involving the desert regions of Atacama and Coquimbo, but occasionally extended to other regions.

The drought data that has been collected over the years, shows that droughts currently affect not only the northern part of the country, but also the central regions. These droughts have been so severe, that their denomination has come to be identified as mega-drought. In 2019, five regions of the country were in a state of agricultural emergency due to water stress. The Maipo Basin, located in the Metropolitan Region, is one of the areas of Chile most affected by severe drought.

Even though Chile is a country where times of drought have always been common, climate change is having an undeniable effect on their frequency and intensity (Aguayo et al., 2021). The need to take measures to mitigate these effects is evident, and a good starting point is by promoting an integrated water resources management approach for critical basins; developing drought management plans that are based on empirical data about the current and projected conditions; and creating local technical capacity for adequate management and planning of water resource and drought events.

## 1.2. OBJECTIVES

The general objective of this project is to support the development of a Drought Management Plan (DMP) for the Maipo Basin that will seek to minimize environmental, economic, and social impacts of drought episodes.

The general objective of the plan is pursued through the following specific objectives:

- Preserve essential services and minimize adverse impacts of a water supply emergency on public health and safety, economic activities, environmental resources, and individual lifestyle.
- Avoid or minimize negative effects of drought on the watershed, causing situations of temporary deterioration of water masses or ecological flows.
- Minimize negative effects on economic activities.

# 2. DROUGHT MANAGEMENT THEORY

Droughts are naturally occurring phenomenon generally characterized by drier-than-average conditions and abnormally low rainfall. Although there is no single definition available for droughts, a helpful framework is to categorize droughts by impact, such as:

- Meteorological: reduced rainfall, higher evapotranspiration rates
- Hydrologic: reduced streamflow, faster melting of snow/ice
- Agricultural: reduced soil moisture, decreased vegetation growth

Drought characterization can vary widely by location, depending on local climate and distribution of rainfall during a normal year. For example, temperate climates with even rainfall throughout the year may experience drought if rainfall is low over the course of two to three months. Mediterranean climates, which can be highly seasonal, may normally experience four or more months of no rainfall. No single definition can be applied to characterize drought in both watersheds without considering local climate history.

## 2.1. CHARACTERIZING DROUGHT WITH INDICES

Droughts are often classified using indices, which can combine multiple factors, such as precipitation, streamflow, and soil moisture, to quantify severity in a local context using historical data. Numerous indices exist, varying greatly in data needs, complexity, and suitability for specific applications. The World Meteorological Organization (WMO) Handbook of Drought Indicators and Indices (Svoboda et. al., 2012) catalogues many of the most popular and scientifically accepted approaches to quantify drought (**Figure 1**). Among the most commonly used are:

**Simple rainfall statistics:**

Involves comparing recent records to historical annual, seasonal, or monthly averages

- Can be misleading, highly dependent on local context

## Standardized Precipitation Index (SPI):

- Based only on rainfall, uses probabilistic approach
- Recommended by World Meteorological Organization as a "starting point for meteorological drought monitoring"
- Relatively simple calculation using WMO procedure

## Palmer Drought Severity Index (PDSI)

- Requires complete records of precipitation, temperature, and soil moisture
- Relatively complex method

| *Meteorology* | *Page* | *Ease of use* | *Input parameters* | *Additional information* |
|---|---|---|---|---|
| Aridity Anomaly Index (AAI) | 11 | Green | P, T, PET, ET | Operationally available for India |
| Deciles | 11 | Green | P | Easy to calculate; examples from Australia are useful |
| Keetch–Byram Drought Index (KBDI) | 12 | Green | P, T | Calculations are based upon the climate of the area of interest |
| Percent of Normal Precipitation | 12 | Green | P | Simple calculations |
| Standardized Precipitation Index (SPI) | 13 | Green | P | Highlighted by the World Meteorological Organization as a starting point for meteorological drought monitoring |
| Weighted Anomaly Standardized Precipitation (WASP) | 15 | Green | P, T | Uses gridded data for monitoring drought in tropical regions |
| Aridity Index (AI) | 15 | Yellow | P, T | Can also be used in climate classifications |
| China Z Index (CZI) | 16 | Yellow | P | Intended to improve upon SPI data |
| Crop Moisture Index (CMI) | 16 | Yellow | P, T | Weekly values are required |
| Drought Area Index (DAI) | 17 | Yellow | P | Gives an indication of monsoon season performance |
| Drought Reconnaissance Index (DRI) | 17 | Yellow | P, T | Monthly temperature and precipitation are required |
| Effective Drought Index (EDI) | 18 | Yellow | P | Program available through direct contact with originator |
| Hydro-thermal Coefficient of Selyaninov (HTC) | 19 | Yellow | P, T | Easy calculations and several examples in the Russian Federation |
| NOAA Drought Index (NDI) | 19 | Yellow | P | Best used in agricultural applications |
| Palmer Drought Severity Index (PDSI) | 20 | Yellow | P, T, AWC | Not green due to complexity of calculations and the need for serially complete data |

**Figure 1. A selection of drought indices with varying complexity, from the World Meteorological Organization (Svoboda et. al., 2012)**

## 2.2. STANDARDIZED PRECIPITATION INDEX (SPI)

The Standardized Precipitation Index (SPI) is recommended by the WMO as a "first step" in beginning a drought monitoring and management program. SPI has numerous advantages over other drought indices, including low data requirements (only rainfall), standardized method (WMO provides clear documentation and software packages for calculation), and widespread acceptance among the meteorological community.

SPI also provides a great deal of flexibility for characterizing drought in a local context. Given a user-specified time scale and input time series of precipitation, the probability of precipitation at each time step is then calculated. The probability values are then converted to an index, with the interpretations provided in Table 1:

**Table 1. SPI Values and Interpretation**

| SPI Value | Classification |
|---|---|
| 2.0+ | Extremely wet |
| 1.5 to 1.99 | Very wet |
| 1.0 to 1.49 | Moderately Wet |
| -99 to .99 | Near Normal |
| -1.0 to -1.49 | Moderately Dry |
| -1.5 to -1.99 | Severely Dry |
| -2 and less | Extremely Dry |

Note that SPI classifies rainfall by historical variance, meaning it can be used to classify the extremity of both wet and dry conditions. Additionally, SPI is designed to allow rainfall to be classified at a variety of timescales (from one month to 48 months or longer). The specific timescale used for calculating SPI must be selected based on the context of the application. The Standardized Precipitation Index User Guide (Svoboda et al., 2012) provides guidance on timescale selection. In general, short timescales can be useful for providing early warning for meteorological droughts or for application in areas with low seasonality in rainfall. Longer timescales are needed to quantify impacts to streamflow and agriculture and are more appropriate for application in areas with highly seasonal rainfall.

# 3. DROUGHT MANAGEMENT IN WaterALLOC

To support analysis of drought conditions, including characterization of spatial coverage, intensity, and duration, a Drought Management module has been implemented in WaterALLOC, an integrated, map-based water resources management tool integrating Hydro-BID (Moreda et al 2014) and MODSIM (Labadie, 2006).

## 3.1. MODELING TOOLS

### 3.1.1. Hydro-BID

The Hydro-BID modeling system for quantitative simulation of hydrology and climate change has three primary components: the Analytical Hydrography Dataset (AHD), the database, and the hydrologic model. The AHD is a digital representation of catchment boundaries and stream segments for the entire LAC region, containing over 230,000 catchments with an average size of 83 km2 for South America and 23 km2 for Central America and the Caribbean. The AHD is a regional platform of spatial data used to integrate the disparate data needed to support hydrologic modeling. It provides a framework for consistently parameterizing models, provides the necessary river network connectivity, and stores the data necessary for displaying results in a Geographical Information System (GIS) format. The database contains information associated with each catchment, including drainage area, stream length, slope, land uses, and soil types. The hydrologic model is an enhanced version of the rainfall-runoff Generalized Watershed Loading Function (GWLF) model (Haith & Shoemaker, 1987), coupled with a novel lag-routing methodology developed by RTI (Moreda et al., 2014).

The model computes runoff and baseflow by catchment. The GWLF estimates runoff using the U.S. Soil Conservation Service's curve number (CN) method. Catchment CNs are stored in the database and are determined by the watershed's combination of soil and land cover conditions, which are represented as hydrologic soil groups, cover type, treatment, and hydrologic condition. After runoff estimates, excess precipitation infiltrates the unsaturated layer, where it is subject to evaporation. Over time, the infiltrated water percolates from the unsaturated layer downward to replenish the saturated storage. Water within the saturated layer enters the stream channel as baseflow, where it combines with runoff from the catchment and any inflows from the upstream catchments to provide the stream flow volume for the day.

A preprocessor referred to as the Climate Data Interpolation Tool (CDIT), built into the Hydro-BID modeling system, automates interpolation of daily temperature and precipitation time series between stations. Hydro-BID can simulate stream flows in unimpaired watersheds for historic, current, and future conditions based on land use, precipitation, and temperature inputs. Model outputs of predicted streamflow are saved in readily usable, comma separated value (.csv) format, at either a daily or monthly time step. The system has a graphical user interface (GUI) to facilitate loading and processing of model input, as well as to display both graphical and tabulated model output. The hydrologic model utilizes the data structure and the catchment and stream network topologies of the AHD to generate flow estimates at the outlet of any catchment or basin selected by the user. In addition to flow generation, Hydro-BID includes other modules for 1) reservoir simulation, 2) sediment transport, and 3) surface and groundwater interactions using MODFLOW.

### 3.1.2. WaterALLOC

WaterALLOC provides a new GIS-based interface that uses the AHD stream representation to create a MODSIM simulation network and imports the results of Hydro-BID to streamline the coupling of the two modeling systems. MODSIM, developed by Colorado State University, is a decision-making support system that uses optimization in a stream network to help watershed managers with the analysis of water supply in the face of hydrological uncertainty and demand growth (http://modsim.engr.colostate.edu/).

WaterALLOC streamlines the data processing between Hydro-BID and MODSIM, offering a solution to perform water availability analysis, including river and reservoir operations with simulation of water permits and priorities, using all the river operations tools and customization provided by MODSIM. WaterALLOC enhances the user experience for both Hydro-BID and MODSIM users, allowing the Hydro-BID user to use the GIS interface to run the system and add easy-to-use input dialogs for agricultural and municipal demands for MODSIM. This tool creates the MODSIM simulation network automatically from the AHD network, using the catchments and streams to define the links and nodes of the MODSIM network. WaterALLOC links the results of local runoff from Hydro-BID to the entry nodes of MODSIM to simulate the routing of the flows in the streams of a basin. Georeferenced demand nodes can be created with the tool to simulate water intake and consumption according to water availability at different points of the basin and in accordance with the permits, priorities, and physical and hydraulic limitations of the system. WaterALLOC also allows the creation and simulation of reservoir systems operation, simulating water supply and power generation operations.

The new robust modeling platform offers a streamlined solution for data management among the models, and the ability to perform comprehensive water balance analysis that includes water infrastructure operation rules, water allocation priorities, and administrative and social constraints. Additionally, the platform allows simulation of dynamic changes to land cover, water demands, population, surface and groundwater interactions, and climate.

This initial implementation of the module has been designed to maintain backward compatibility with older, existing WaterALLOC models. Inputs to the drought management module are derived from Hydro-BID databases and AHD shapefiles, meaning no new inputs are needed from existing WaterALLOC users with functioning projects.

## 3.2. DROUGHT INDEX CALCULATOR

The first major feature of the Drought Management module is a form allowing users to set up and calculate Drought Index values. Currently, Standardized Precipitation Index (SPI) is the only index supported by the module. Future development work could involve the addition of more complex drought indices, such as the Palmer Drought Severity Index. SPI is an excellent first application of the module because it is widely accepted and recommended by the WMO (see Section 2), and the calculation only requires precipitation data. Input precipitation data is provided to the calculator from the Hydro-BID database using the active meteorological data table defined during model setup.

To begin, users must open the new Drought drop-down menu in the tool bar and click “Drought”, then “Calculate index”. A dialog box will open with options for parameterizing the calculation (**Figure 2**). Currently, SPI is the only option listed in the Drought Index field.

Index values are calculated for two time periods, near-term and long-term, which must be defined by users. Further guidance on selecting near-term and long-term periods for evaluation can be found in Svoboda et al., 2012. Additionally, calculations can be evaluated at a weekly or monthly cadence. A monthly time frame is appropriate for most applications of WaterALLOC for long-term water resources planning.

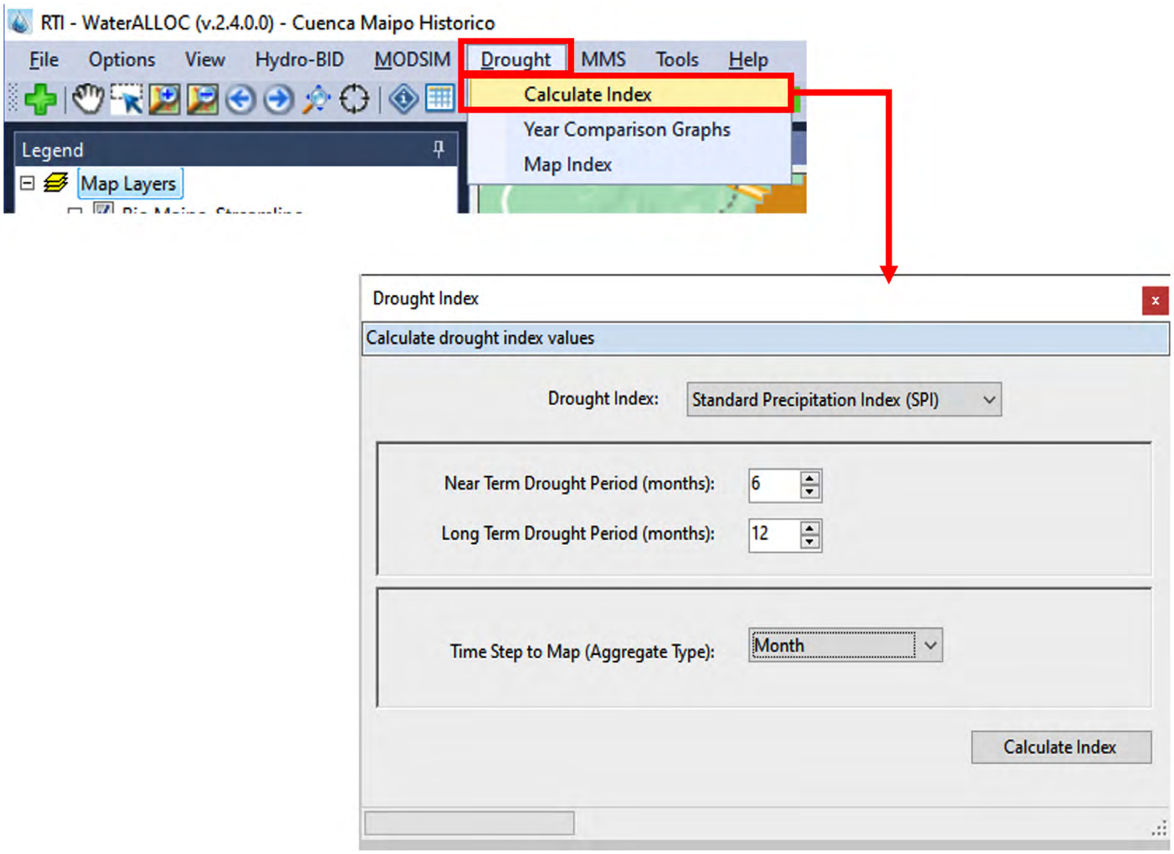


**Figure 2. Drought Index Calculation Setup Form**

Once the user has set up the index, processing will begin by simply clicking “Calculate Index”. Note that the calculation of SPI can take several minutes to complete. Users should also note that drought indices require sufficiently long (two+ decades) periods of record for acceptable accuracy. However, longer periods of meteorological data can also result in slower calculations.

The output of the Drought Index calculator is a time series of short-term and long-term index values for each catchment present in the input met data table. These time series are loaded to the WaterALLOC project database for use in the Drought Index Mapper.

## 3.3. DROUGHT INDEX MAPPER

Values can be visualized for any time step using the Drought Index Mapper once the Drought Index Calculator has been run and a table of results has been loaded into the WaterALLOC project database. To begin the mapping process, users must first activate the Drought Index Mapper by clicking the Drought drop-down menu and selecting “Map Index.” A toolbar will be added to the bottom of the map pane with several fields for users to populate (**Figure 3**).

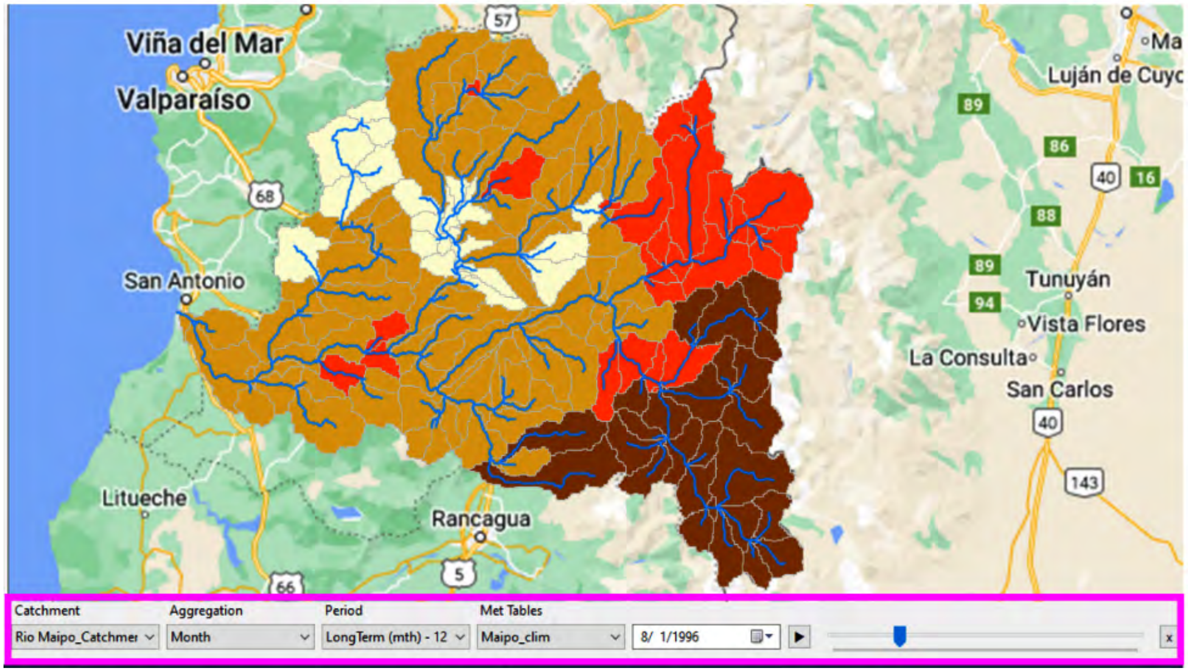


**Figure 3. WaterALLOC Map Interface with Drought Index Mapper Module (highlighted in pink)**

In the Drought Index Mapper, users must specify the following:

- Catchment: Corresponds to the AHD catchment layer loaded in WaterALLOC. May need to be manually defined by the user.
- Aggregation: Should match the Time Step to Map selected in the Drought Index Calculator. It is recommended to use Month for most applications.
- Period: Short-term or Long-term.
- Met Tables: If the index has been calculated for multiple met tables, each will be shown here. Users should select the Met Table that was used to calculate the Index values.

Once the information above is populated, the Drought Index values can be mapped for any time step in the Met data table. Catchments are symbolized according to **Figure 4**, which is derived from the SPI User Guide (Svoboda et al., 2012; **Table 1**).


**Figure 4. SPI Symbology used in the Drought Management Module**

The Date field allows users to select a given time step for mapping. The slider on the right enables rapid visualization and comparison of drought conditions across the watershed at different timesteps. Additionally, users can click the “Play” button to automate the mapping and dynamically visualize drought across the model period.

The mapping tools allow users to visualize drought impacts across space and time. Droughts can be classified not just by intensity, but also by location and duration of impacts. Observing how drought patterns form, migrate, and dissipate across the watershed can inform management strategies.

## 3.4. YEAR COMPARISON CHARTS

The final feature added to the initial Drought Management module is the Year Comparison charts. These allow users to visualize the accumulation of precipitation throughout the year and contextualize different drought years. An example of these plots is shown below in **Figure 5**.

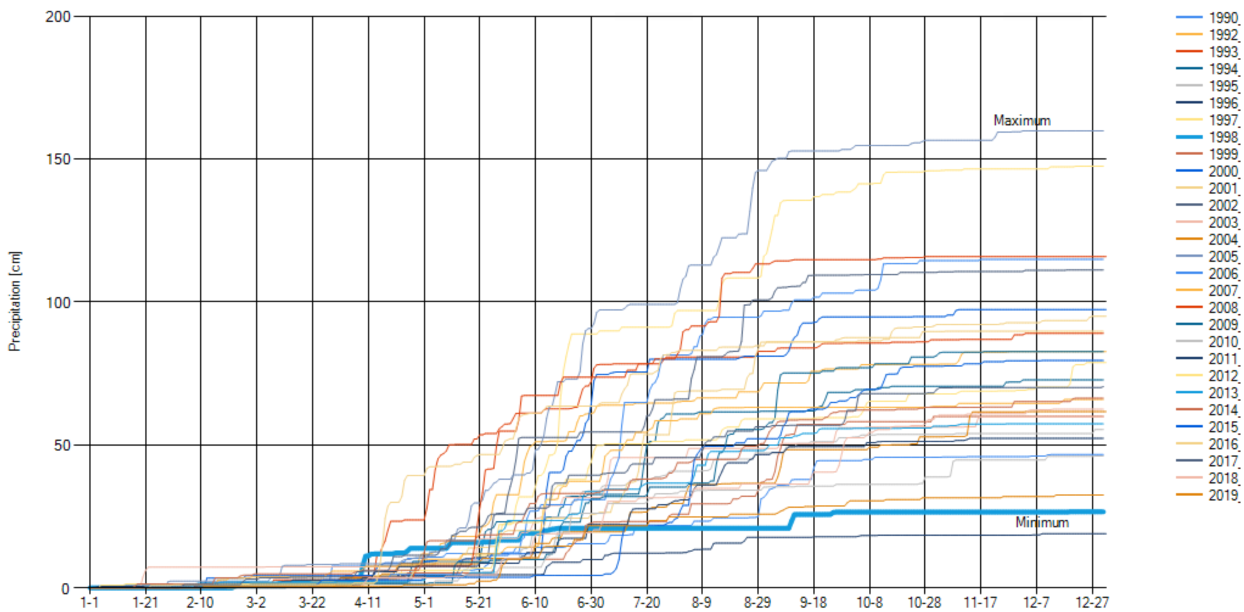


**Figure 5. Year Comparison Chart for all years at Estación 14 in the Maipo Basin. The highlighted line shows the cumulative precipitation for 1998, the second-driest year. Note the x-axis is labelled in 20-day increments.**

These plots show daily cumulative precipitation for every simulation year in a given catchment. Each year is plotted with a single line, with the minimum and maximum labelled for context. Individual years can be evaluated quickly in relation to others. For the example shown in the Maipo watershed, most precipitation falls between April and September. This can be clearly seen in **Figure 5**, with most lines staying close to zero, then rising sharply beginning in April, before flattening again in September. The right-most value on each line indicates the total cumulative rainfall for the respective year. Individual lines/years can be highlighted to give additional context.

In the example above, 1998 is highlighted. This was the second-driest year in the simulation (as indicated by the final value of the line). April 1998 had above-average precipitation, but the remainder of the wet season yielded very little rainfall, leading to a drought year.

**Model development characteristics:**

- Climate data included gauge data and gridded-derived precipitation and temperature estimates from the period spanning 1990 – 2017. **Figure 6** shows the precipitation and temperature spatial variability in the Maipo Basin.
- Natural generated flow was simulated with Hydro-BID for all 176 catchments within the basin.
- The model was calibrated using naturalized flows at 14 hydrologic stations mainly by adjusting calibration parameters of the hydrological model incorporated in Hydro-BID.
- Water demands were configured for the domestic, agricultural, industrial, mining, livestock, and energy sectors, and they were grouped at each of the 14 calibration points.
- Two main reservoirs’ operations were included in the model: El Yeso and Rungue reservoirs.
- Glacial contribution was also incorporated in the model.
- The model included historic and future scenarios to evaluate historic drought and possible impacts of projected changes in climate and demand.

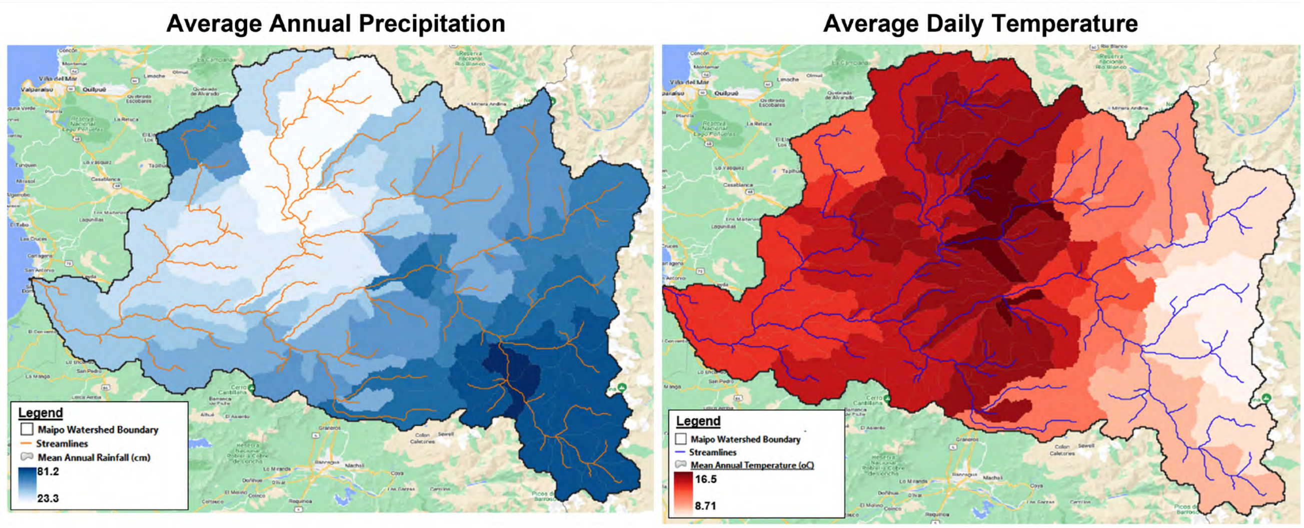


**Figure 6. Mean annual precipitation and temperature spatial variation in the Maipo Basin (1990 – 2017)**

**Figure 7** presents the MODSIM flow network created in WaterALLOC to represent the water resources system for the Maipo River Basin. The network is composed of non-storage (blue circles) nodes for each simulated catchment, which allow simulating inflows to the stream network; demand (pink square) nodes that represent consumptive water use (i.e., agricultural, domestic, industrial, etc.) grouped at the calibration points; reservoir (red triangle) nodes for modeling reservoir storage operations; and a sink (green square) node that is required to simulate downstream flows leaving the stream network.

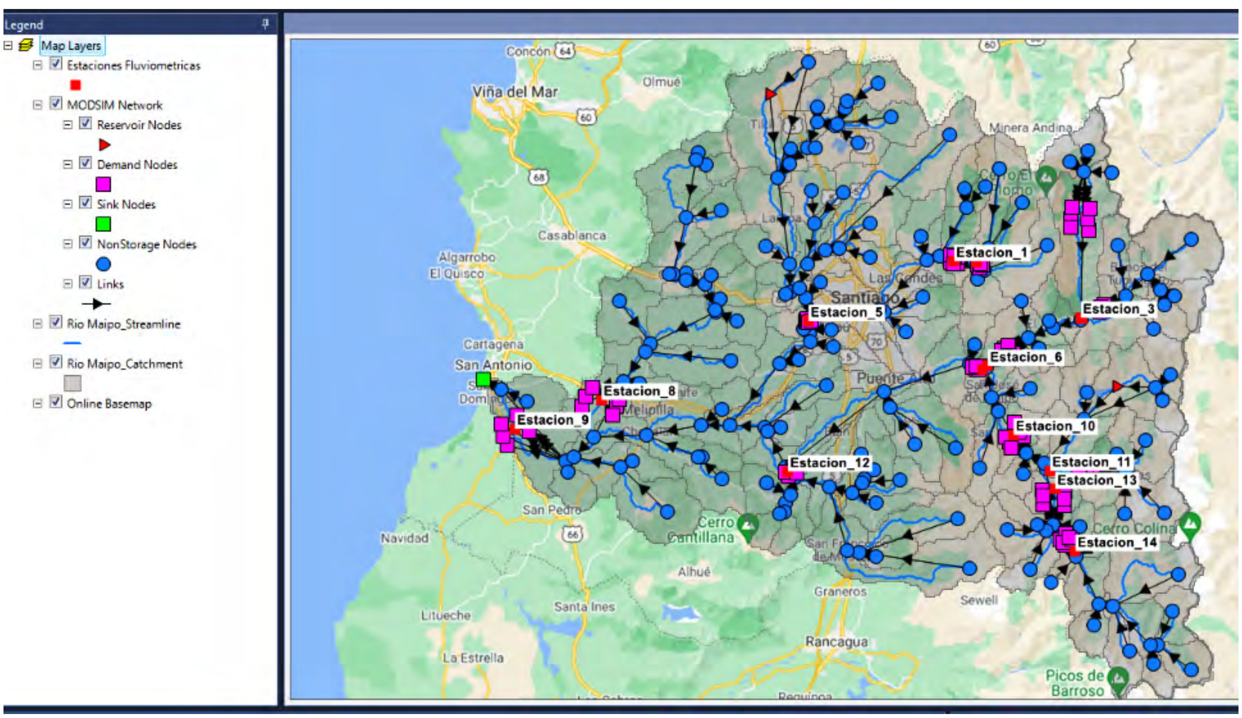


**Figure 7. MODSIM network developed for the Maipo River Basin in WaterALLOC**

## 3.5. ESTIMATION OF DROUGHT INDICES IN THE MAIPO BASIN

To quantify drought in the Maipo Basin, we utilized the Drought Management Module developed in WaterALLOC (Section 3) to calculate SPI for all catchments in the watershed. Based on the guidance of the SPI User Guide (Svoboda et al., 2012), SPI was calculated at two timescales: six-months (short-term) and 12-months (long-term).

The short-term duration of six months allows planners to visualize near-term precipitation deficits. This is particularly useful for monitoring drought conditions during the rainy, winter months in the watershed. The long-term duration of 12 months captures the total rainfall of the past calendar year, which will also include the previous year's rainy season. In a watershed with highly seasonal rainfall such as Maipo, the long-term SPI can implicitly capture the effects of snowpack and soil moisture in the headwaters. An example of SPI values during drought conditions for both durations is shown in **Figure 8**.

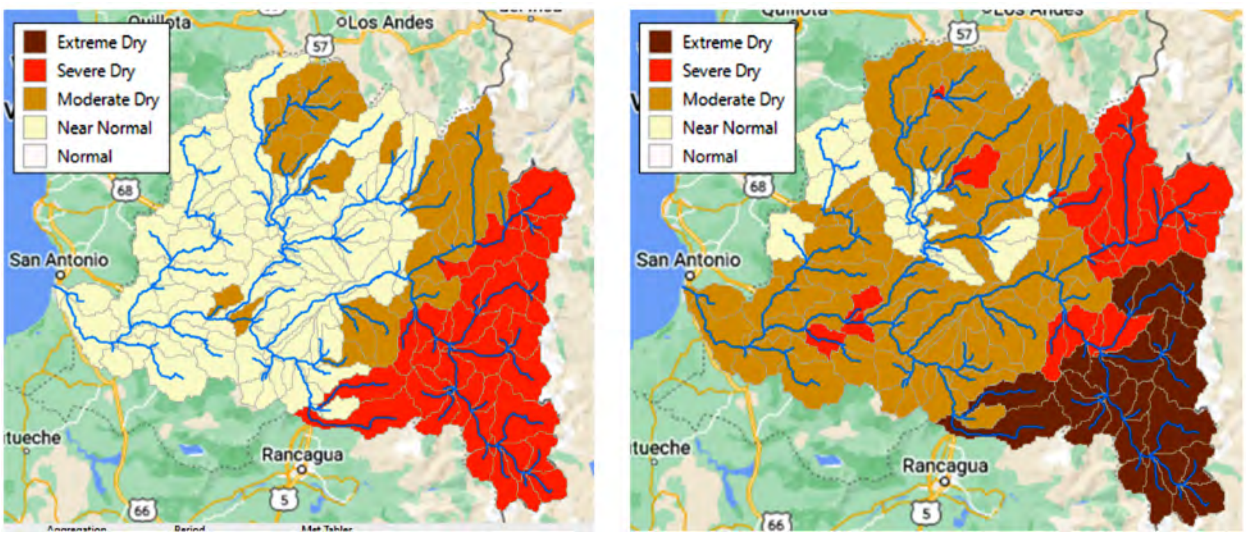


**Figure 8. Short-term (left) and Long-term (right) SPI values for the Maipo watershed on August 1, 1996. The long-term SPI values indicate a more severe drought than short-term values. 1996 is the year with lowest precipitation in the model.**

SPI was considered at a single point in the watershed rather than for all points for the drought management plan. This allows managers to simplify analysis, but care must be taken in selection of the location. Estación 14, located in the southeastern headwaters, was selected for further analysis. This station is located in a high-precipitation area and is an effective indicator of conditions throughout the watershed. The maps above consistently show Estación 14 as a leading indicator of drought conditions in the remainder of the watershed.

**Figure 9** shows the time series of near-term (six months) and long-term (12 months) SPI values alongside monthly precipitation from 1991 to 2017. Both SPI trends are highly dependent on rainfall. Following periods of low rainfall, both SPI trends show drought conditions emerging. If conditions remain dry, SPI intensifies and enters more severe drought phases. SPI values slowly approach positive values as rain occurs and conditions move closer to average.

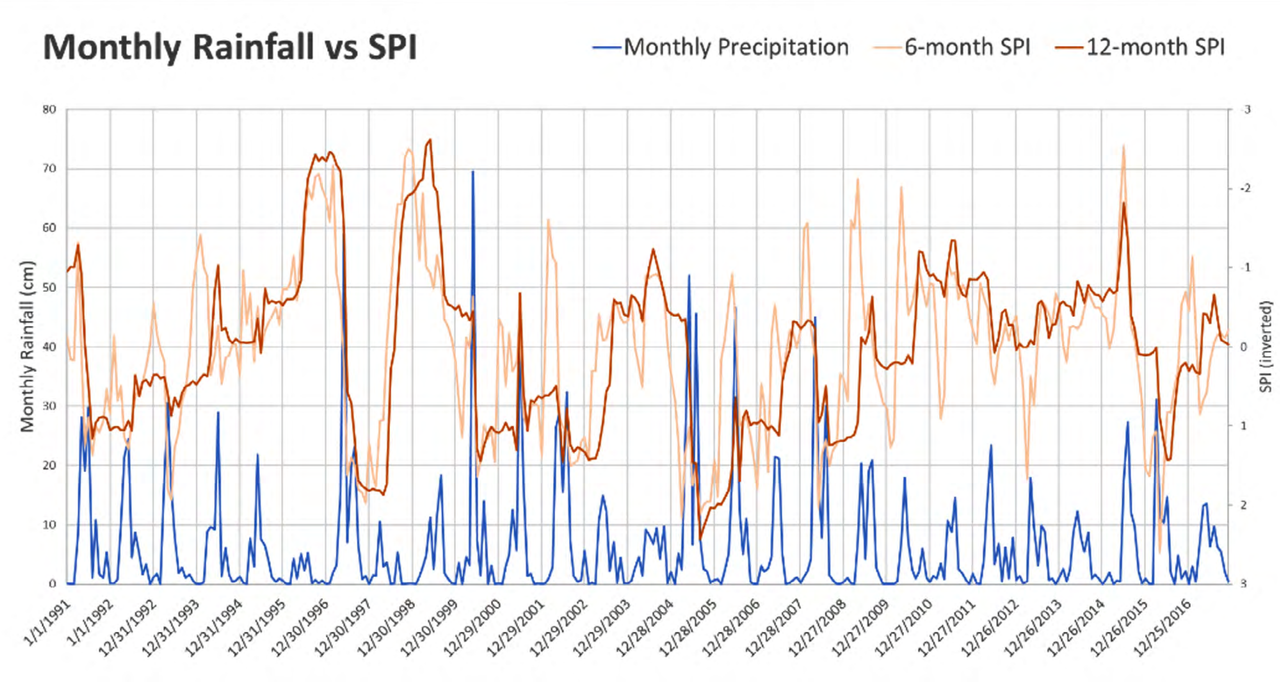


**Figure 9. Near-term and Long-term SPI plotted against monthly rainfall. Note that SPI is on the right-side axis and is inverted for ease of view**

While both SPI time series follow the same overall trend, the six-month trend is much noisier than the 12-month trend. Near-term drought classified by SPI is characterized by rapid onset and exit of drought conditions. By contrast, the 12-month SPI is less reactive to short-term rainfall and stabilizes the trends over an annual time frame. For the purposes of drought management and analysis of historic events, the 12-month SPI is more appropriate in the Maipo watershed.

### 3.5.1. Detailed SPI analysis

A more detailed view of the 12-month SPI values and monthly rainfall from 1994 to 2000 is shown in **Figure 10**. This period catches multiple extreme events. 1995 and 1994 provide near-normal conditions in the watershed (SPI values between -1 and 1). Rainfall seasonality is clearly visible, with yearly spikes in rainfall corresponding to the rainy seasons. However, the rainy season in 1996 has significantly lower rainfall than previous years, indicating the possible onset of drought conditions. SPI quickly decreases in April and May of 1996, confirming the rapid intensification of drought. From July 1996 to June 1997, the 12-month SPI characterizes "Extremely Dry" conditions in the watershed.

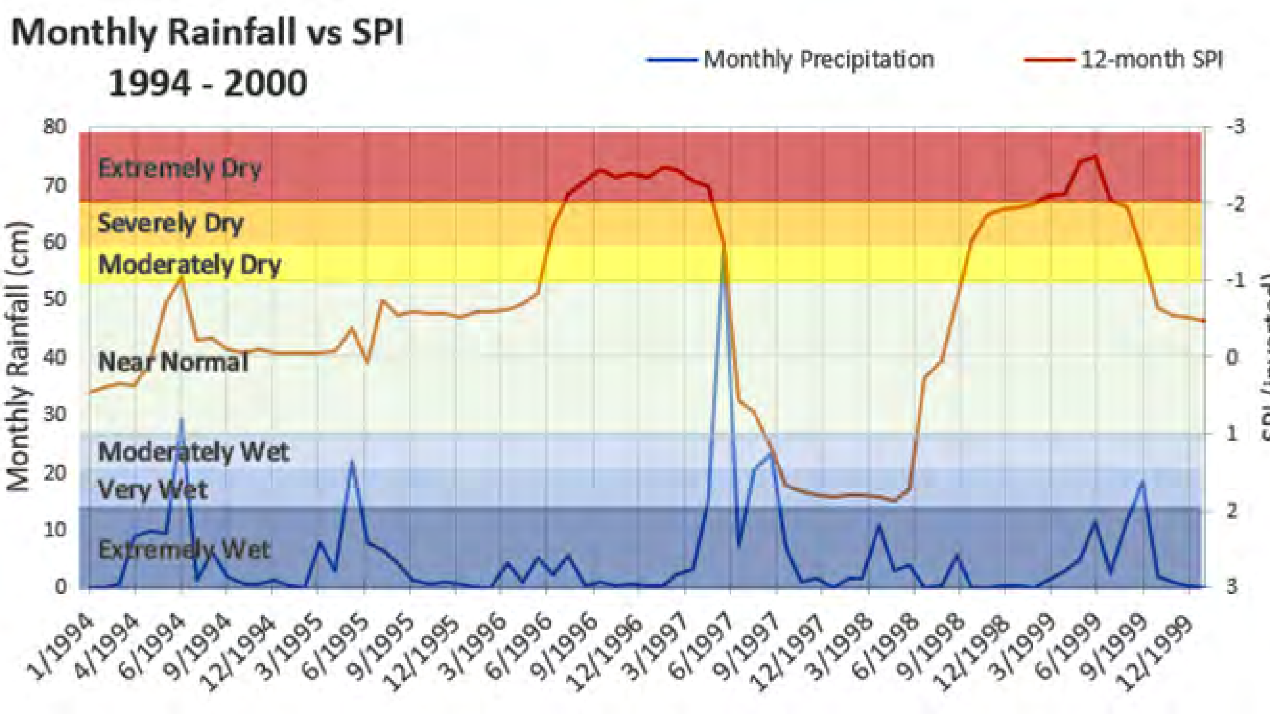


**Figure 10. Detailed view of 12-month SPI from 1994 to 2000. Note the large fluctuations in SPI value between 1996-1998, indicating onset and retreat of drought conditions.**

An extremely wet July in 1997 provides relief from drought conditions. SPI quickly rises as the following months continue to bring large amounts of rainfall. By the end of 1997, SPI indicates the watershed has entered "very wet" conditions. However, another abnormally dry rainy season in 1998 causes the watershed to enter drought conditions again. Note that rapid changes in drought conditions occur primarily during the wet season. Months with little to no rainfall during normal conditions have an extremely small effect on SPI. Since most rainfall occurs during the wet season, any deviations from normal in this time period will have an amplified impact on SPI values.

Further analysis using the Year Comparison Chart (**Figure 11**) confirms these findings. 1996 was the driest year on record (shown as the minimum), whereas 1997 was the second wettest. This was followed by the second driest year on record in 1998 (**Figure 5**).

Given that the severity of the consequences of drought vary greatly depending on its location, timing, extent, and that the trend in SPI varies by season, recommendations for future work include conducting a vulnerability analysis of long-term drought and extreme climate patterns that will further understanding of spatial and temporal patterns in drought occurrence throughout the Maipo Basin.

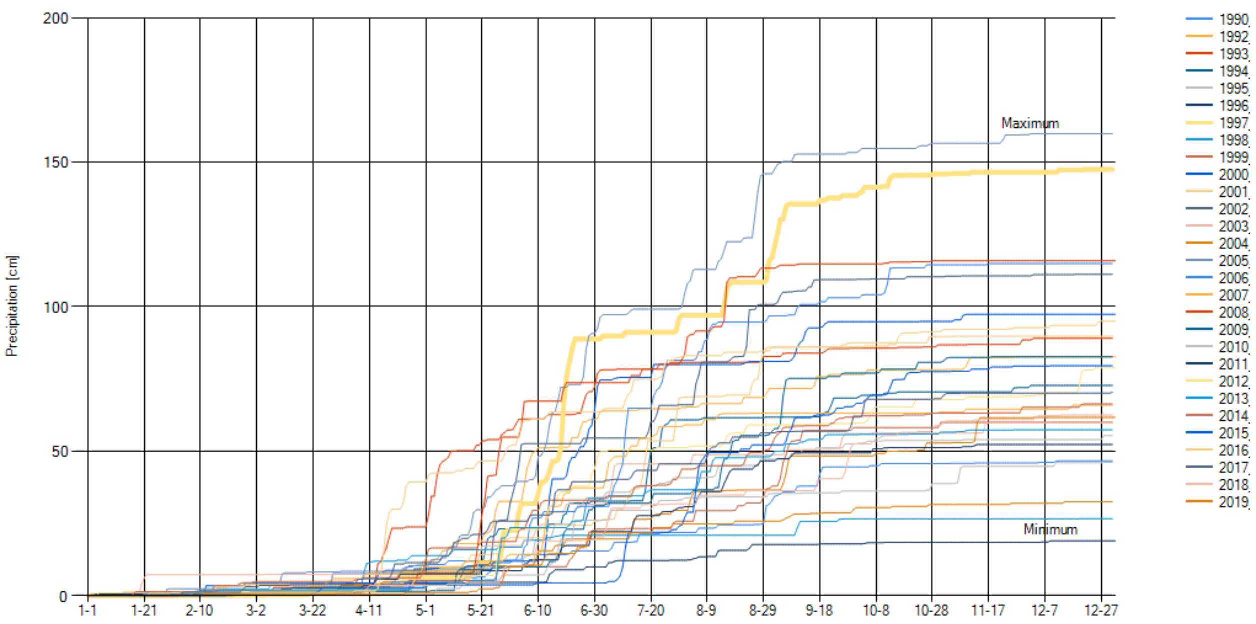


**Figure 11. Year Comparison Chart at Estación 14. 1996 is the minimum year. 1997 is highlighted in yellow and is the second wettest year. Note the x-axis is labelled in 20-day increments.**

## 3.6. DROUGHT IMPACTS IN THE MAIPO RIVER BASIN

To evaluate drought impacts in the Maipo Basin, we set up a baseline scenario in WaterALLOC. The baseline scenario allows us to understand reference conditions that will be used for comparison purposes and to evaluate impacts of future conditions in the basin. Also, the baseline scenario allows us to know the value of the indicators at the time of initiating the planned actions; that is, it establishes the starting point of an intervention or strategy to mitigate droughts.

The baseline scenario simulation assumes current water demand superimposed on the historical hydrology context. This simulation represents water allocation conditions that would have happened if current demand levels were required in the past hydrology. Current demand levels were assumed to have the same level as 2017 monthly demand for every year of the simulation.

Results of the baseline scenario show that the average monthly simulated shortages were 13 hm3 for the entire Maipo Basin. Shortages are estimated by the difference between water demand and water supply and are only observed when water demand is higher than the amount of water supplied. Shortages can be estimated for each demand node and type, at each calibration point, and/or at the basin scale. It is important to note that the simulated water supply to the demands included in the model not only depends on the amount of water available in the basin, but also on the priority distribution configured in the model. **Figure 12** displays the 12-month SPI values and the monthly shortages for the simulation period 1991-2017. Average peak shortages occurred during the drought events of 1996/97 and 1998/99, where it can be observed that the 12-month SPI is below -1.

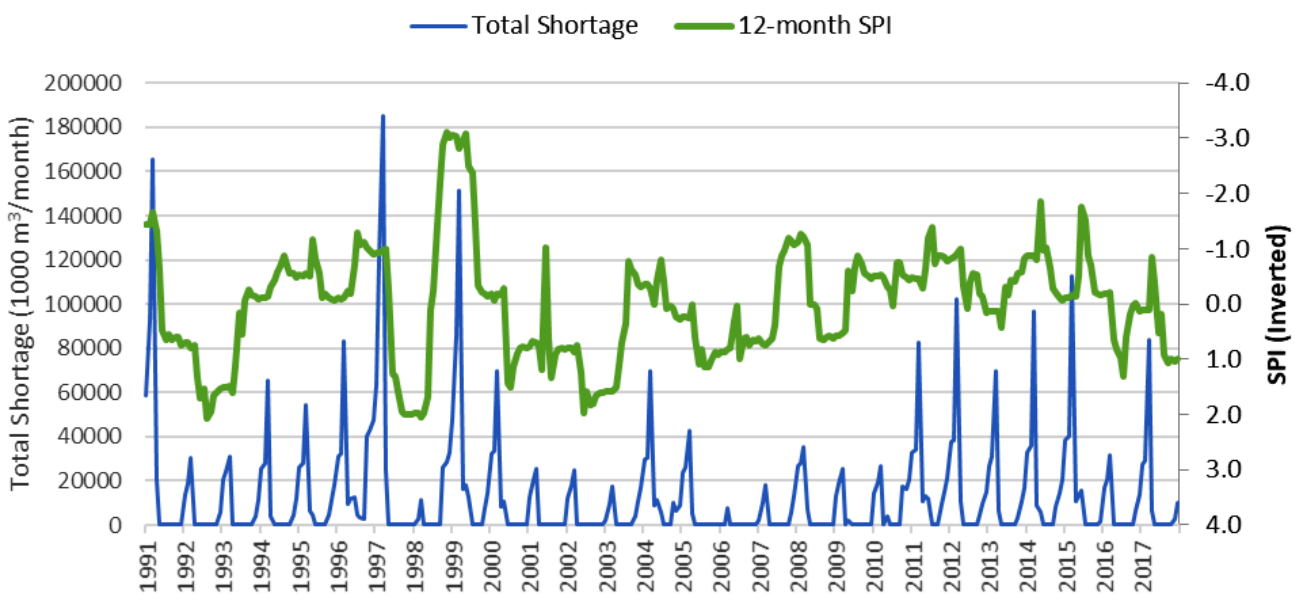


**Figure 12. Total shortages under the baseline scenario versus the 12-month SPI values**

Shortages are mainly observed in the middle and lower parts of the basin (**Figure 13**), specifically in the demand nodes around calibration stations 12, 8, 9, and 5, representing 70%, 17%, 11%, and 1% of the total shortages simulated in the basin, respectively (**Table 2**).

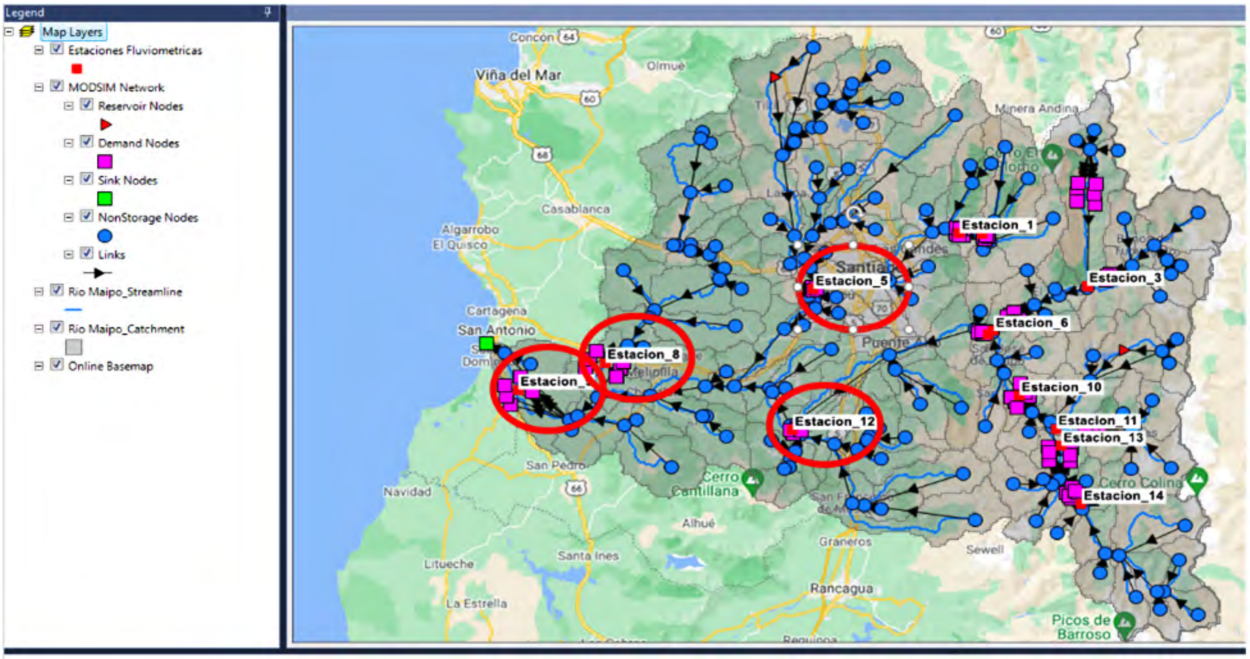


**Figure 13. Location of shortages simulated in the Maipo Basin**

**Table 2. Total shortages simulated around each of the calibration points**

| Calibration point | Location Name | Total Shortages (1000 m³) | % of Total Shortage |
|---|---|---|---|
| Estación_1 | Río Mapocho Alto | 8,357 | 0% |
| Estación_2 | Río Mapocho Alto | 4,094 | 0% |
| Estación_3 | Río Maipo Alto | 0 | 0% |
| Estación_4 | Río Maipo Alto | 0 | 0% |
| Estación_5 | Río Mapocho Bajo | 66,594 | 1% |
| Estación_6 | Río Maipo Alto (Hasta Despues Junta Rio Colorado)D | 0 | 0% |
| Estación_7 | Río Maipo Medio | 7 | 0% |
| Estación_8 | Río Maipo Bajo (Entre Rio Mapocho Y Desembocadura) | 853,268 | 17% |
| Estación_9 | Río Maipo Bajo (Entre Rio Mapocho Y Desembocadura) | 548,756 | 11% |
| Estación_10 | Río Maipo Alto | 0 | 0% |
| Estación_11 | Río Maipo Alto | 0 | 0% |
| Estación_12 | Río Maipo Medio | 3,512,785 | 70% |
| Estación_13 | Río Maipo Alto (Hasta Después Junta Rio Colorado) | 0 | 0% |
| Estación_14 | Río Maipo Alto (Hasta Después Junta Rio Colorado) | 0 | 0% |
| | **Total** | **4,993,860** | |

Basin-wide, the agricultural sector accounts for 93% of total shortages and the domestic sector for 6%. Nevertheless, as shown in **Figure 14**, shortage distribution by sectors can differ at each calibration point. Simulated shortages in the domestic sector are higher around calibration station 5, mainly because this is where the city of Santiago is located.

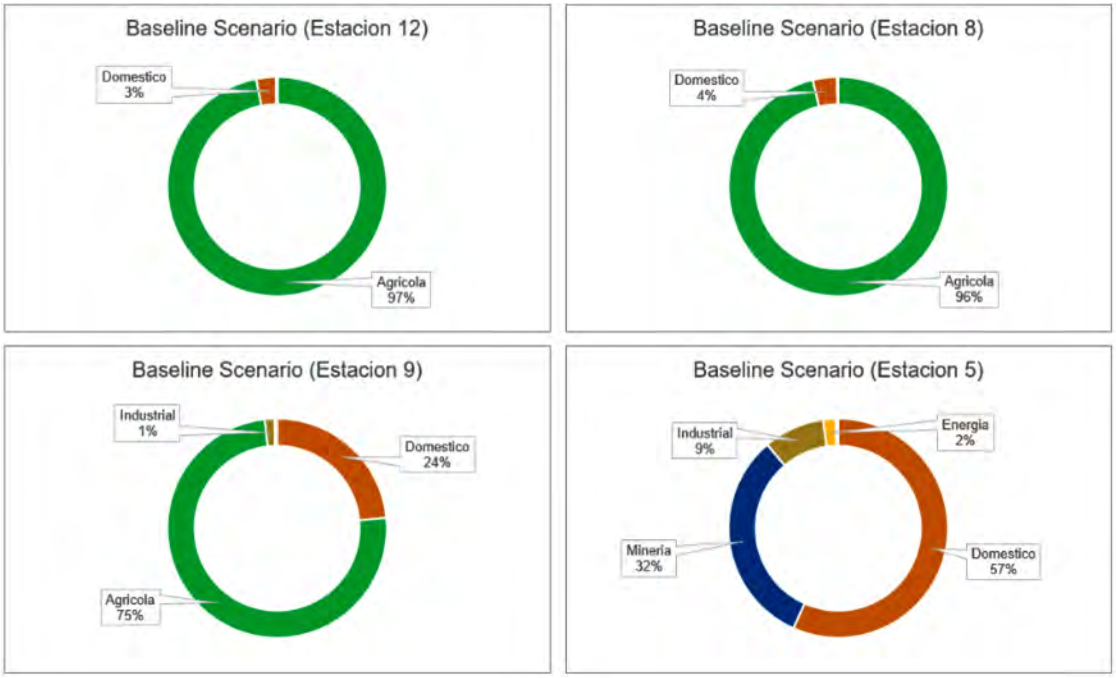


**Figure 14. Shortage distribution by sector**

## 3.7. DROUGHT MANAGEMENT PLAN

For the development of a Drought Management Plan, we conducted the following standardized steps (Watercare, 2020):

1. Classify drought stage using a locally appropriate indicator, such as reservoir storage levels, observed streamflow, or drought index values

To declare a drought event depends on the context. For example, severity of a past drought event is often measured by the sum of monetary losses due to occurred negative impacts; whereas, drought detection is based on thresholds, thus monitoring of drought-related variables, such as precipitation and streamflow (Oertel et al. 2021). Minimizing negative drought impacts is feasible if drought events are detected as early as possible. Early drought detection is an ongoing challenge in drought research, and several improvements in detection methods have been presented in recent years.

Drought detection methods have mainly been based on the analysis of precipitation records. Drought indices are tools used to synthesize information and present it as a single value, which can be used easily for communication purposes. The variety of drought indices reflects the diversity of drought definitions and classifications; hence, there is no unique drought index satisfying all requirements. Given the number of different indices and the complexity of the phenomenon, for illustration purposes, we selected for this case study the 12-month SPI as the drought indicator for the Maipo Basin. More detail is provided on the selection in Section 4.3.

2. Identify threshold levels of indicator at which actions are needed to mitigate impacts

The set threshold for our analysis was -1, which is frequently used to determine severely dry periods (Guttman 1998). With additional time and stakeholder feedback, a more precise SPI threshold could be selected for the Maipo Basin by comparing calculated SPI values against observed experiences during historical drought events. This was conducted for this analysis by comparing simulated shortage levels against SPI values.

3. Identify key impacts to be avoided (for example, loss of domestic water supply or maintaining navigability in a stream reach)

The variables we selected to evaluate drought impacts for this case study were the loss of water to users -- in other words, water deficits or shortages -- and the reduction of stream flow in Angostura River.

4. Develop strategies for mitigating key impacts, such as demand management or infrastructure design

Our mitigation strategy consisted of a rule-based demand management system, where water demand restrictions were implemented when the drought indicator (12-month SPI) was below the selected threshold of -1. Water demand restrictions were applied throughout the basin, for all demand nodes represented in the model, regardless of whether they were experiencing shortages. This implies shared responsibility across sectors to reduce water consumption in the event of a drought. We conducted a sensitivity analysis to evaluate the impact of different levels of water demand restrictions: at 10%, 20%, 30%, 40%, and 50% demand reductions from the baseline conditions.

**Figure 15** highlights when SPI indicates moderately dry conditions under the baseline scenario, and therefore drought conditions area triggered and demand management strategies were implemented in the basin.

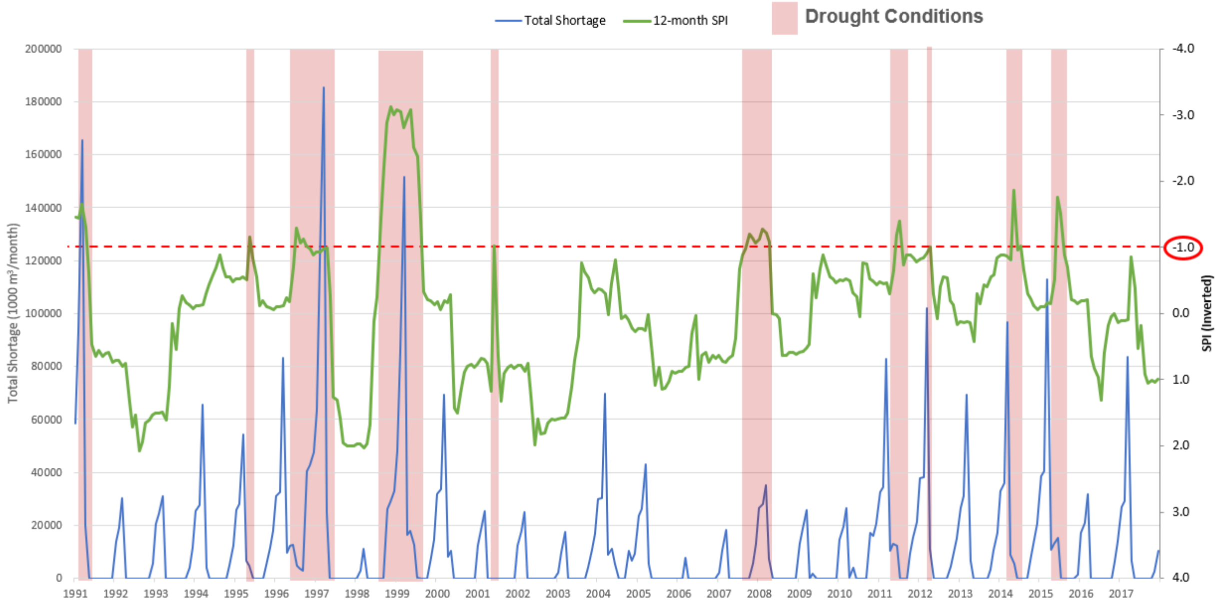


**Figure 15. Total shortages under the baseline scenario versus the 12-month SPI values, highlighting the periods when drought conditions were triggered**

The results of the sensitivity analysis show that with mild demand management measures, such as reducing demand in the entire basin by 10% when drought conditions were triggered, the total water shortage was reduced by 5%. By contrast, with severe measures, such as reducing demand by 50%, it is possible to reduce shortages by 16% (**Figure 16**).

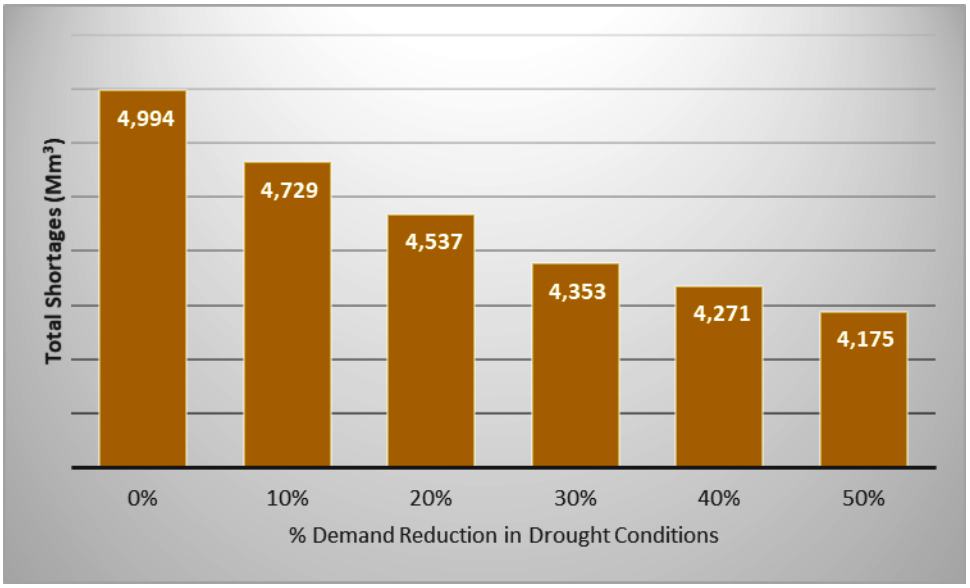


**Figure 16. Total shortages in the Maipo Basin at different levels of demand management reduction**

Although there is a directly proportional relationship between demand measures and water deficits or shortages at the basin level, what we see is that the stricter the demand reduction measures, the greater the reductions in water deficits. We must point out, however, that this relationship does not hold at some calibration points. For instance, at calibration Estación 9, the highest reduction in water shortages is achieved under a 40% demand reduction scenario, and for Estación 8, there is not significant change in shortages under the 40% and 50% demand reduction scenarios (**Figure 17**).

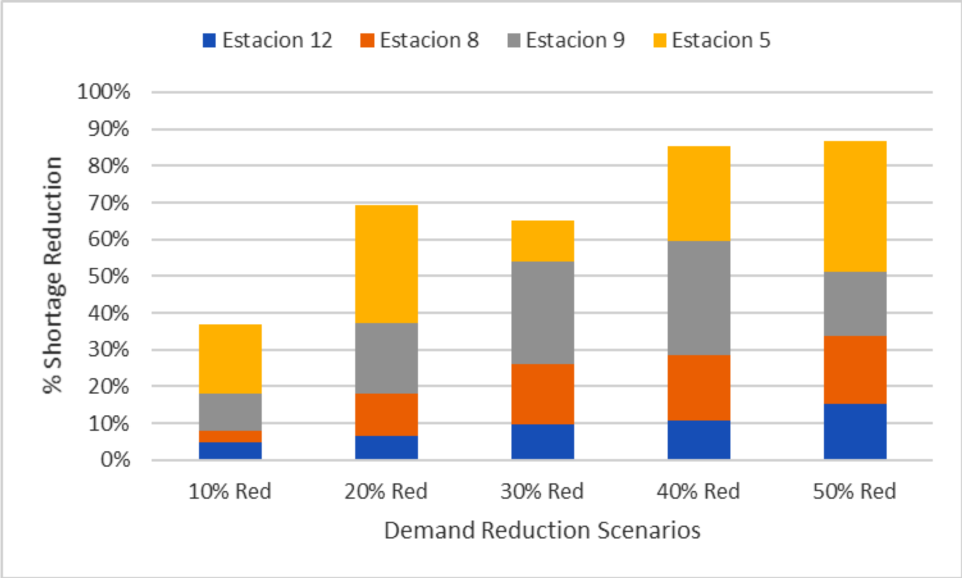


**Figure 17. Percent of shortages reduction under different demand reduction scenarios**

Additionally, the distribution of the shortages by production sectors does not vary among the demand management scenarios at calibration stations 12 and 8, located at the middle and lower parts of the Maipo River, respectively, where agricultural activities are dominant (**Figure 18**). On the other hand, the distribution of the shortages by production sectors at Estación 9 and 5 changes significantly depending on the demand management scenario. For instance, at Estación 9, 75% of the shortages are seen in the agricultural sector under baseline conditions, but under the 10%, 20%, and 50% demand reduction scenarios, water shortages in the agricultural sector are 20%, 67%, and 81%, respectively. It is important to note that these results are highly dependent on the configurations of the cost (priorities) of water allocation assigned in the model to meet water demand. For instance, it was noted that all demands in the model were set with the same priority for water allocation, which is not optimal for achieving a feasible network solution, particularly under water scarcity scenarios. Details in the model configuration can be obtained in the report (CEA, 2021), where Hydro-BID and WaterALLOC configurations are described.


**Figure 18. Total shortages distribution by sectors, for different demand management reduction strategies**

The effect of the drought management strategies' implementation in the stream flows in Angostura River are presented in **Figure 19**. In-stream flow can be important for managing aquatic ecosystems, political agreements, and navigability. This is a demonstration approach; other locations in the watershed may be more important for decisionmakers.

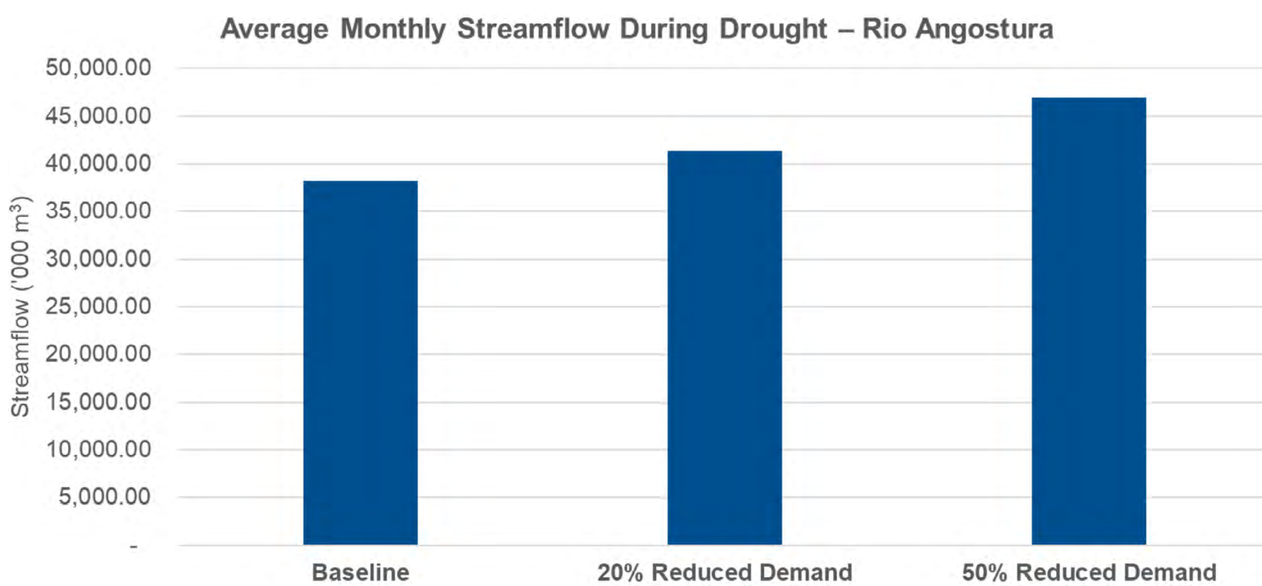


**Figure 19. Average monthly streamflow during drought at Río Angostura**

# 4. CAPACITY BUILDING

A capacity training program using analytical tools was delivered, with the objective of strengthening technical capacities of local stakeholders in water resource management and planning. This activity was carried out in tandem with other project activities so that local officials could acquire the necessary knowledge and technical skills on data preparation, configuration, and implementation of the water assessment models.

Under the training program provided, local officials were trained to:

- Apply Hydro-BID and WaterALLOC as tools for efficient water resource management.
- Assess the effects of climate change, population growth, and changes in demand on the availability and variability of water resources.
- Develop specialized analyses in the basins that include the simulation of demands and water infrastructure (reservoirs, transfers, drinking water treatment plants, among others).
- Prepare data series to configure models and analyze results obtained with these tools to serve as input for preparation of basin management plans.

The training program consisted of four virtual sessions of two-and-a-half to three hours, conducted in December 2020, which covered the theory, configuration, and application of the water resources assessment tools, Hydro-BID and WaterALLOC. **Figure 20** shows the training program topics. The training program was designed and based on the "learning by doing" approach, where participants could process the required data and configure and calibrate the models in the basins of interest through theoretical concepts, guided exercises, and practical sessions.

Different stakeholders participated in the training program, including the CEA, Universidad de Desarrollo (UDD), Universidad de Concepción (UDEC), and Fundación Chile.

In addition to the training program, a session about the Drought Management Module developed in WaterALLOC was carried out on November 30, 2021. That session covered drought management theory, drought module development in WaterALLOC, and an overview of the case study implemented in the Maipo Basin. The same stakeholders above participated in this session. During this session, time was offered for discussion of the methodology and recommendations, but no participant feedback was obtained.

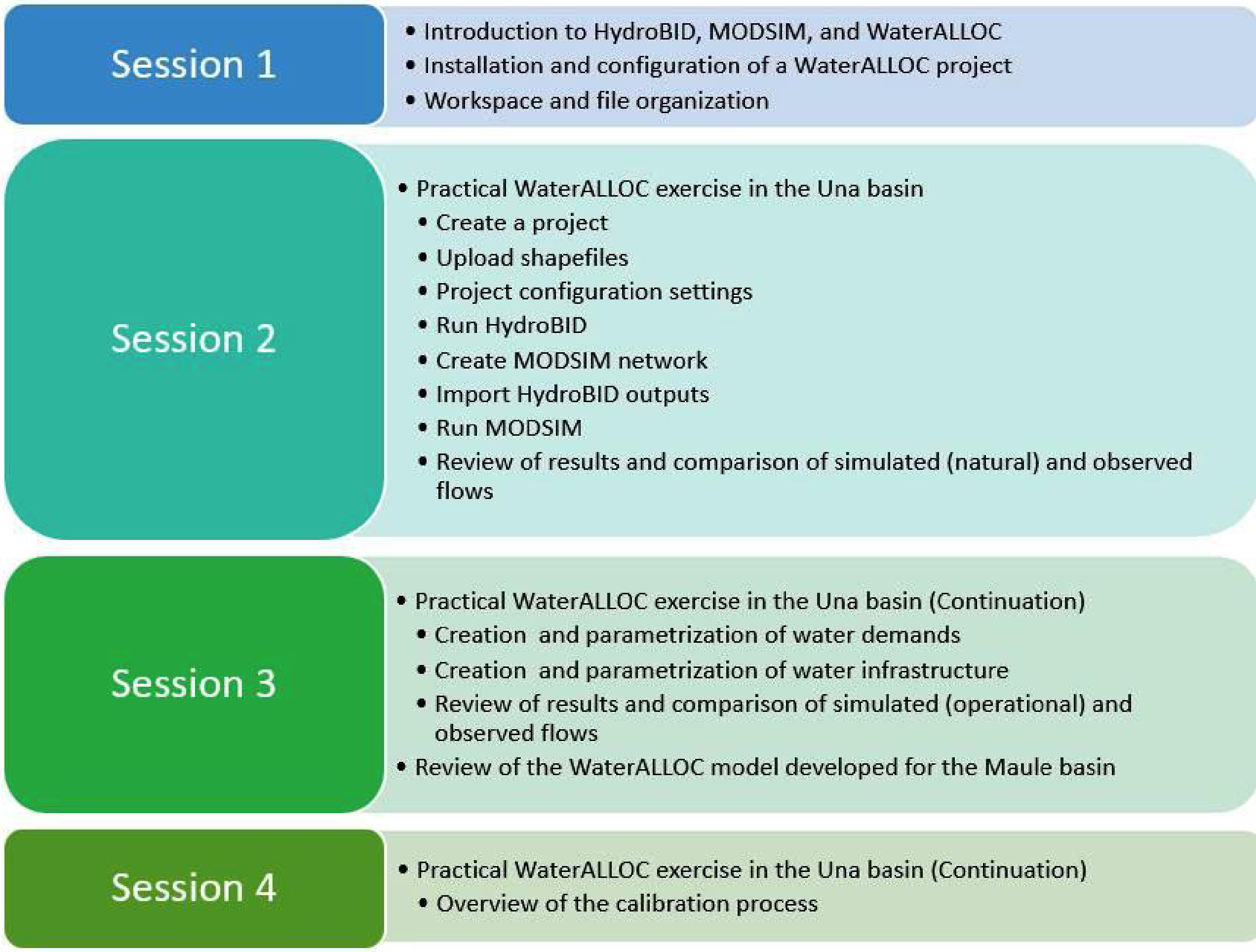


**Figure 20. Topics covered in the capacity training program**

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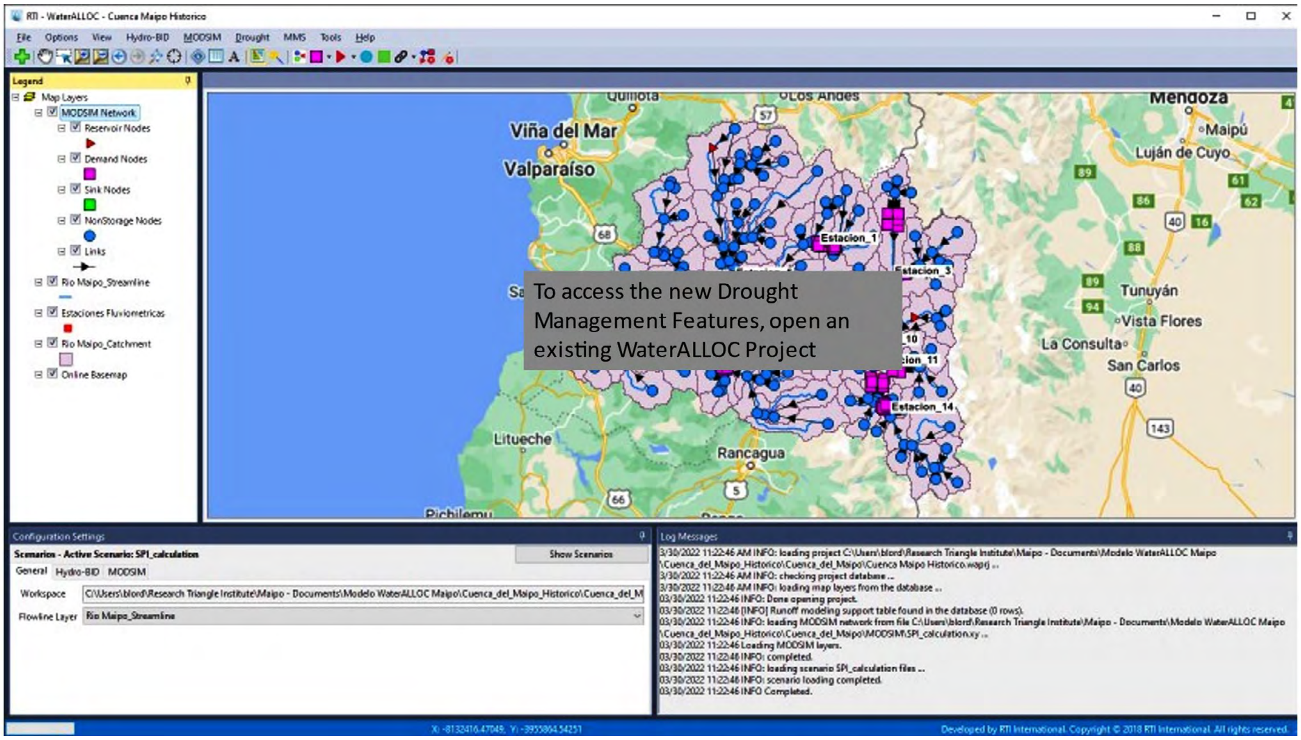
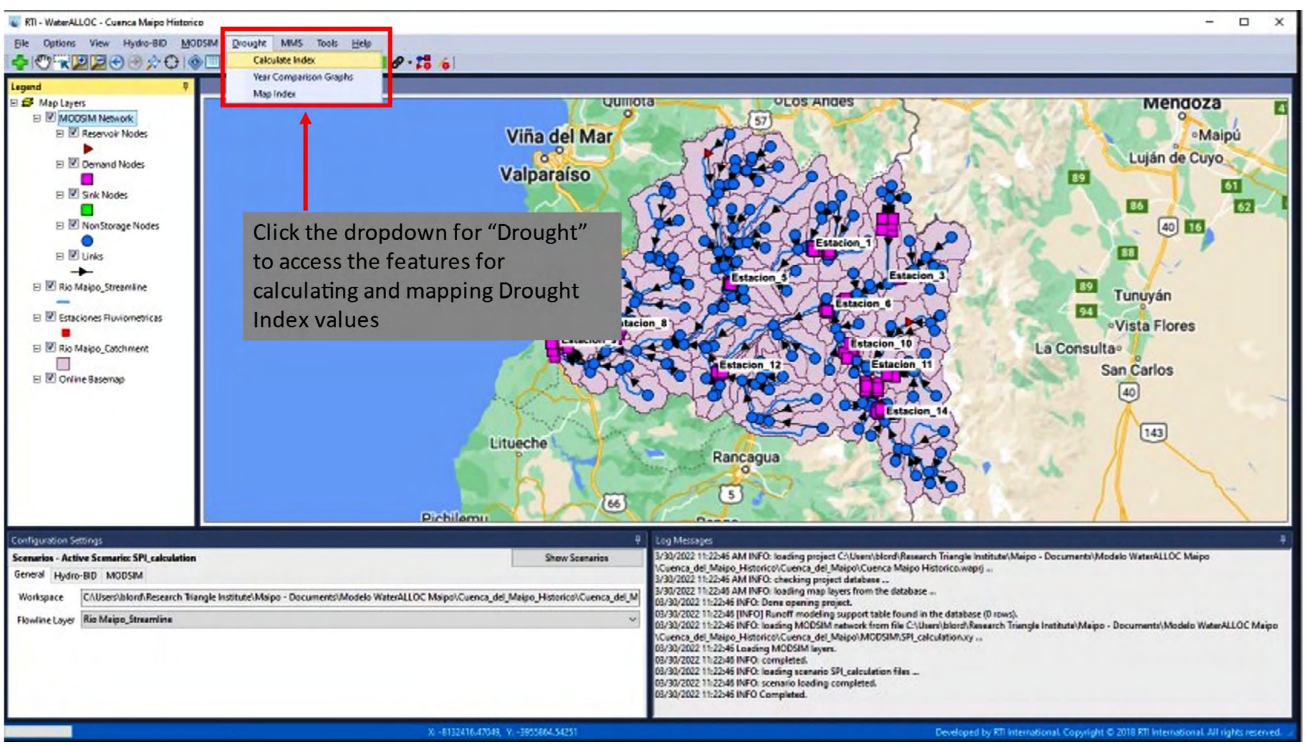
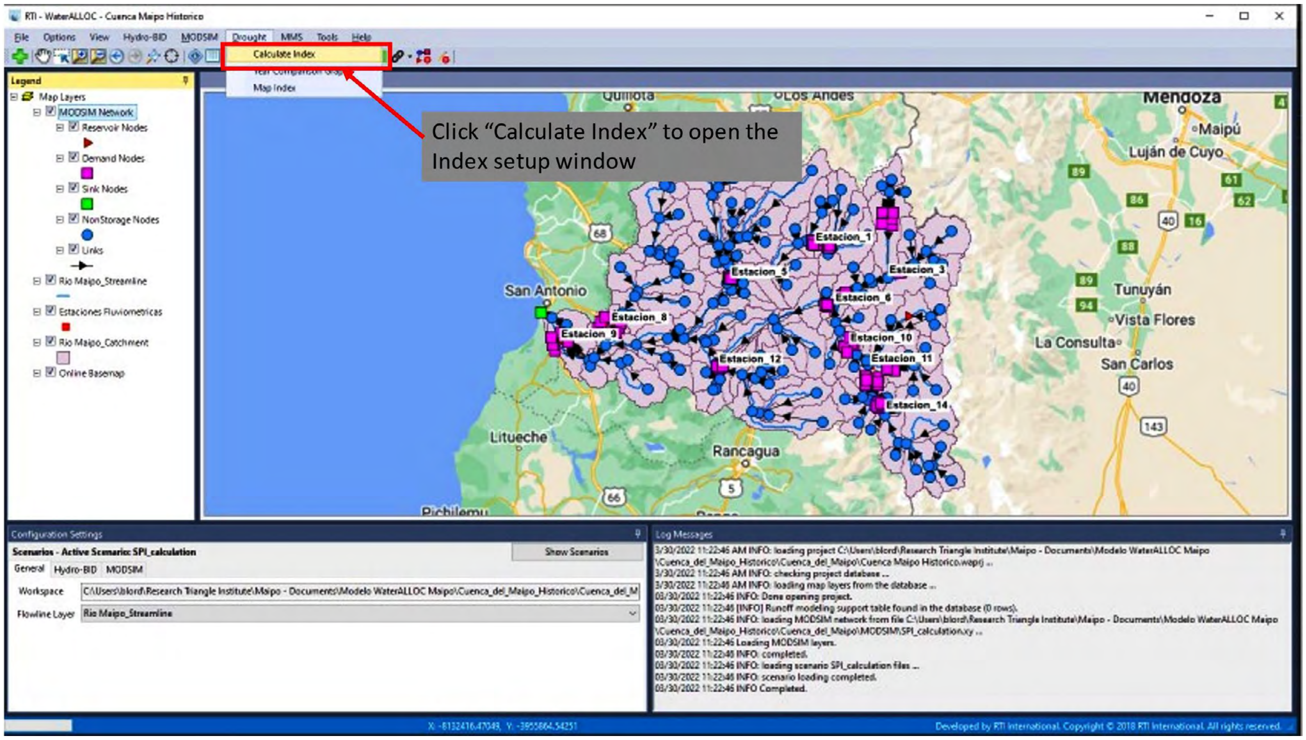
# APPENDIX 1 – WaterALLOC DROUGHT FEATURES WALKTHROUGH

The following guide (beginning on the next page) provides users a step-by-step walkthrough of the new drought management features in WaterALLOC.


RTI - WaterALLOC - Cuenca Maipo Historico
To access the new Drought Management Features, open an existing WaterALLOC Project
Developed by RTI International. Copyright © 2018 RTI International. All rights reserved.


RTI - WaterALLOC - Cuenca Maipo Historico
Drought
Calculate Index
Year Comparison Graphs
Map Index
Click the dropdown for "Drought" to access the features for calculating and mapping Drought Index values
Developed by RTI International. Copyright © 2018 RTI International. All rights reserved.


RTI - WaterALLOC - Cuenca Maipo Historico
Calculate Index
Map Index
Click "Calculate Index" to open the Index setup window
Legend
Map Layers
MODSIM Network
Reservoir Nodes
Demand Nodes
Sink Nodes
NonStorage Nodes
Links
Rio Maipo_Streamline
Estaciones Fluviometricas
Rio Maipo_Catchment
Online Basemap
Configuration Settings
Log Messages
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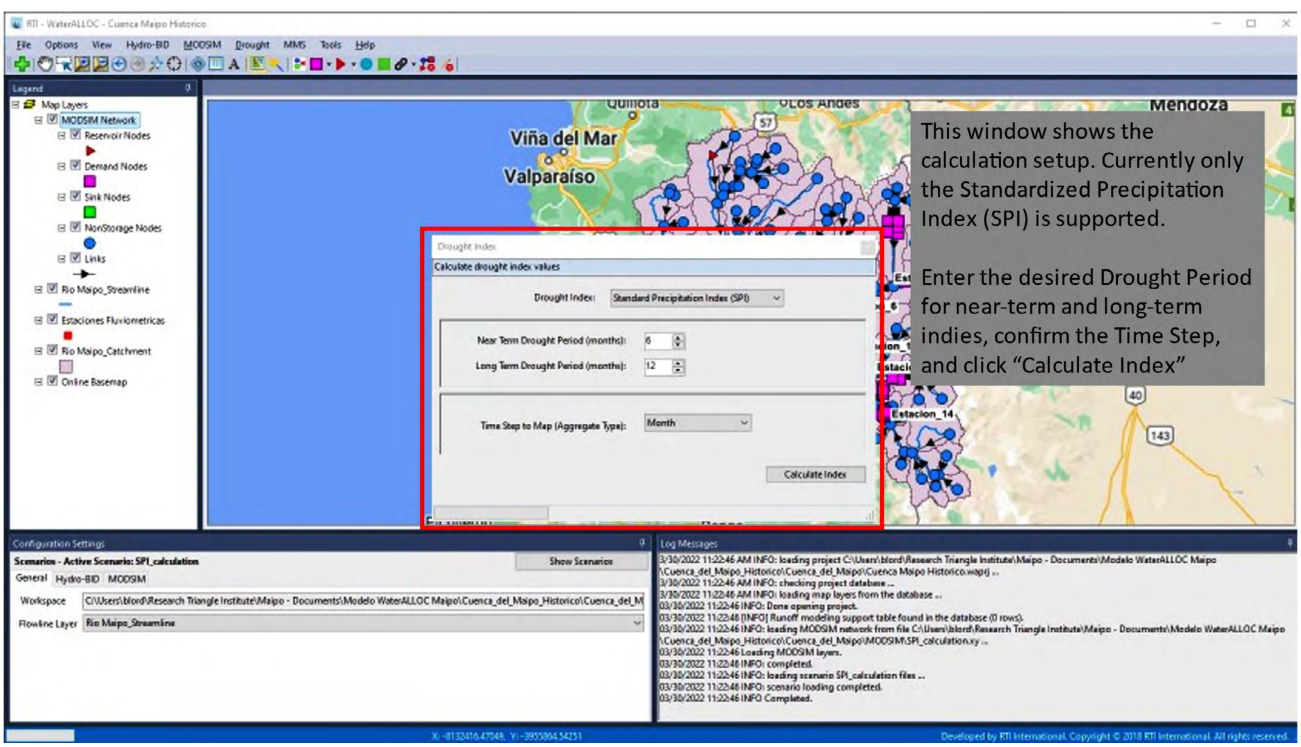
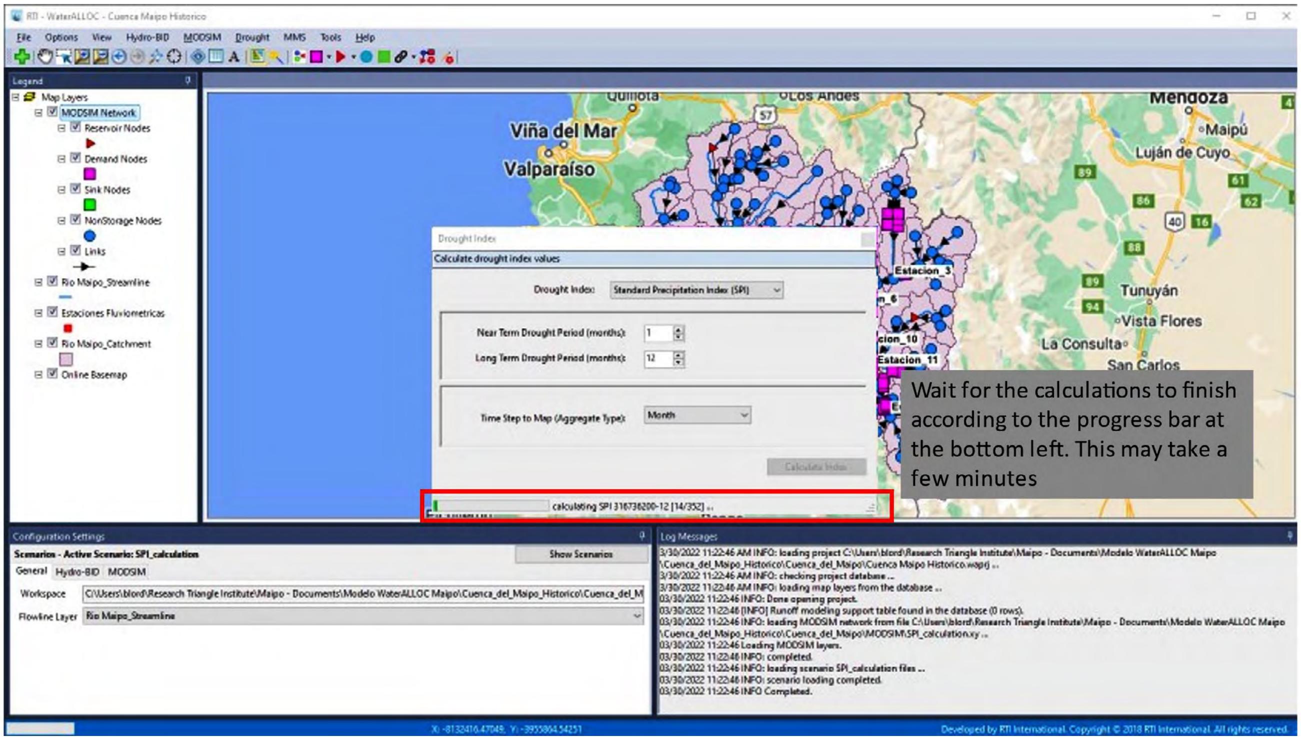
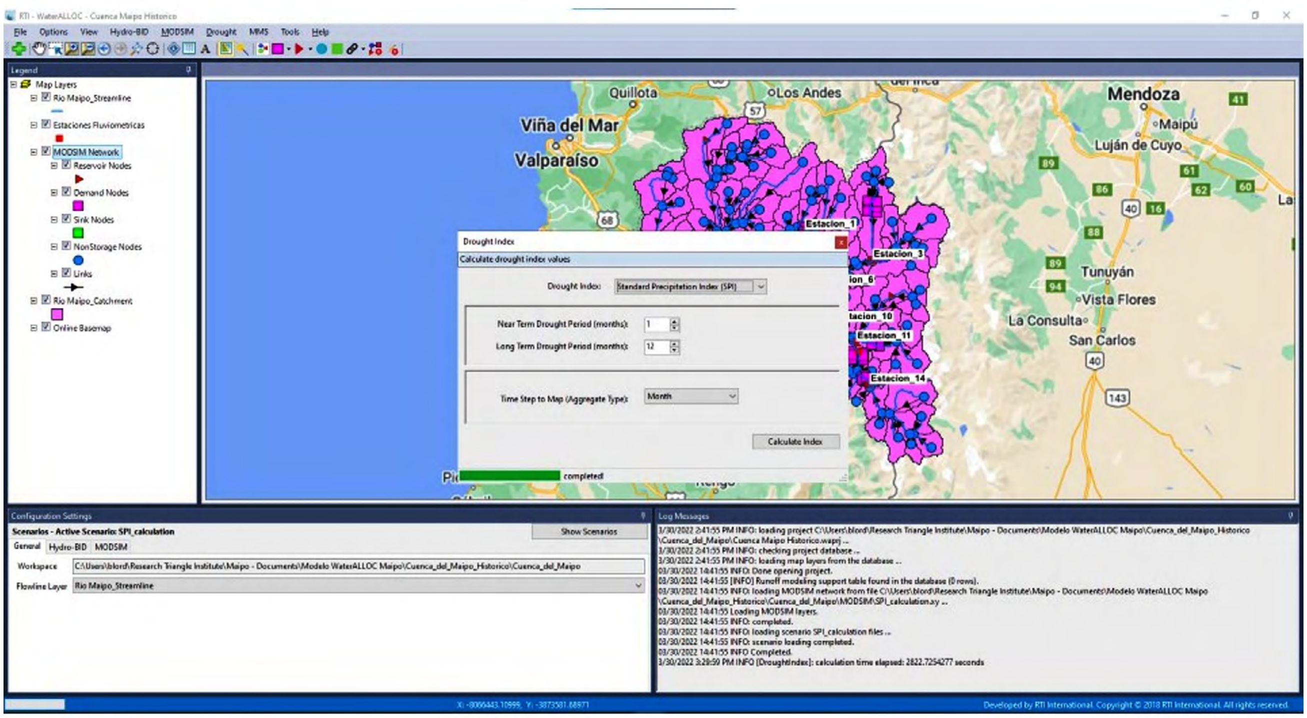

This window shows the calculation setup. Currently only the Standardized Precipitation Index (SPI) is supported.
Enter the desired Drought Period for near-term and long-term indies, confirm the Time Step, and click "Calculate Index"
Drought Index
Calculate drought index values
Drought Index:
Standard Precipitation Index (SPI)
Near Term Drought Period (months):
6
Long Term Drought Period (months):
12
Time Step to Map (Aggregate Type):
Month
Calculate Index


RTI - WaterALLOC - Cuenca Maipo Historico
Drought Index
Calculate drought index values
Drought Index: Standard Precipitation Index (SPI)
Near Term Drought Period (months): 1
Long Term Drought Period (months): 12
Time Step to Map (Aggregate Type): Month
Calculate Index
calculating SPI 316736200-12 [14/352] ...
Wait for the calculations to finish according to the progress bar at the bottom left. This may take a few minutes
Configuration Settings
Log Messages
Developed by RTI International. Copyright © 2018 RTI International. All rights reserved.


RTI - WaterALLOC - Cuenca Maipo Historico
Drought Index
Calculate drought index values
Drought Index: Standard Precipitation Index (SPI)
Near Term Drought Period (months): 1
Long Term Drought Period (months): 12
Time Step to Map (Aggregate Type): Month
Calculate Index
completed
Configuration Settings
Log Messages
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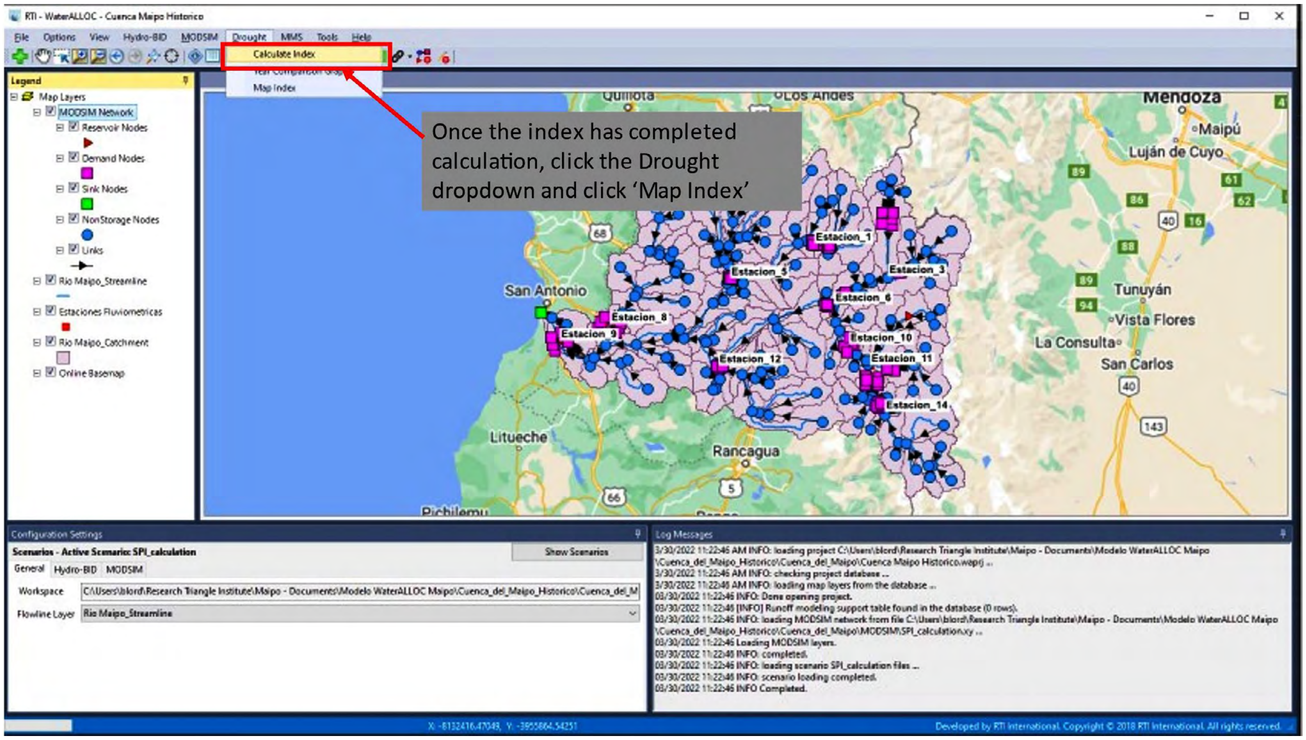
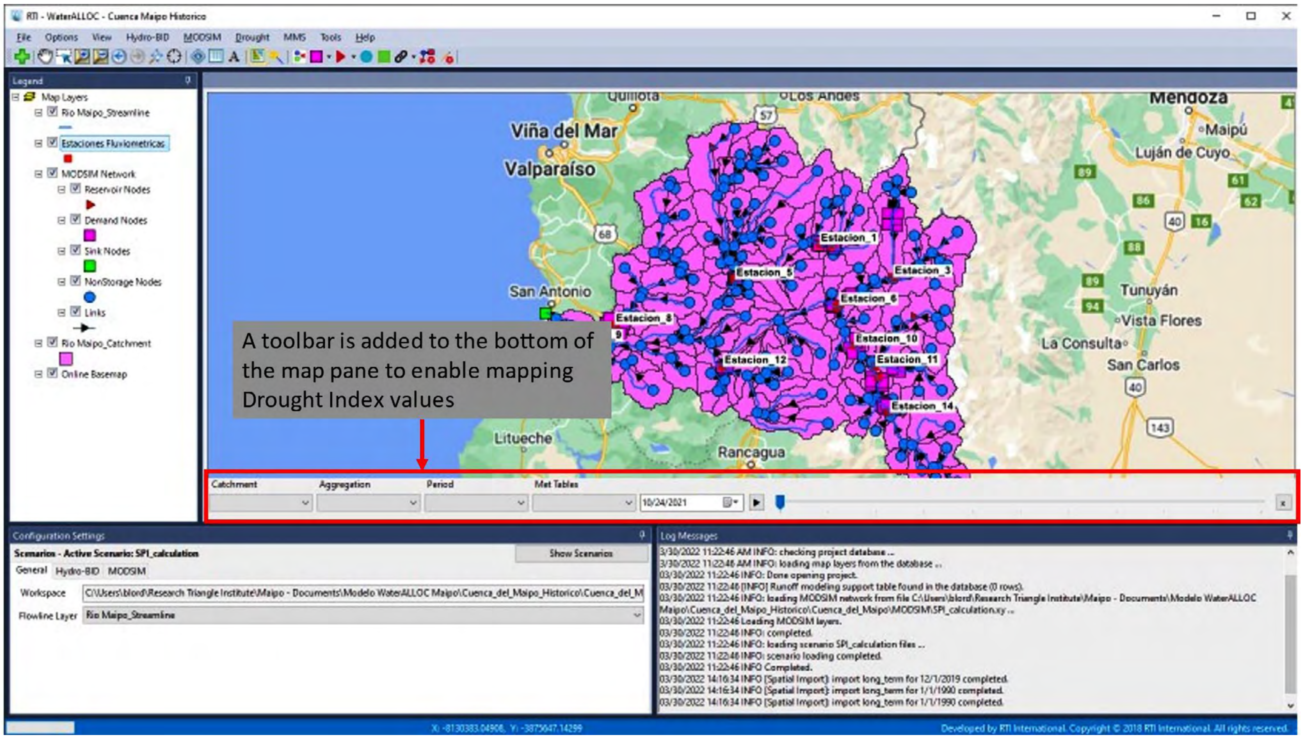
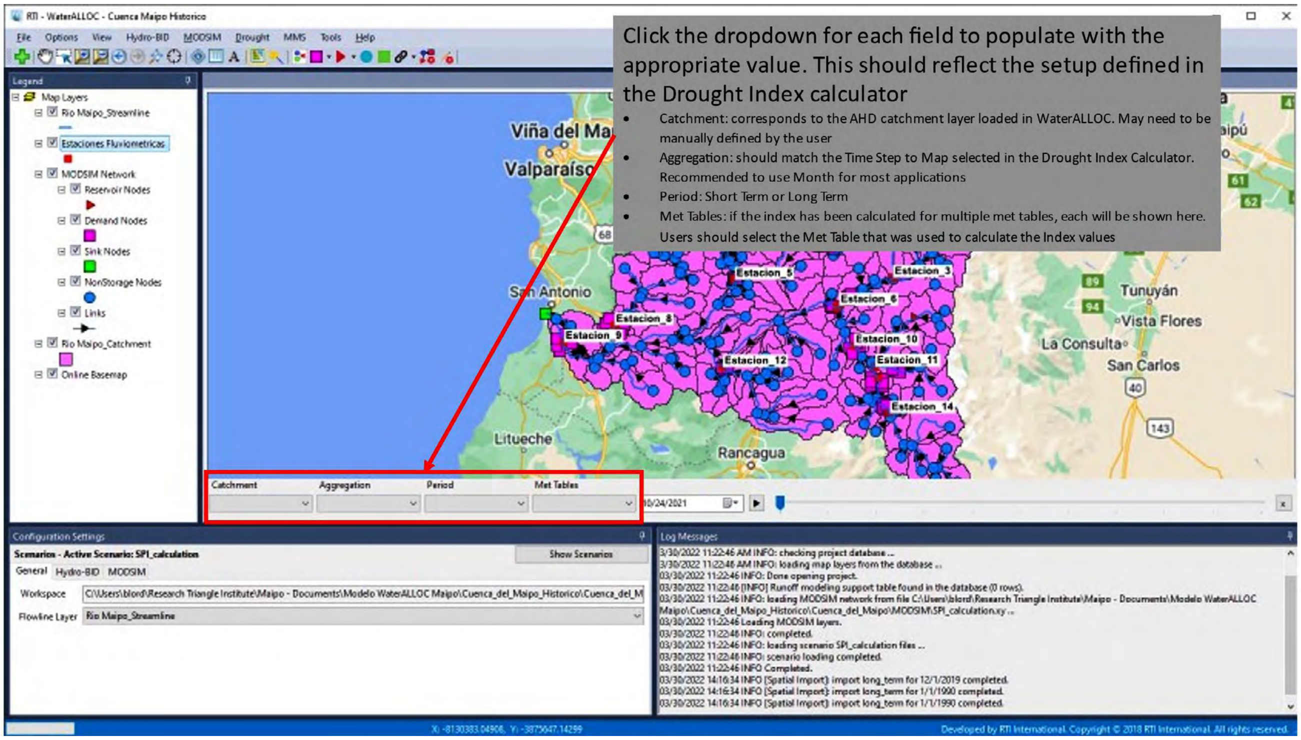

RTI - WaterALLOC - Cuenca Maipo Historico
Calculate Index
Map Index
Once the index has completed calculation, click the Drought dropdown and click 'Map Index'


RTI - WaterALLOC - Cuenca Maipo Historico
A toolbar is added to the bottom of the map pane to enable mapping Drought Index values
Catchment
Aggregation
Period
Met Tables


RTI - WaterALLOC - Cuenca Maipo Historico
Click the dropdown for each field to populate with the appropriate value. This should reflect the setup defined in the Drought Index calculator
• Catchment: corresponds to the AHD catchment layer loaded in WaterALLOC. May need to be manually defined by the user
• Aggregation: should match the Time Step to Map selected in the Drought Index Calculator. Recommended to use Month for most applications
• Period: Short Term or Long Term
• Met Tables: if the index has been calculated for multiple met tables, each will be shown here. Users should select the Met Table that was used to calculate the Index values
Catchment
Aggregation
Period
Met Tables
Configuration Settings
Log Messages
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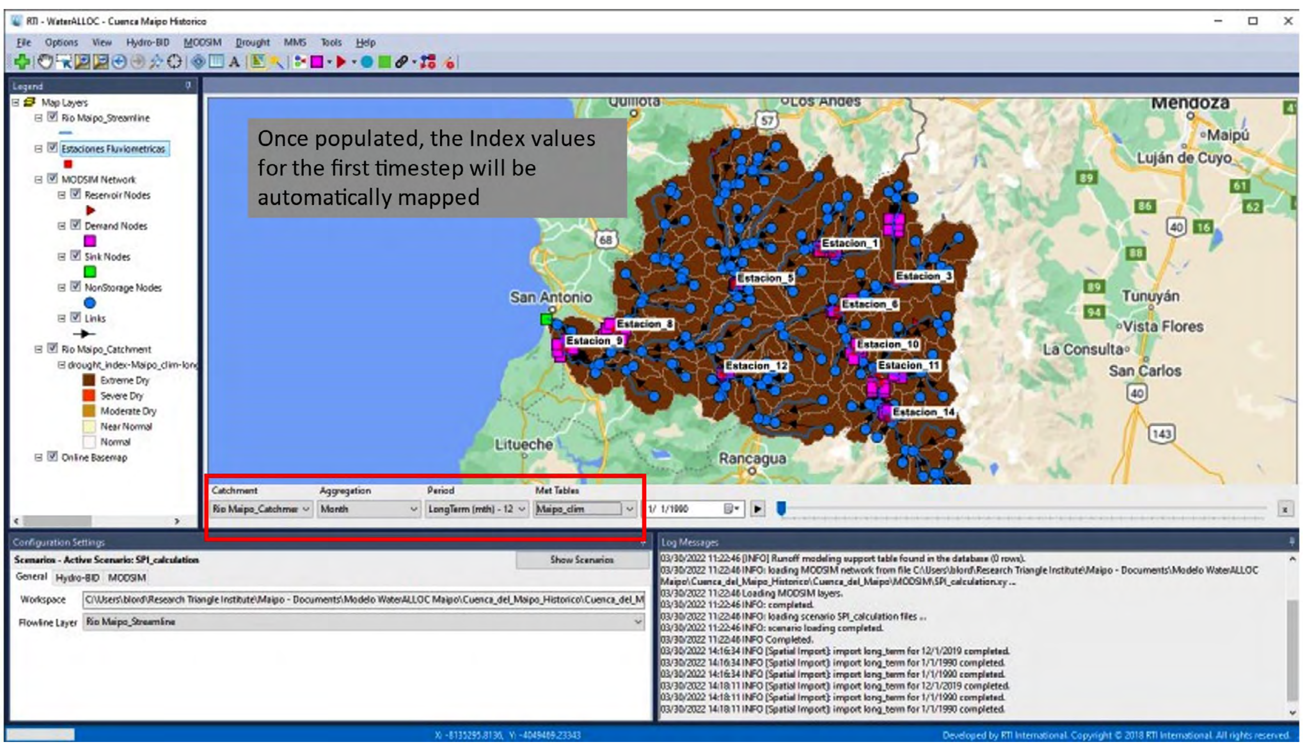
RTI - WaterALLOC - Cuenca Maipo Historico
Once populated, the Index values for the first timestep will be automatically mapped
Extreme Dry
Severe Dry
Moderate Dry
Near Normal
Normal
Catchment
Aggregation
Period
Met Tables
Rio Maipo_Catchmer
Month
LongTerm (mth) - 12
Maipo_clim
Configuration Settings
Log Messages
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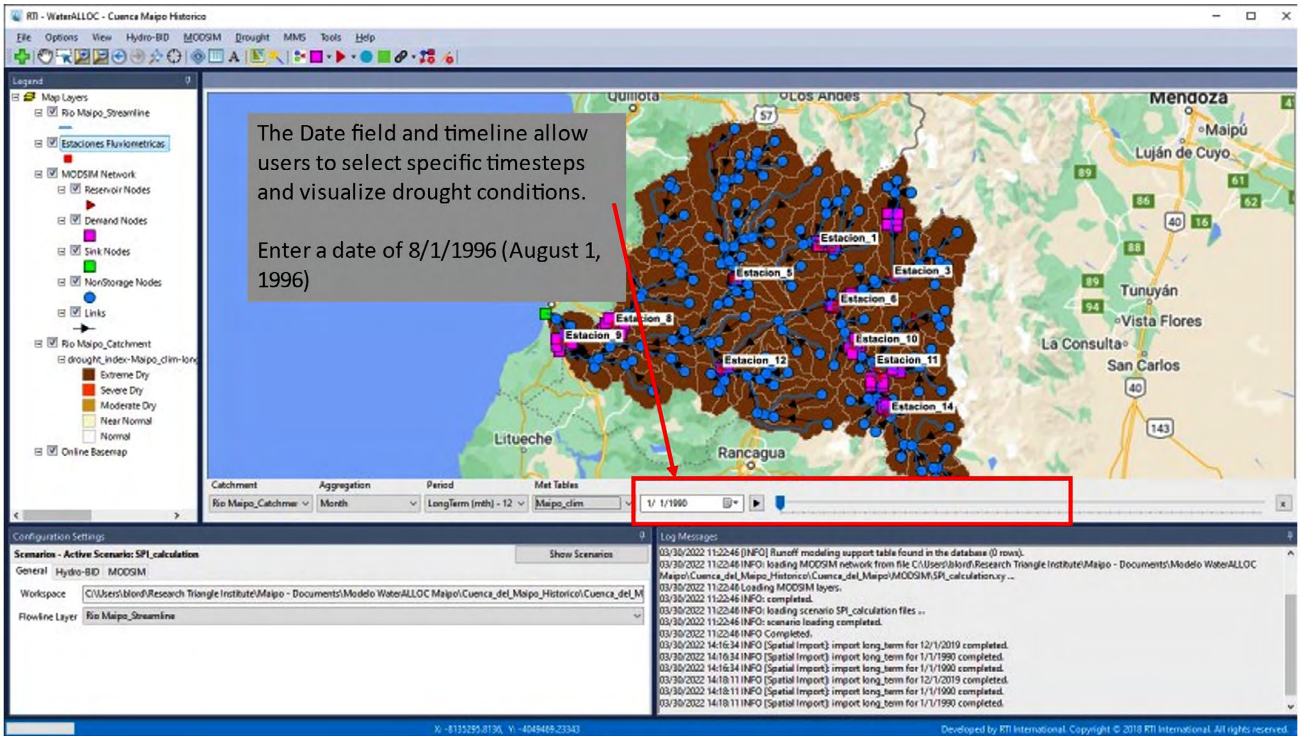
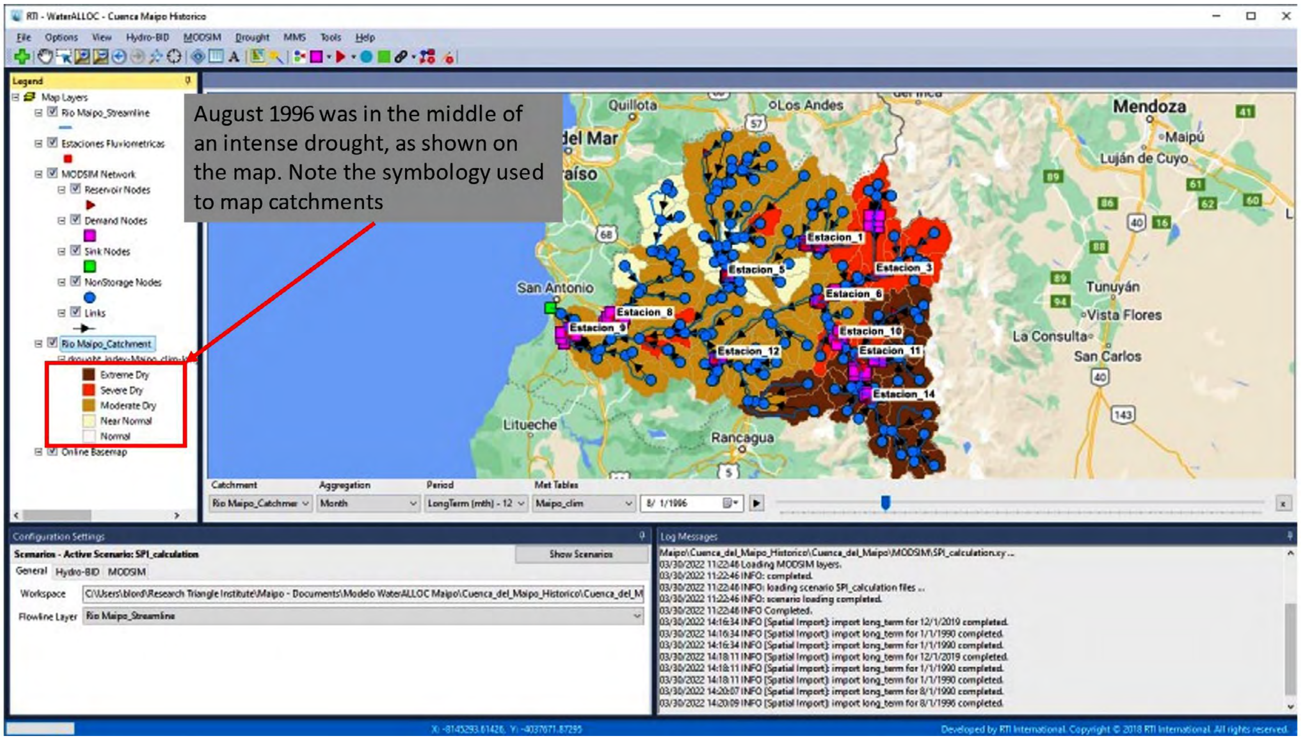
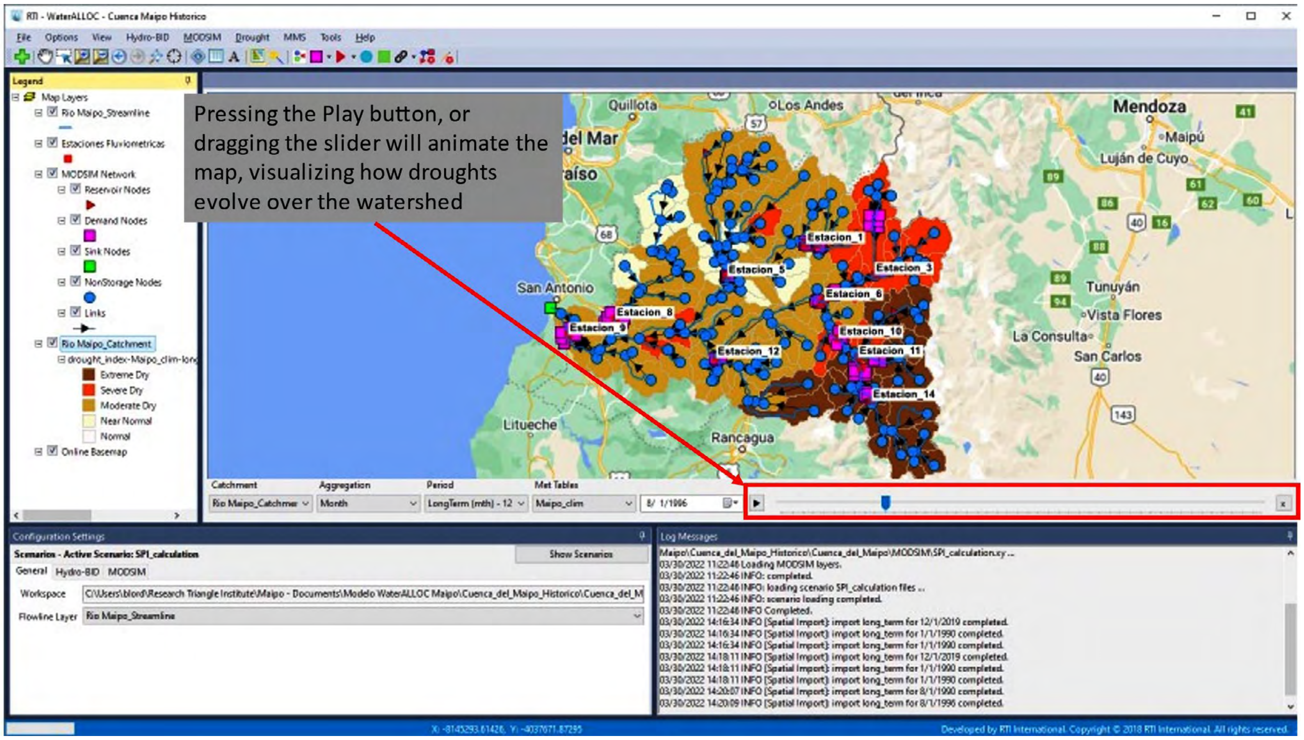

RTI - WaterALLOC - Cuenca Maipo Historico
The Date field and timeline allow users to select specific timesteps and visualize drought conditions.
Enter a date of 8/1/1996 (August 1, 1996)
Extreme Dry
Severe Dry
Moderate Dry
Near Normal
Normal


RTI - WaterALLOC - Cuenca Maipo Historico
August 1996 was in the middle of an intense drought, as shown on the map. Note the symbology used to map catchments
Extreme Dry
Severe Dry
Moderate Dry
Near Normal
Normal


RTI - WaterALLOC - Cuenca Maipo Historico
Pressing the Play button, or dragging the slider will animate the map, visualizing how droughts evolve over the watershed
Legend
Map Layers
Rio Maipo_Streamline
Estaciones Fluviometricas
MODSIM Network
Reservoir Nodes
Demand Nodes
Sink Nodes
NonStorage Nodes
Links
Rio Maipo_Catchment
Extreme Dry
Severe Dry
Moderate Dry
Near Normal
Normal
Online Basemap
Catchment
Aggregation
Period
Met Tables
Configuration Settings
Log Messages
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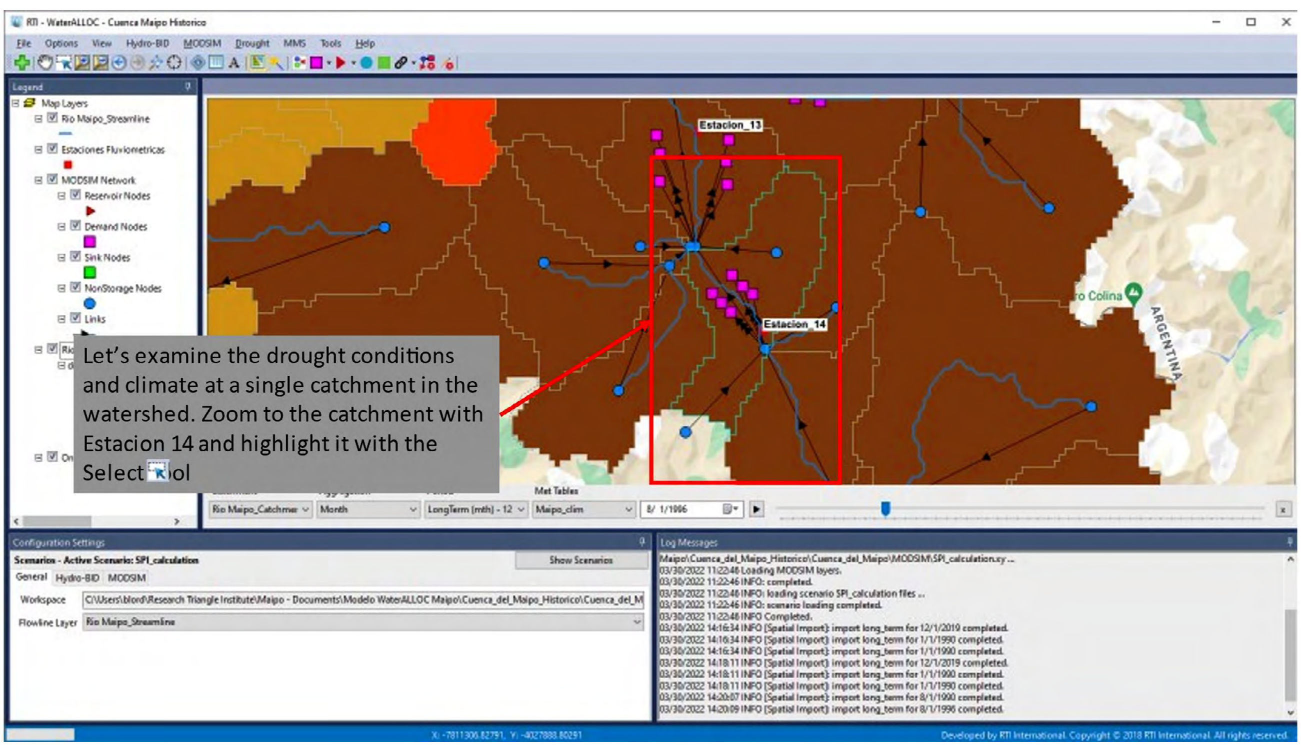
RTI - WaterALLOC - Cuenca Maipo Historico
Let's examine the drought conditions and climate at a single catchment in the watershed. Zoom to the catchment with Estacion 14 and highlight it with the Select tool
Estacion_13
Estacion_14
Configuration Settings
Log Messages
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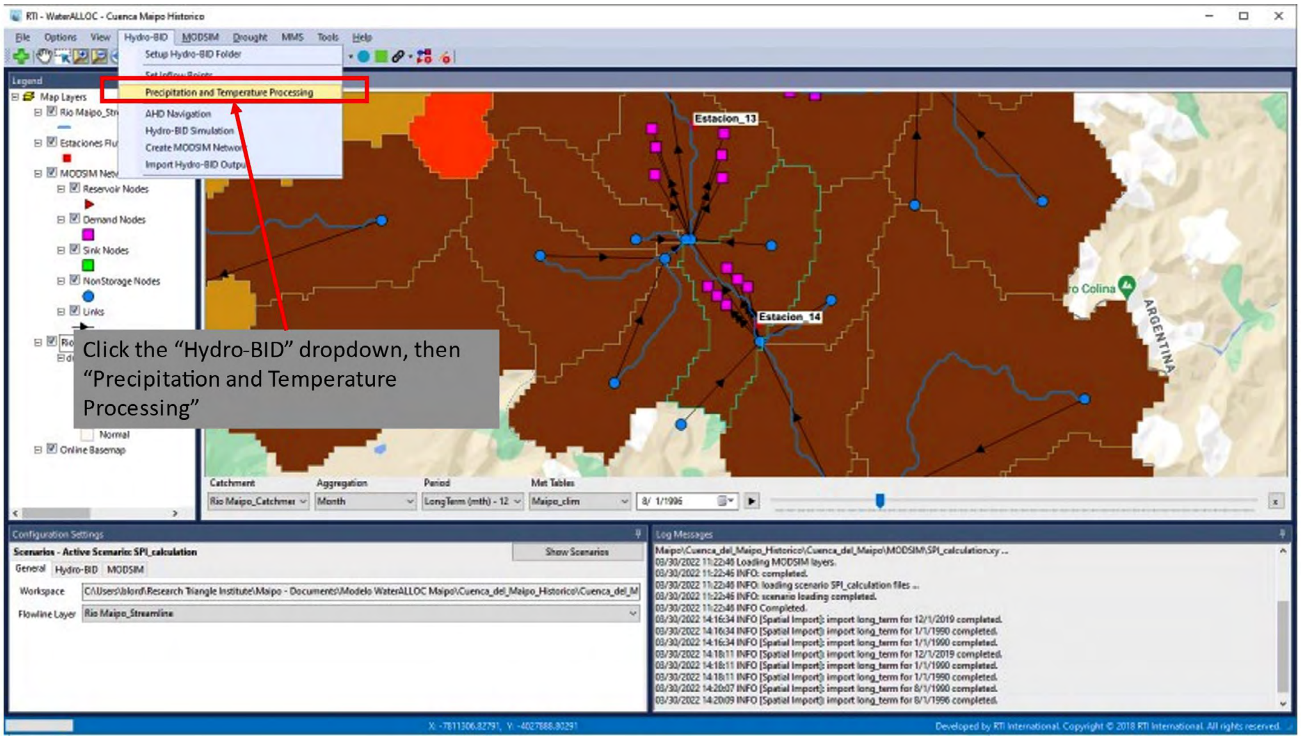
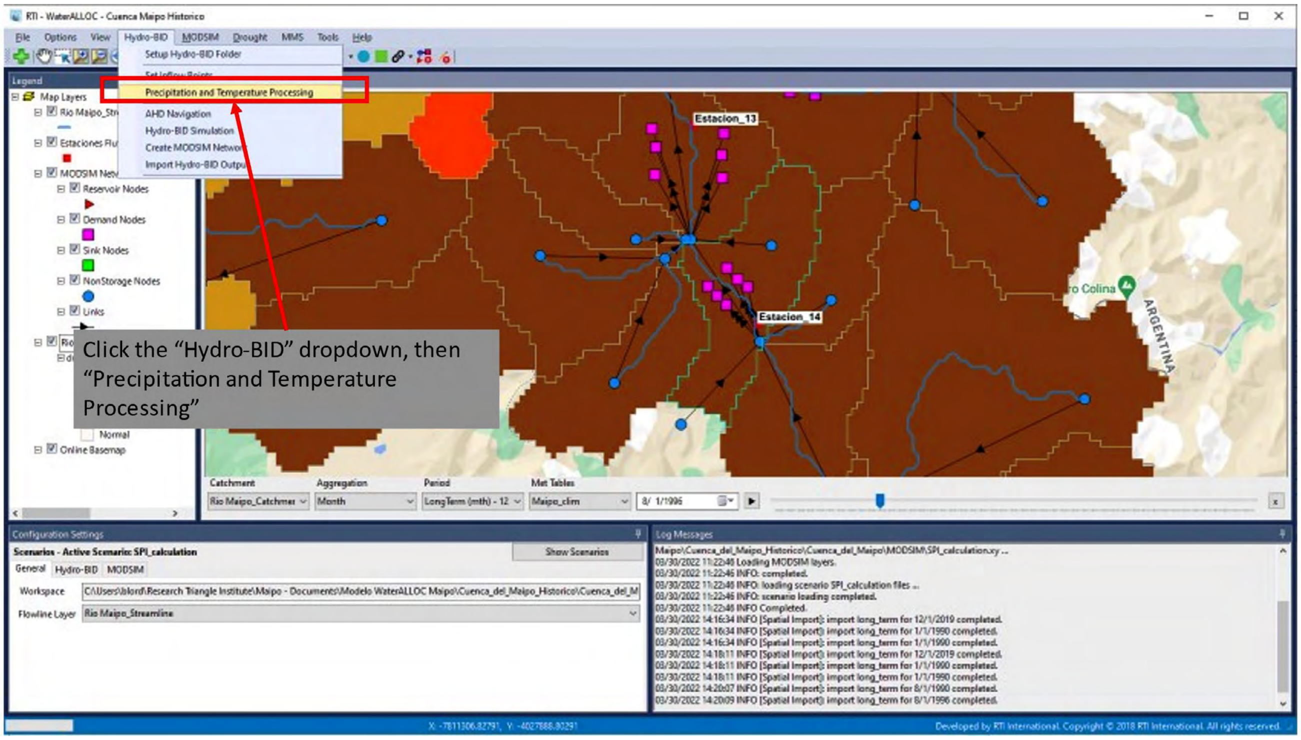
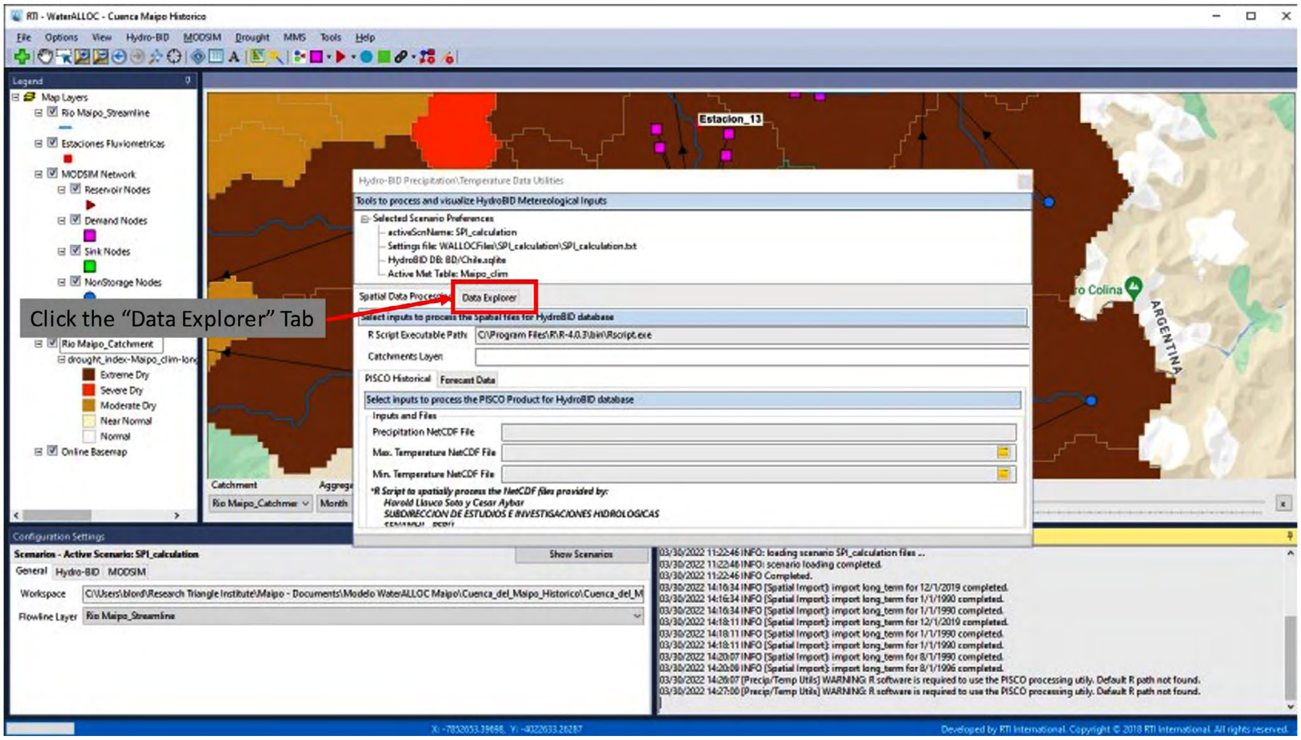
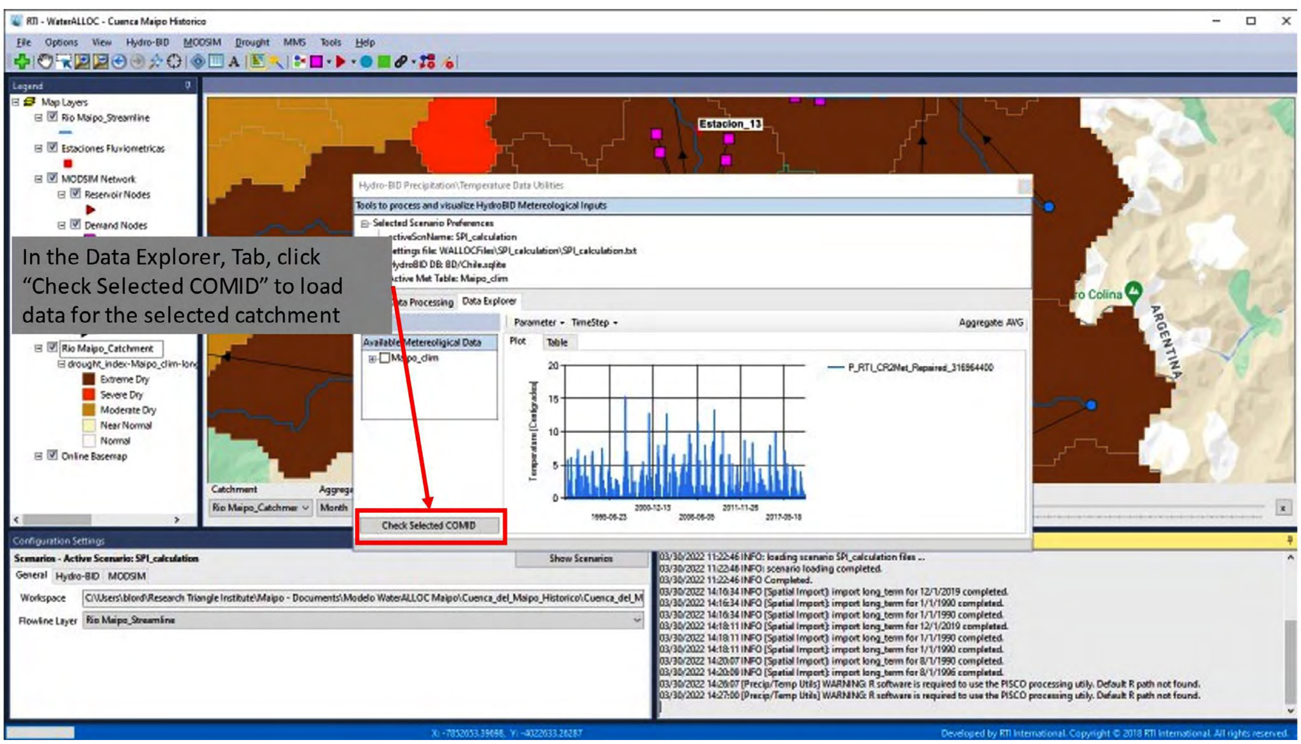
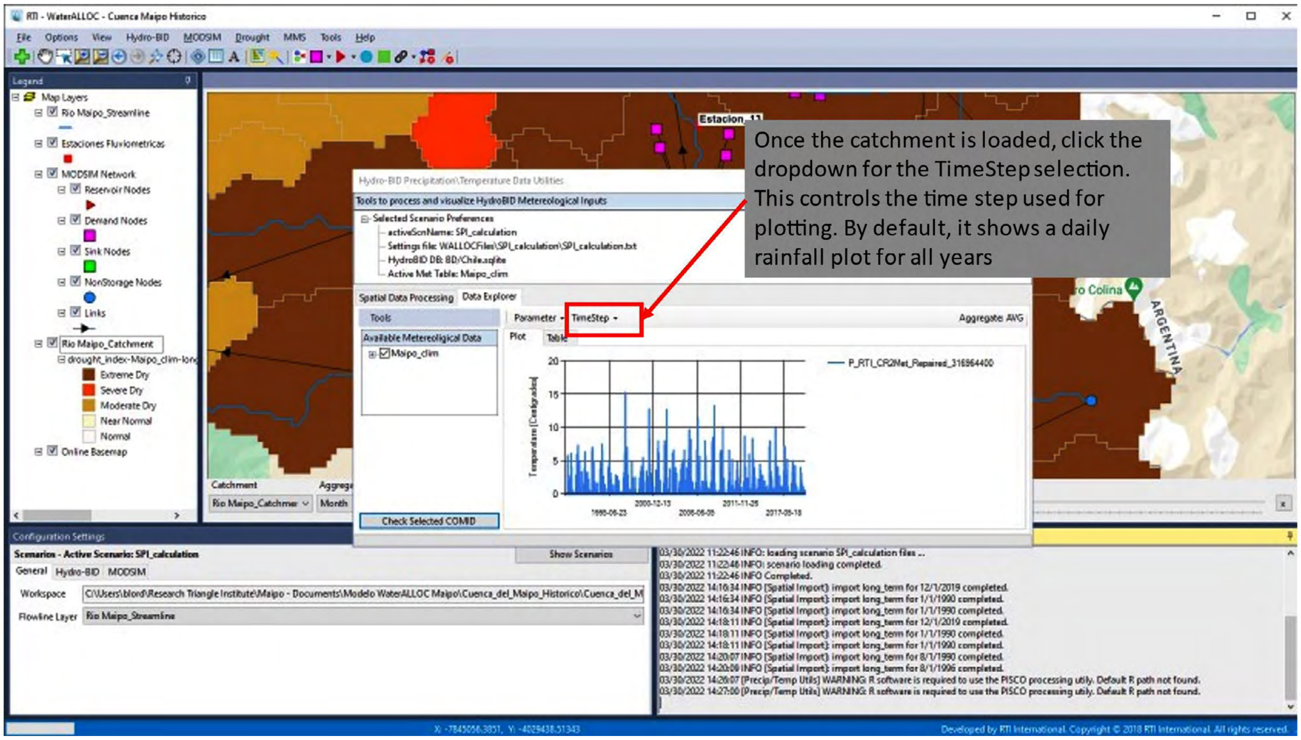
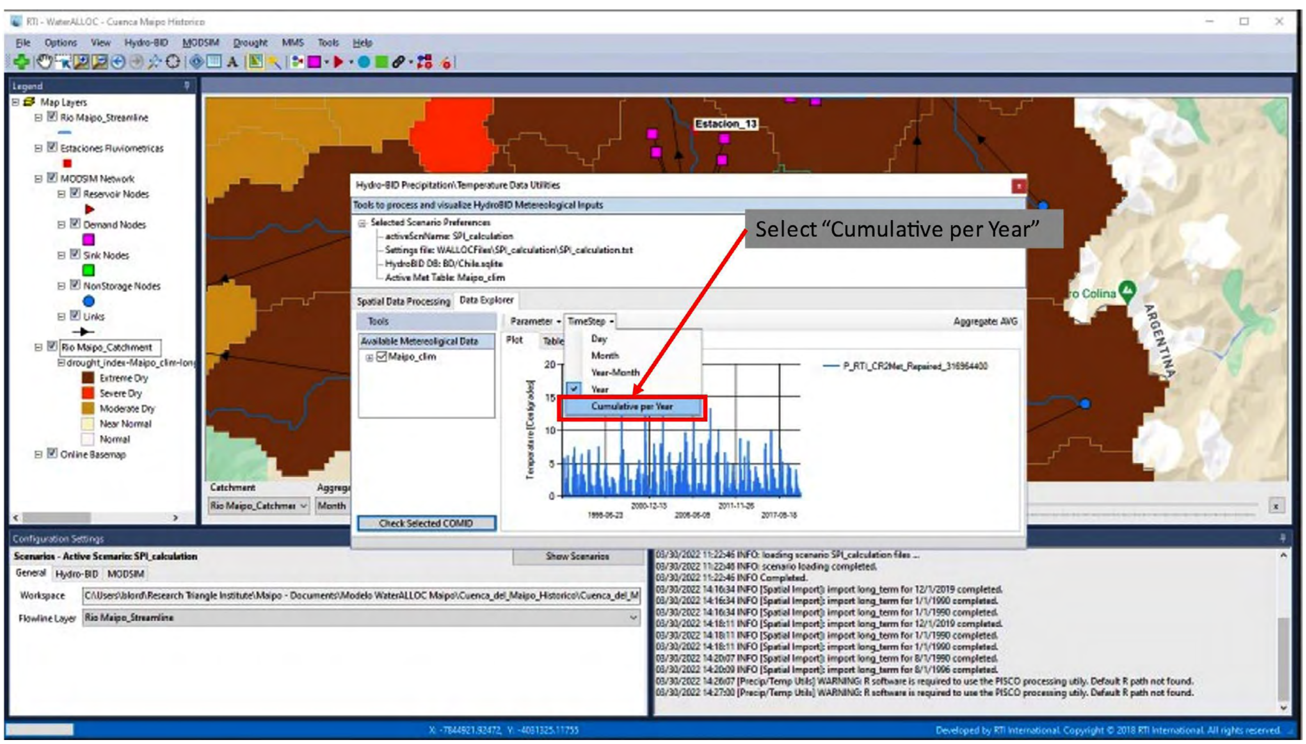

RTI - WaterALLOC - Cuenca Maipo Historico
Setup Hydro-BID Folder
Precipitation and Temperature Processing
AHD Navigation
Hydro-BID Simulation
Click the "Hydro-BID" dropdown, then "Precipitation and Temperature Processing"

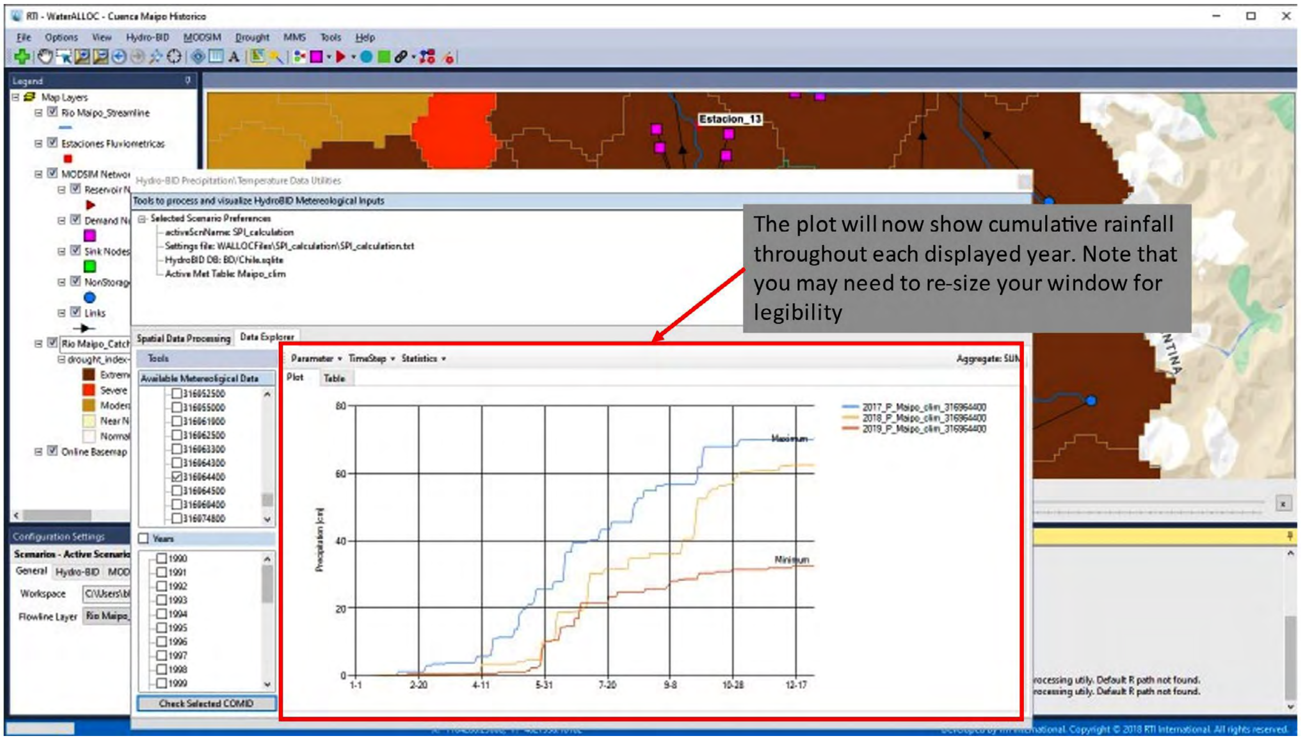

RTI - WaterALLOC - Cuenca Maipo Historico
Setup Hydro-BID Folder
Precipitation and Temperature Processing
AHD Navigation
Hydro-BID Simulation
Click the "Hydro-BID" dropdown, then "Precipitation and Temperature Processing"

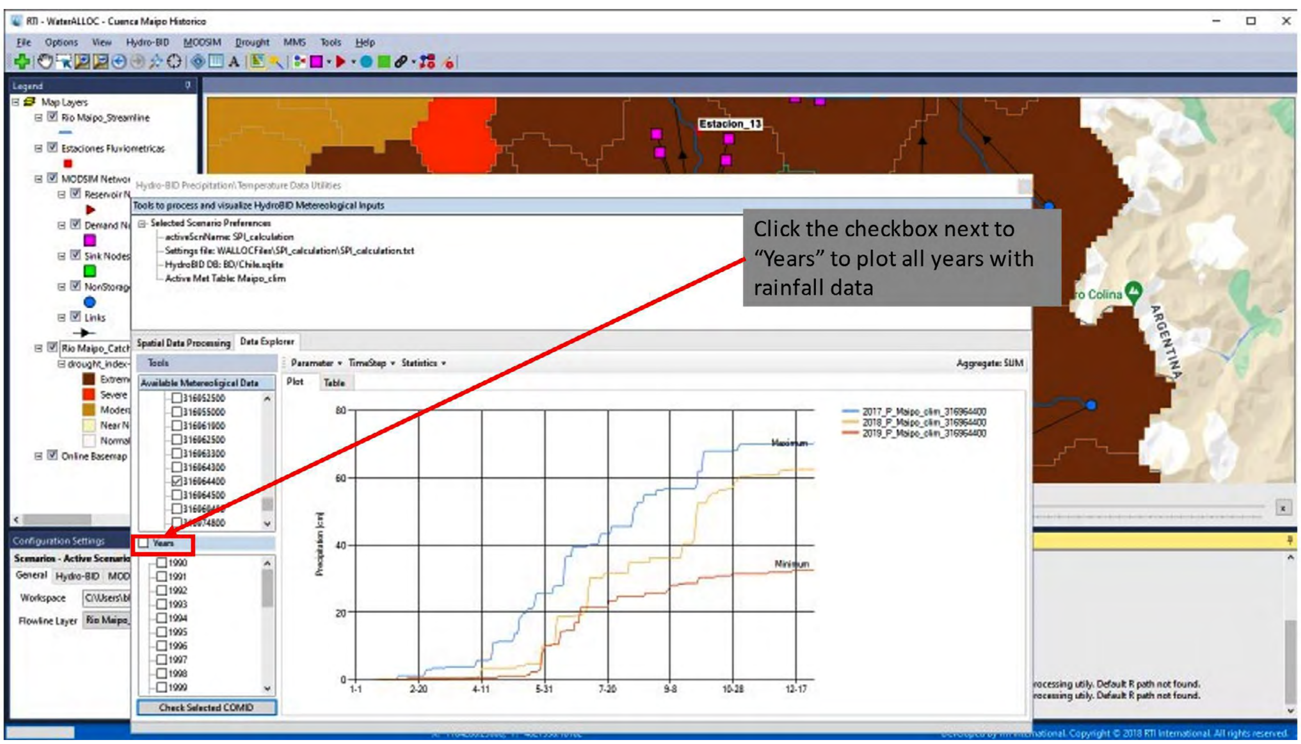

Click the “Data Explorer” Tab

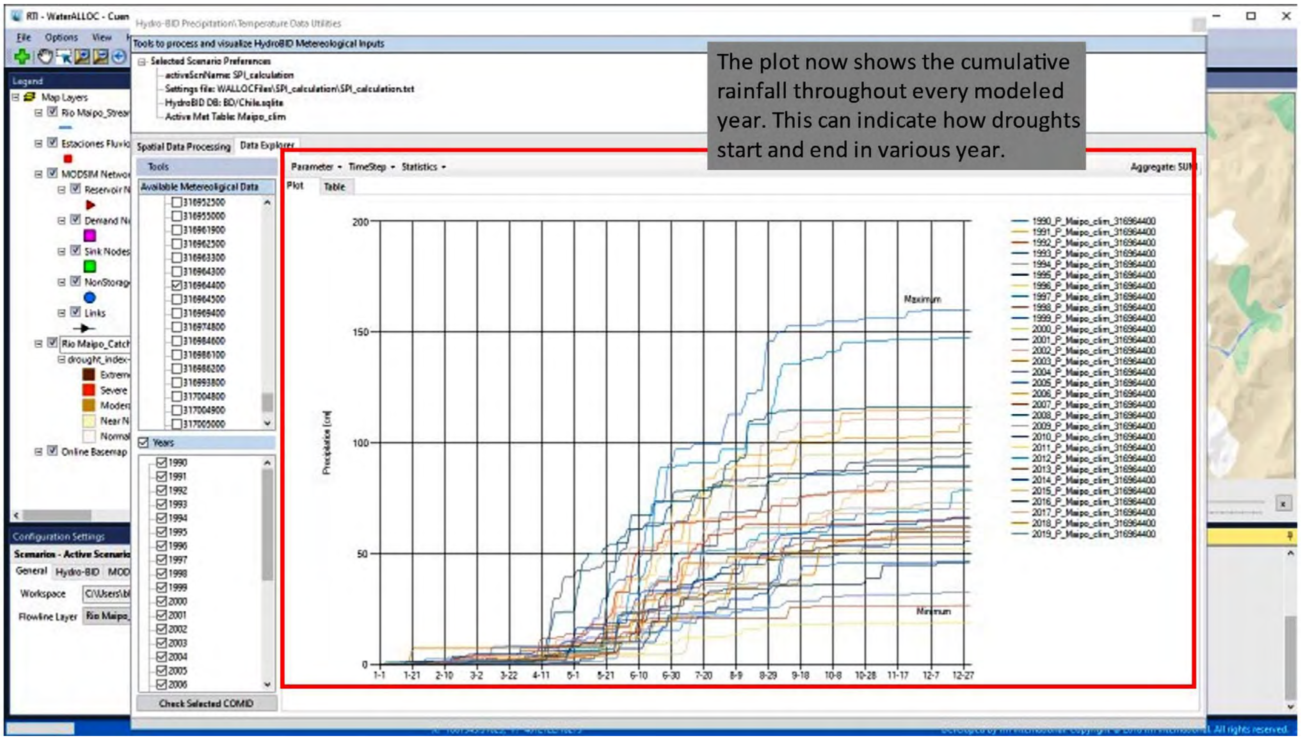

In the Data Explorer, Tab, click
“Check Selected COMID” to load
data for the selected catchment
Check Selected COMID

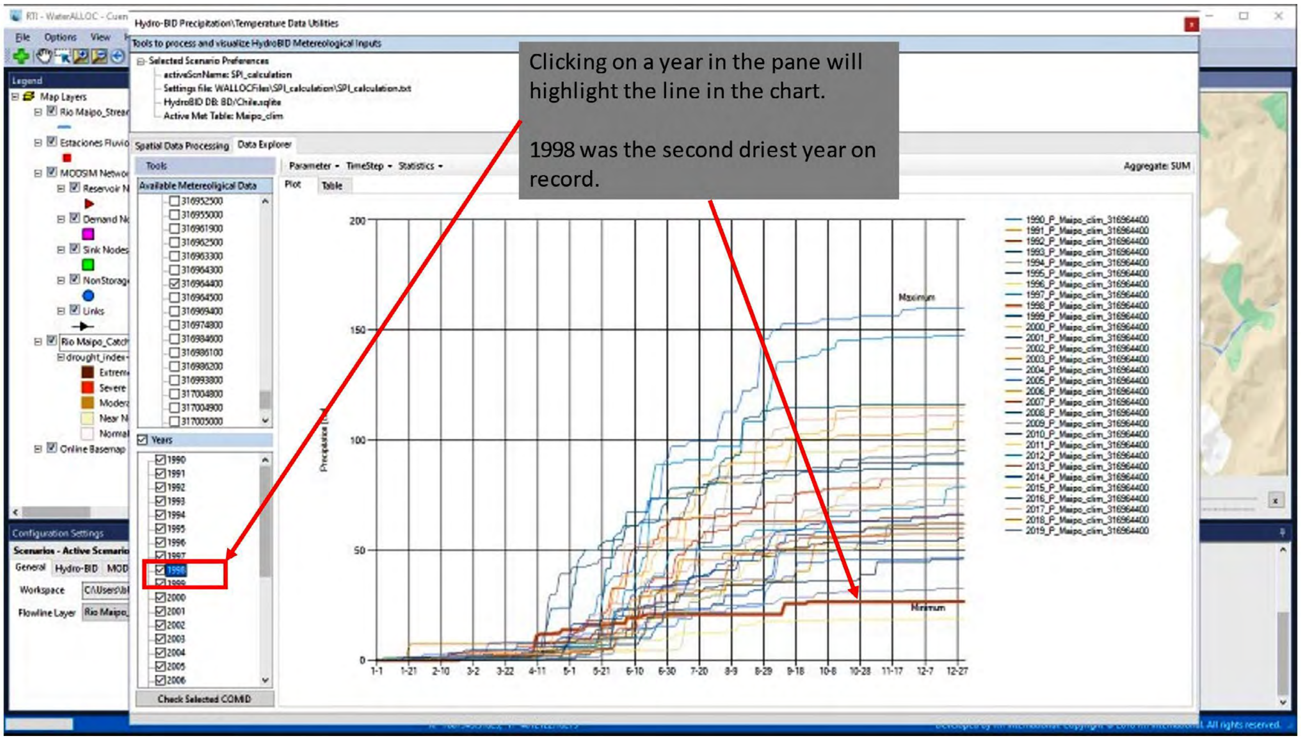

Once the catchment is loaded, click the dropdown for the TimeStep selection. This controls the time step used for plotting. By default, it shows a daily rainfall plot for all years


Select "Cumulative per Year"


The plot will now show cumulative rainfall throughout each displayed year. Note that you may need to re-size your window for legibility


Click the checkbox next to "Years" to plot all years with rainfall data


The plot now shows the cumulative rainfall throughout every modeled year. This can indicate how droughts start and end in various year.


Clicking on a year in the pane will highlight the line in the chart.

1998 was the second driest year on record.

IDB