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Summary and Instructions for Monthly AWARE-US Model

(Public Version)

Energy Systems Division

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(Public Version)

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1 INTRODUCTION

Fresh water is a critical resource to sustain both societal needs and ecosystem services. Although fresh water is a renewable resource that can be replenished through hydrological cycles, increasing demand from existing and new societal needs, including energy system deployments, may exacerbate water stress. Traditionally, a water footprint approach, which sums up consumptive water use along the supply chain, has been the primary method used in life-cycle analyses (LCAs) to account for water use impact (Lee et al., 2019). However, both freshwater supply and demand vary substantially across the United States; therefore, the impact of water consumption on local water resources should reflect spatial variations in water availability (Xu et al., 2019b).

To enable cross-regional comparison of the water-stress impact of regional water consumption scenarios, Argonne National Laboratory developed the Available Water Remaining for the United States (AWARE-US) model (Lee et al., 2019). AWARE-US uses the global AWARE framework proposed by the Water Use in LCA (WULCA) Working Group (Boulay et al., 2018). Argonne improved this framework by incorporating observed freshwater supply and demand data and refining the spatial scale to enable analysis at the U.S. county level. The AWARE-US model has been applied to evaluate the water-stress impact caused by water consumed for the deployment of hydrogen fuel cell vehicles and algae biofuel production in the United States (Lee et al., 2019; Xu et al., 2019a). In addition, because water availability also changes seasonally, Argonne developed a monthly version of the AWARE-US model to enable seasonal water-stress impact assessment (Xu et al., 2020). To support easy access and interactive analysis, we developed an online version of the AWARE-US model, which is publicly available at https://greet.es.anl.gov/aware. The present report provides a summary of the monthly AWARE-US model and instructions for using the web-based water-stress analysis model. More details regarding the development and the applications of AWARE-US can be found in our previous publications (Lee et al., 2019; Xu et al., 2020, 2019a).

2 DESCRIPTION OF AWARE-US MODEL

2.1 METHOD FOR WATER-STRESS IMPACT ASSESSMENT

The metric used in AWARE-US for water-stress impact assessment is the water-scarcity footprint (WSF), which is the product of monthly water consumption and monthly county-level water-stress characterization factors (CFs) (Eq. 1). This approach is consistent with the terminology and framework recommended by the United Nations Environment Programme–Society of Environmental Toxicology and Chemistry Life Cycle Initiative (Boulay et al., 2018):

$$\mathrm{WSF_{i,j}} = \mathrm{WC_{i,j}} * \mathrm{CF_{i,j}} \tag{1}$$

where $WSF_{i,j}$ refers to the monthly WSF in county *i* and month *j*, expressed in U.S. equivalent m^3 (m^3 eq. $month^{-1}$); $WC_{i,j,k}$ is the monthly water consumption (m^3 $month^{-1}$) in county *i* and month *j*; and $CF_{i,j}$ is monthly water-stress CF (dimensionless) in county *i* and month *j*.

Analogously to global warming potential, in which CFs are used to characterize the global warming impact of different greenhouse gases (e.g., CH_4 and N_2O) in terms of CO_2 equivalence, a water-stress CF can be used to characterize the potential water stress caused by freshwater consumption in a given county and month, enabling quantification of water scarcity using a common basis of U.S. m^3 equivalence. County-level water-stress CFs were constructed on a monthly basis by normalizing county water availability (m^3 m^{-2}/$month^{-1}$) by the national U.S. average monthly water availability (m^3 m^{-2} $month^{-1}$). The latter term, herein referred to as the "U.S. Reference," represents the U.S. average remaining water availability (0.009 m^3 m^{-2} $month^{-1}$, total annual remaining water divided by 12 months) on a monthly basis (Eq. 2) (Xu et al., 2020). Consequentially, the marginal impact of a volumetric unit of water consumption on local water stress is higher in counties with higher CFs (e.g. lower remaining water availability).

$$\mathrm{CF_{i,j}} = \frac{\mathrm{AMD_{US}}}{\mathrm{AMD_{i,j}}} \tag{2}$$

where $CF_{i,j}$ (dimensionless) is the CF in county *i* and month *j*; AMD_{US} (m^3 m^{-2} $month^{-1}$) is the national average monthly remaining available water; and $AMD_{i,j}$ (m^3 m^{-2}/$month^{-1}$) is the remaining available water in county *i* and month *j*.

Remaining water availability, or Availability Minus Demand (AMD), is calculated as the difference between natural runoff (NR) and freshwater demand (Eq. 3). Freshwater demand includes societal water consumption (SWC), which is the same as human water consumption referenced in our past papers (Lee et al., 2019; Xu et al., 2020), and environmental water requirement (EWR).

$$\mathrm{AMD_{i,j}} = \mathrm{NR_{i,j}} - \mathrm{EWR_{i,j}} - \mathrm{SWC_{i,j}} \tag{3}$$

where $AMD_{i,j}$ refers to remaining available water in county *i* and month *j*; $EWR_{i,j}$ is the EWR in county *i* and month *j*; and $SWC_{i,j}$ is SWC in county *i* and month *j*.

2.2 DATABASE FOR MONTHLY AWARE-US

2.2.1 Runoff Data

NR can be estimated by adding actual or measured runoff and existing SWC within the watershed (Eq. 4) (Hoekstra et al., 2012). Specifically, monthly NR is calculated from long-term (1971–2015) observed runoff reported by the United States Geological Survey (USGS) (Table 1). In regions where groundwater consumption exceeds renewable groundwater supply, only the portions that comes from renewable groundwater resources are counted as NR (Eqs. 5, 6). In areas with limited freshwater resources, such as the irrigated High Plains and California Central Valley, groundwater abstraction rates can far exceed recharge rates (Scanlon et al., 2012). As such, adding non-renewable groundwater consumption to observed runoff would distort NR estimates. To address this issue, we differentiated renewable versus non-renewable groundwater use by comparing monthly groundwater recharge rates with groundwater consumption rates in each county (Eqs. 5, 6):

$$NR_{i,j} = OR_{i,j} + SWC_{i,j} \tag{4}$$

$$SWC_{i,j} = SWC\_S_{i,j} + SWC\_G_{i,j} \qquad \text{if } SWC\_G_{i,j} < GWR_{i,j} \tag{5}$$

$$SWC_{i,j} = SWC\_S_{i,j} + GWR_{i,j} \qquad \text{if } SWC\_G_{i,j} \geq GWR_{i,j} \tag{6}$$

where $NR_{i,j}$ is NR in county *i* and month *j*; $OR_{i,j}$ is observed runoff in county *i* and month *j*; $SWC_{i,j}$ is SWC in county *i* and month *j*; $SWC\_S_{i,j}$ is SWC sourced from surface water resources in county *i* and month *j*; $SWC\_G_{i,j}$ is SWC sourced from groundwater resources in county *i* and month *j*; and $GWR_{i,j}$ is groundwater recharge rate in county *i* and month *j*.

TABLE 1 Data sources for monthly AWARE-US development

Variable	Year or Duration	Spatial Scale	Data Source
Human water consumption	2015	County	USGS (Dieter et al., 2018)
Observed runoff	1971–2015	HUC-8	USGS (https://waterwatch.usgs.gov/)
Streamflow statistics	1930–2015	Point	USGS (Wolock, 2003a)
Disaggregation factors	1980–2000	County	Moore et al. (2015)

2.2.2 Groundwater Recharge

We calculated groundwater recharge rates using runoff and base-flow index (BFI). This method assumes that the BFI reasonably represents the long-term percentage of groundwater discharge in streamflow, and that natural groundwater recharge is equal to groundwater discharge when averaged over a long time horizon (Wolock, 2003b).

Monthly BFI values are calculated using streamflow statistics (Table 1) from USGS stream gages. A total of 6,366 stream gages were selected in accordance with the following criteria: (1) duration of the data record is 10 years or longer, (2) drainage area of the monitored watershed is less than 1,000 square miles, and (3) the data cover all 12 months in a year (Xu et al., 2020). At each of the 6,366 gage stations, monthly surface flow is separated into base flow and quick flow, using a hydrograph separation computer program called the BFI program (Walh and Walh, 1995). Monthly baseflow data were provided by Dr. David Wolock at USGS. Baseflow represents the portion of streamflow that comes from groundwater (Arnold et al., 1995), while the remaining fraction of streamflow represents quick flow. The monthly BFI index is the ratio of monthly base flow volume to monthly total flow volume. Gage-level BFI values were interpolated to 1-km-spatial-resolution grids covering the conterminous United States, using an empirical Bayesian kriging method and the ArcGIS software (ESRI, 2019). Monthly groundwater recharge rates were estimated as the product of observed monthly runoff values and BFI grids. To calculate the long-term mean monthly groundwater recharge rate for each county, grid-level results were aggregated to the county level using ArcGIS software.

2.2.3 Societal Water Consumption

County-level SWC data are primarily derived from a recent USGS report (Dieter et al., 2018). This report provides annual consumptive water use for irrigation and thermoelectricity generation, and annual withdrawal data for the remaining economic sectors. For sectors with withdrawal data only, we estimated consumptive water use using consumption-to-withdrawal ratios derived from previous USGS reports (Lee et al., 2019). To obtain monthly water consumption estimates, we disaggregated annual consumption data by economic sector and month using temporal disaggregation factors from previous studies (Moore et al., 2015).

2.2.4 Environmental Water Requirement

The EWR refers to the portion of streamflow reserved for aquatic ecosystems to maintain a fair ecological status (Pastor et al., 2014). In AWARE-US, we calculated EWR using the variable monthly flow method recommended by Pastor et al. (2014). Specifically, EWR was calculated as a fraction of monthly NR, varying from 30% to 60% of mean monthly flow (MMF), and contingent on hydrological season (Table 2). Determination of hydrological seasons (low-, intermediate-, and high-flow months) is based on comparison of MMF and mean annual flow (MAF) rates. Namely, consumers can extract more water for societal demands in high-flow months, while more water is required to remain in streams during low-flow months.

TABLE 2 Calculation of environmental water requirement

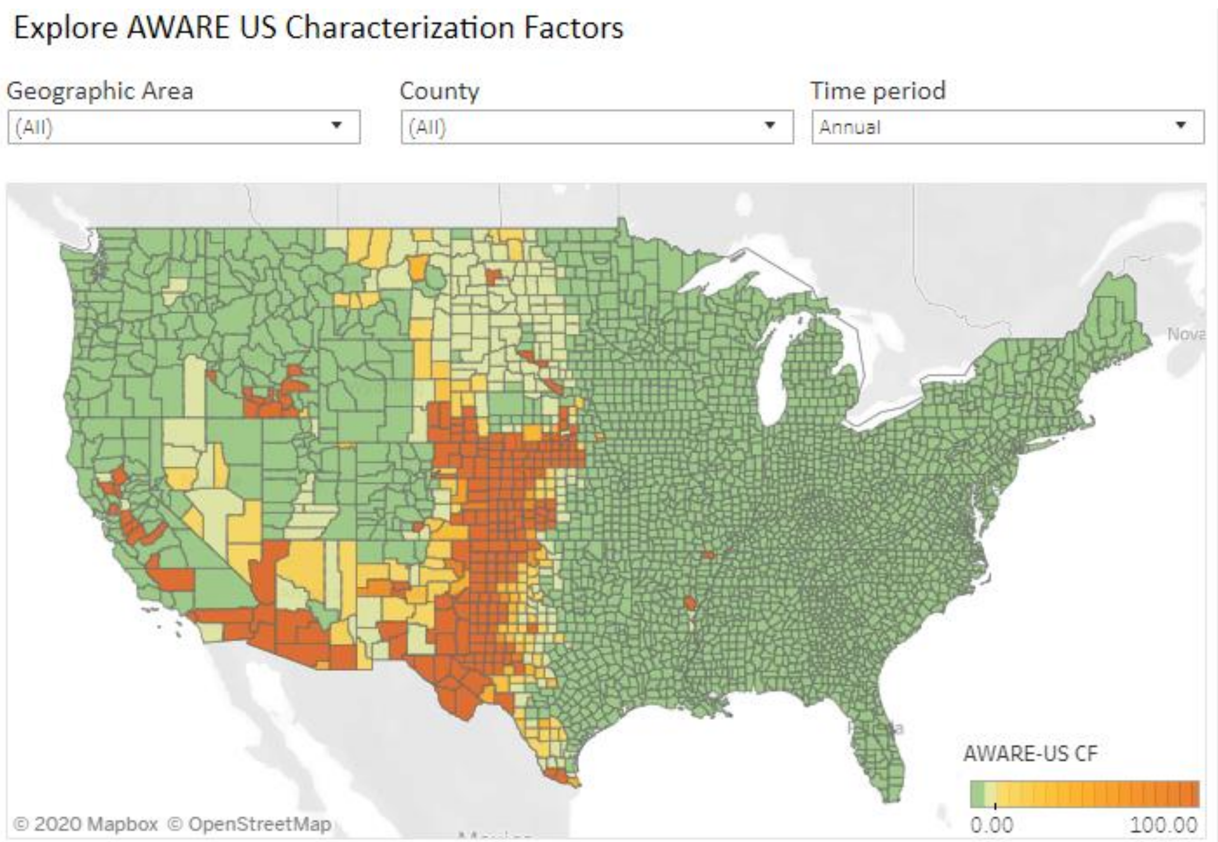
Hydrological Season		Variable Monthly Flow
Low-flow months	($MMF \leq 0.4 \times MAF$)	60% of MMF
Intermediate-flow months	($0.4 \times MAF < MMF \leq 0.8 \times MAF$)	45% of MMF
High-flow months	($MMF > 0.8 \times MAF$)	30% of MMF

3 INSTRUCTIONS FOR WEB-BASED WATER-STRESS ANALYSIS MODEL

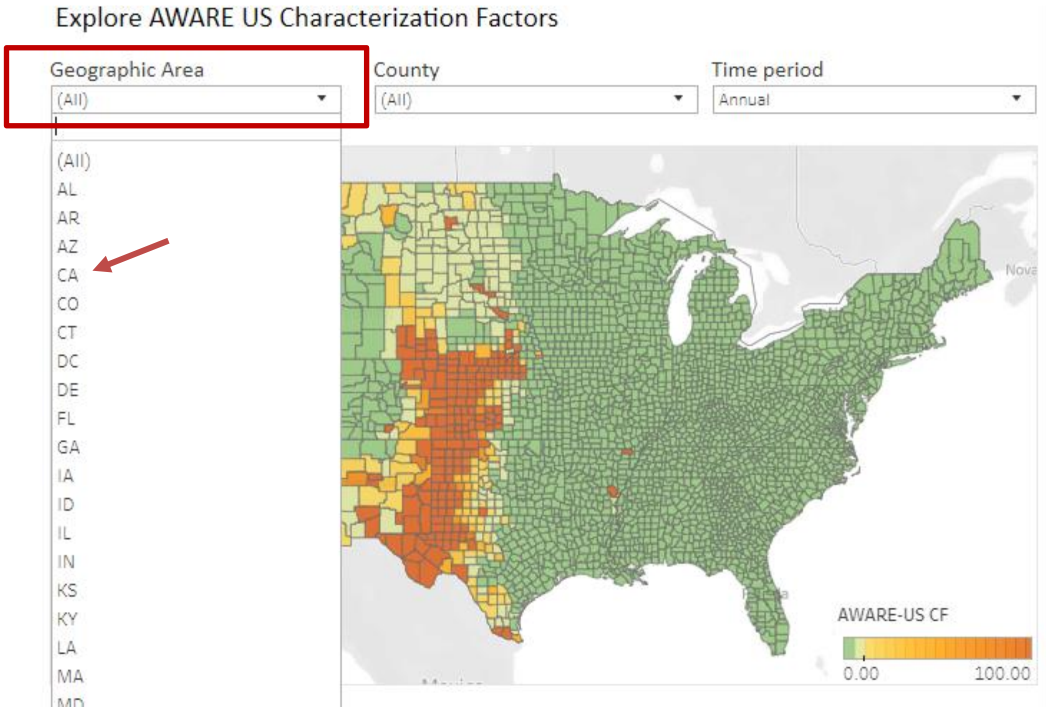
The purpose of this section is to provide instructions for using a web-based water-stress analysis model, which is available at https://greet.es.anl.gov/aware. The online version of the AWARE-US model provides spatiotemporally resolved water-stress CFs for all counties in the conterminous United States. The online tool provides a General User Interface that enables users to custom-tailor results on the basis of multiple criteria, including Geography (State), County (Name), and Time Period (Annual, Monthly). Further, the model supports the calculation of regionalized WSFs, contingent on user-provided monthly water consumption data.

3.1 EXPLORE AWARE-US CHARACTERIZATION FACTORS

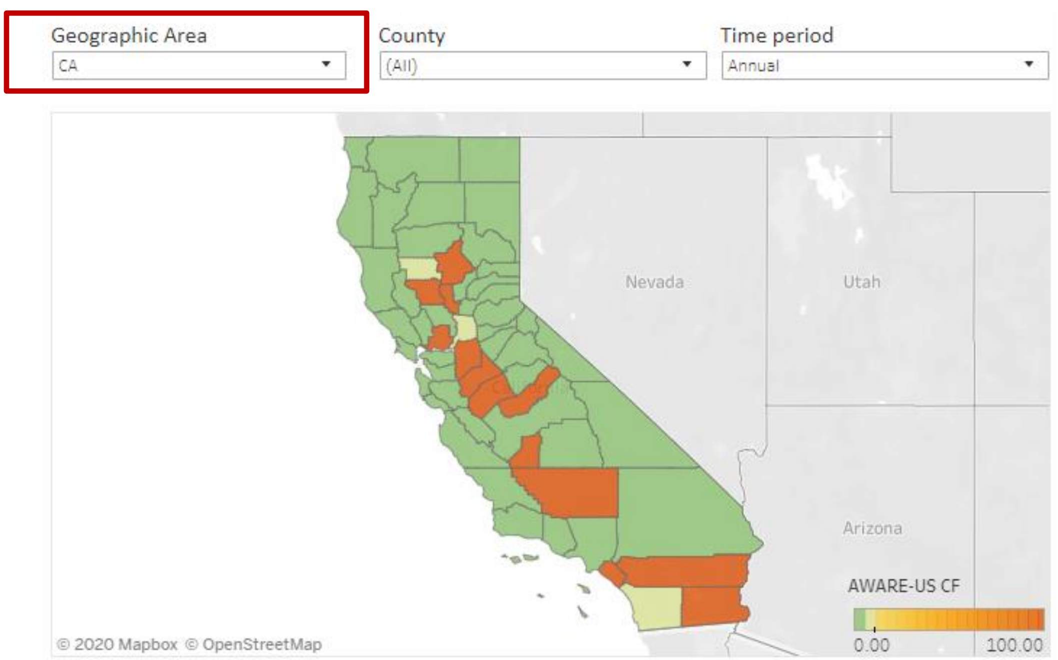
Users can explore county-level, monthly CF values in multiple ways. By default, the county-level map shows CF values for all counties in the conterminous United States. Users can select data by "Geographic Area," "County," and "Time period."



To display data for one of the 48 lower states, users can click on the "Geographic Area" drop-down menu and select a state abbreviation.

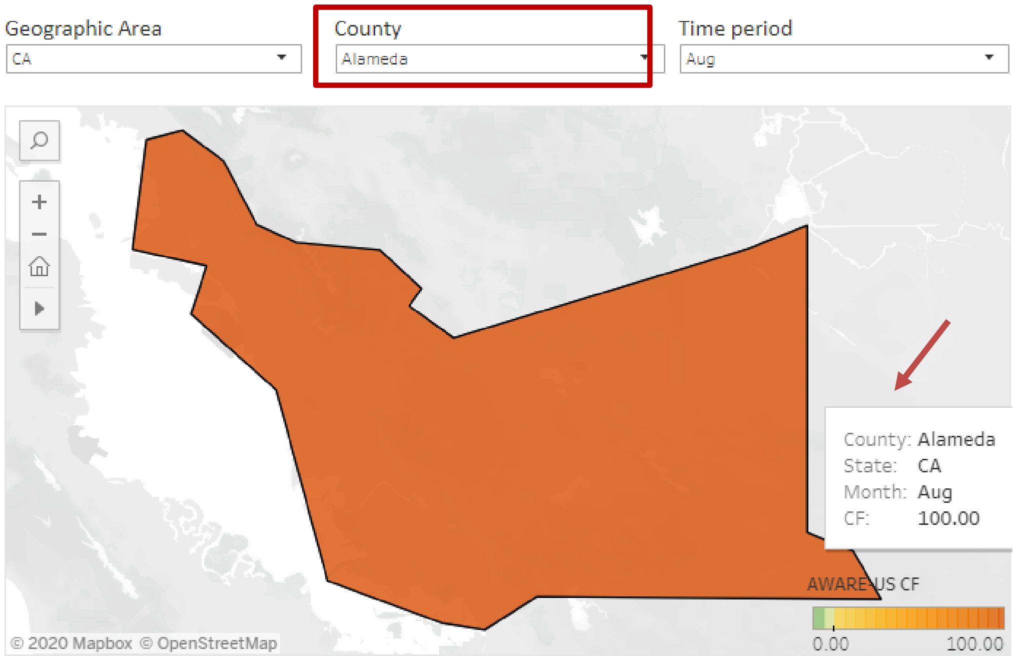


When a state name is selected from the drop-down menu, the map will zoom in to the selected state and display CF values for counties in that state only. For instance, one can select “CA,” and the map will show annual CF values for all counties in California.

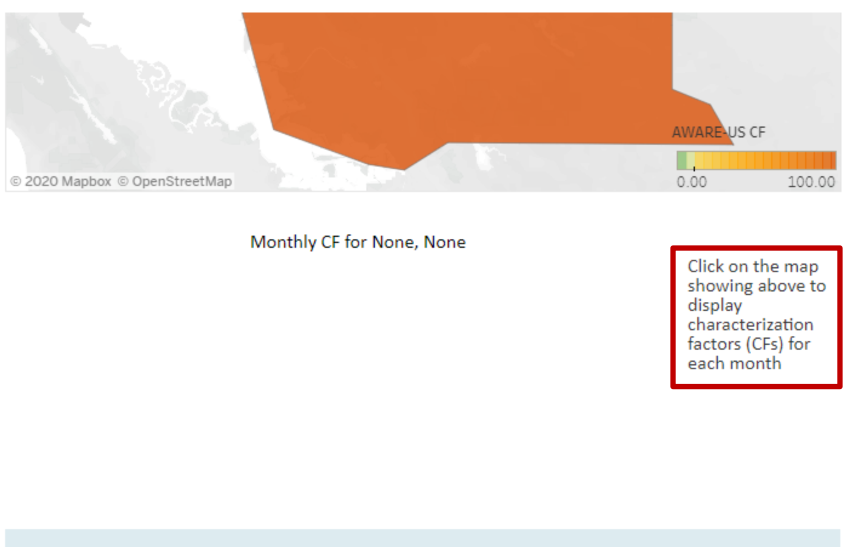


To view CF values for a specific month, users can select a time period from the "Time period" drop-down menu. For instance, if "Aug" is selected, the map will show August CF values for all counties in California.

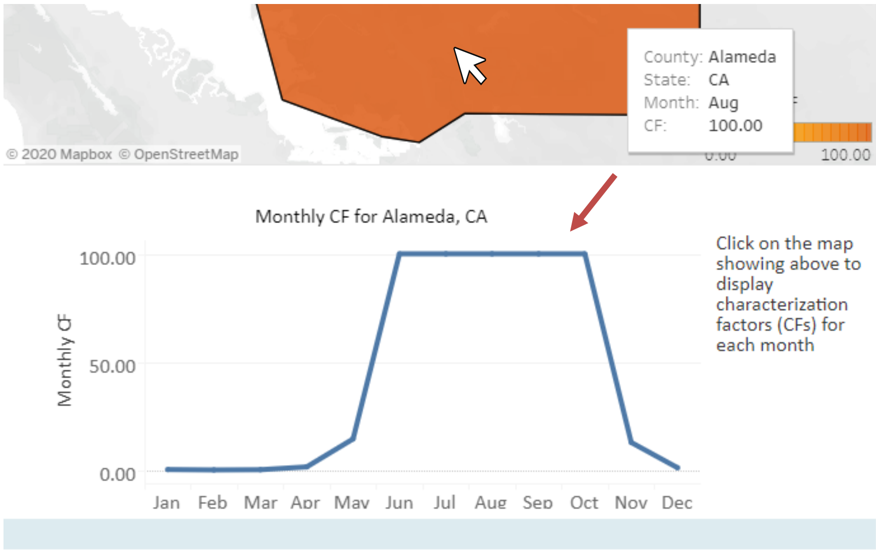
To narrow down geographic area to a specific county, one uses the "County" drop-down menu. For instance, if one selects "Alameda," then the map will automatically zoom in to Alameda County in California. If the cursor is placed over the county area, information for that county will pop up automatically as a text box, including state, county, month, and CF value.



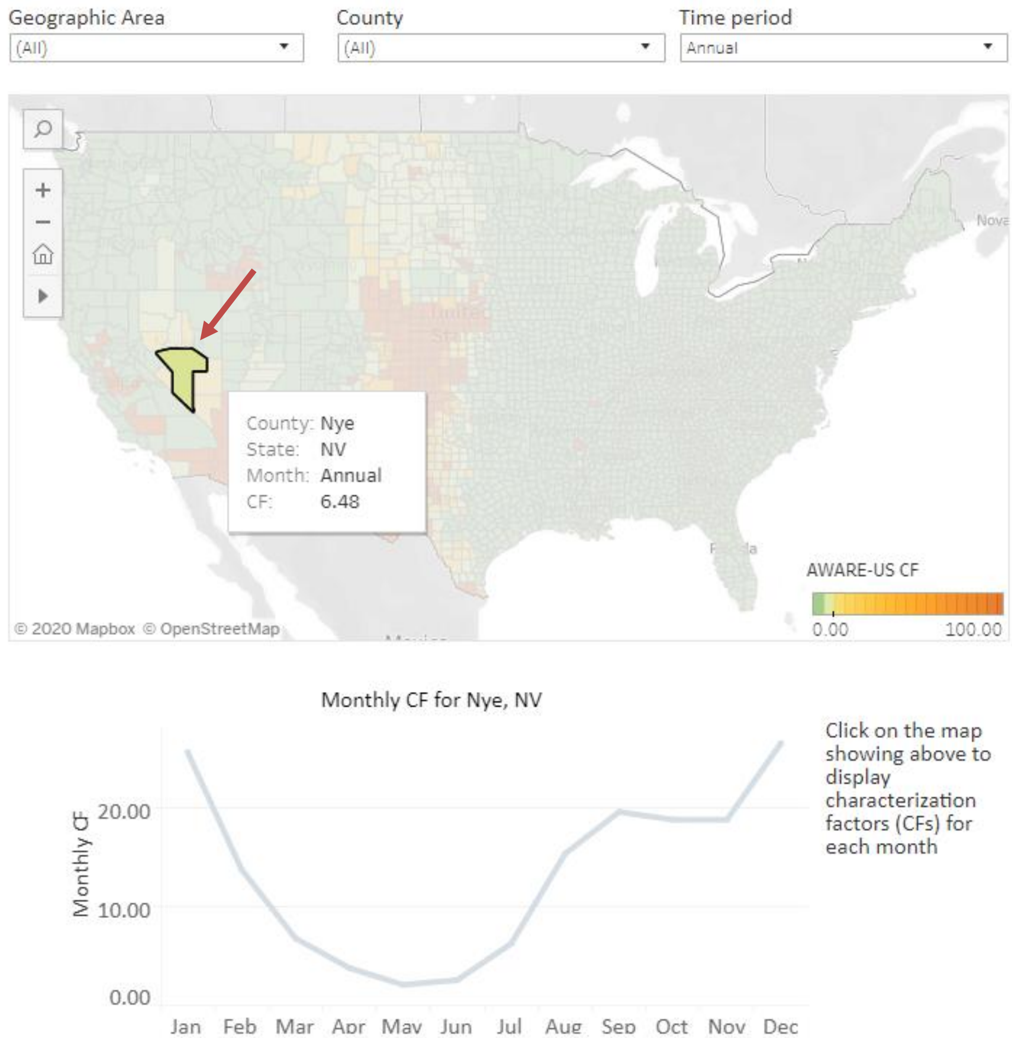
The "Monthly CF" graph will display monthly CF values for the selected county. By default, the plot is empty. To turn on the plot, users need to click within the geographic boundary of the selected county.



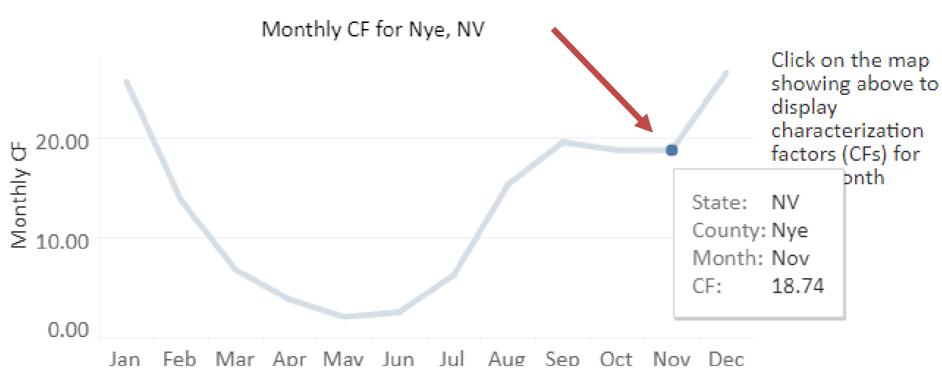
For instance, if the user clicks within Alameda County, the "Monthly CF" plot will display monthly CF values for Alameda County.



Alternatively, one can hover over the map and double-click a county of interest. The map will highlight the selected county, and the graph below the map will be updated automatically to display monthly CF values for the selected county.



Instead of selecting month from the “Time period” dropdown menu, one can hover over the line graph to view CFs for each month quickly. When the user clicks on a dot along the curve, a textbox will pop up to show state, county, month, and CF value.



3.2 CALCULATE WATER-STRESS RESULTS

To calculate water-stress impact caused by water consumption in the selected county in terms of WSF, users need to enter estimated monthly water consumption (m^3/month) in the red box below. If water consumption is zero for a given month, zero is entered.

Calculate Water Stress Results

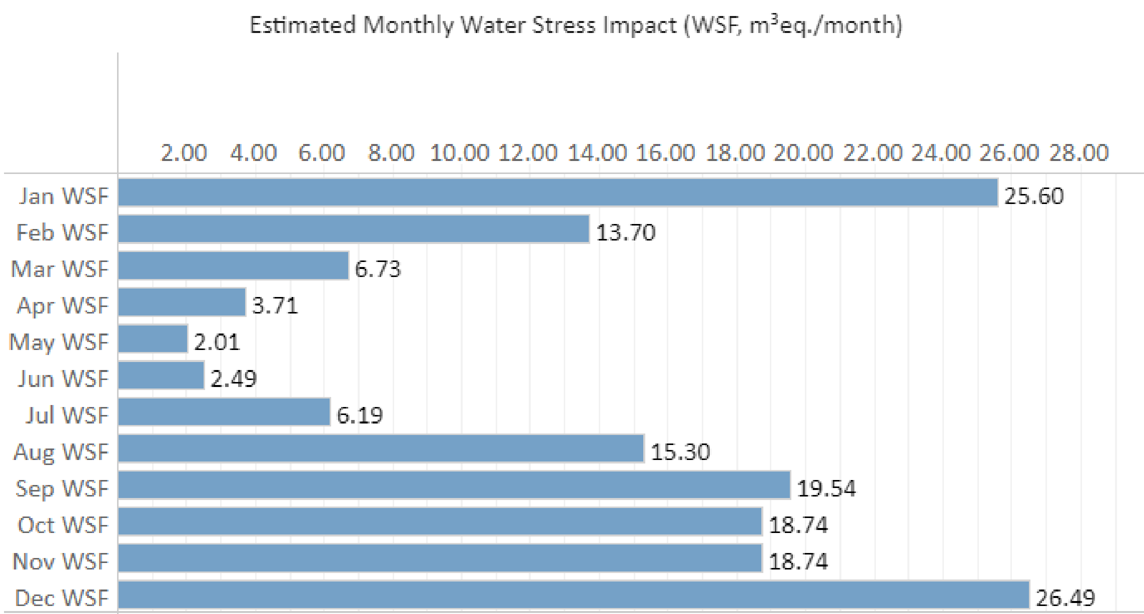
Please enter monthly water consumption (m^3/month) for Nye,NV

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	1	1	1	1	1	1	1	1	1	1

The table below shows annual water consumption and the annual WSF. The annual total WSF is the sum of monthly WSFs. We do not recommend using annual average CF and annual total water consumption to calculate annual WSF, as this would assume that both water consumption and water availability are equally distributed across 12 months.

Annual summary	
Annual Total Water Consumption (m3)	12.00
Annual Total Water Scarcity Footprint (m3 eq.)	159.25

The bar chart below displays monthly WSF (m^3 eq./month) for the monthly water consumption that a user entered in the selected county.



4 POTENTIAL APPLICATIONS

The AWARE-US model can be used to compare water-stress impacts caused by marginal new water consumption in different U.S. counties and seasons. For instance, the model can be combined with resource assessment models to identify suitable sites for biomass production. As an example, prior work utilized the AWARE framework to quantify the regional water stress induced by large-scale algae cultivation; this information was incorporated into the pond siting process to balance water sustainability and biomass productivity. By using AWARE-US, we identified sites with high yield and low water-stress impact (Xu et al., 2020, 2019a). With that information, our analysis suggested that it is possible to scale U.S. algae biofuel production to 5.5 billion gallons of renewable diesel per year without significant water-stress impact (Xu et al., 2020). Similarly, the model can be used to screen sites for other water consumption scenarios, such as increased irrigation use, deployment of new energy production facilities, or changes in cooling water demand by power plants.

It should be noted that existing SWC as of 2015 has already been factored into the baseline data, so the model is suitable for evaluating potential water-stress impact caused by new water users or changes in existing water demand. In addition, the model is intended for marginal-impact use, which means significant increase in new water demand will require additional steps for water-stress impact assessment. As a rule of thumb, if new water consumption exceeds 5% of supply (runoff), then CFs need to be updated on the basis of the projected new remaining water availability condition.

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