12-2020

Projecting Water Available for Irrigation Use and Identifying Water Supply Stress Under Climate Change Scenarios in Selected U.S. Fruit and Vegetable Production Regions

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Projecting Water Available for
Irrigation Use and Identifying Water Supply Stress Under Climate Change Scenarios in Selected U.S. Fruit and Vegetable Production Regions

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Biological Engineering

by

Andrew Shaw
University of Arkansas
Bachelor of Science in Biological Engineering, 2017

December 2020
University of Arkansas

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Abstract

Climate change affects water resources differently across geospatial regions in the United States (U.S). There is a concern of how water availability will be affected by changes in long-term temperature and precipitation patterns, specifically in major production regions for eight fruit and vegetable crops. The effects on surface water available for irrigation use and supply stress in five regions containing 31 Agricultural Statistics Districts (ASDs) were assessed. The Water Supply Stress Index Model was used and modified to project water available for irrigation use across nine climate scenarios driven by historical data, five General Circulation Models, two population scenarios, and two Representative Concentration Pathways. Through the incorporation of Hydrologic Unit Code 8 subbasin boundaries (HUC8), and ASDs, a new border was defined from the HUC8 borders which allowed water availability in the ASDs and regions to be quantified through hydrologic boundaries and flow characteristics between HUC8s. Projected surface water available for irrigation use increased at the annual time step from 2040-2070 across ASDs in the Pacific West for two moderate warming scenarios. Two high warming scenarios projected decreased water availability in the Pacific West. The results all showed decreased projected surface water available for irrigation use in the Midwest and Southeast. Across all climate scenarios in the Midwest, Southeast, and Northeast, average watershed surface water supply stress induced by irrigation is projected to increase. The Plains and Pacific West showed decreased supply stress in certain scenarios, but this does not tell us how the watersheds will be affected during growing seasons. Past research shows that in areas of the Western U.S., precipitation will increase annually due to climate change. Overall, the results showed that water availability would decrease in the selected regions across climate change scenarios, but more work is needed to understand how the specific fruit and vegetable crops will be affected.

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Chapter 1- Introduction

1.1. Problem Statement

Increasing greenhouse gas concentrations in the atmosphere, resulting in climate impacts, are raising concerns over the hydrologic cycle and its effects upon agricultural productivity. If rainfall patterns change, meeting an increased demand for fruits and vegetables will pose a challenge for domestic production regions in the United States (U.S.). Previous studies have shown that climate change will result in changes in both precipitation and temperature resulting in a change to the available water supply (Cisneros, Blanca; Oki, 2014; Dahlman, 2018; Duan et al., 2016; Roy et al., 2012). Large areas of croplands across the central U.S. are predicted to be threatened by rising temperature and decreasing water availability for irrigation (Duan et al., 2017). California is one of the leading domestic sources of many vegetable and fruit crops, but climate change, as well as increased competition for land, water, and other natural resources, have the potential to limit production in the current major centers of production. Over the entire continental United States (CONUS), increases in temperature is projected to have a greater role than precipitation.

Climate change will impact the overall hydrologic cycle and will affect sectors dependent on water resources. The availability of water has a major impact on the yield and quality of selected crops in current conditions. The projected shifts in surface water availability are not uniform across the U.S. (Averyt et al., 2013; Seager et al., 2013; US EPA, 2016). Total surface water supplies in the Pacific Northwest are projected to increase, while in the Southwest, runoff is projected to decline by 10% (Averyt et al., 2013).

Analyzing the historical and future water availability for fruit and vegetable producing regions could provide a method for assessing the viability of production in a region in response to climate change. Evaluating whether a water gap exists in the current production regions provides decision makers with critical information for risk assessment. Management of water in the production systems must also include preserving the ecosystem services provided by freshwater to sensitive habitats in these regions.

1.1.1. Areas of interest

The fruit and vegetable crops that provided the basis for the research areas in this study are tomatoes, potatoes, oranges, green beans, carrots, spinach, strawberries, and sweet corn. These eight crops were selected based on their importance to human nutrition as well as cropping system model and data availability (Gustafson et al., 2018). Based on these eight crops, 31 Agricultural Statistics Districts (ASDs) were chosen for assessment.

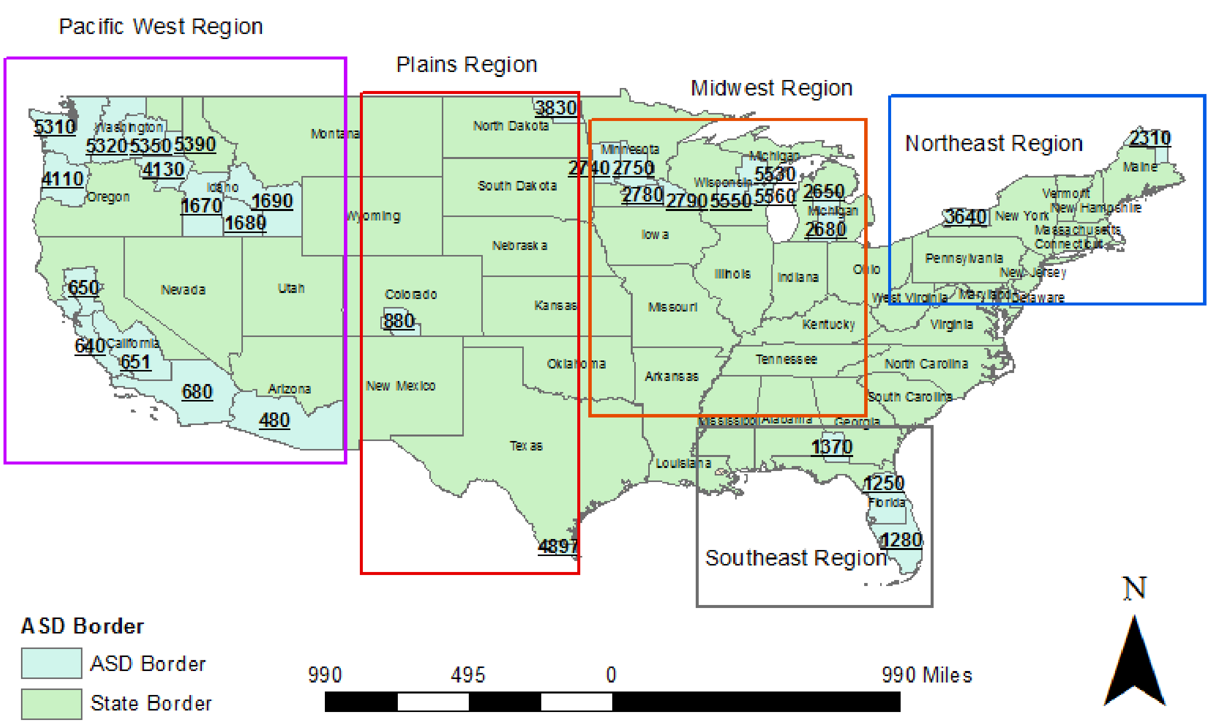

Figure 1. Agricultural Statistics Districts (ASDs) chosen for project within their Agricultural Research Service (ARS) regions

Table 1. List of the ASDs selected for the project

State	State Agricultural Statistics District (ASD)	Agricultural Research Service (ARS) region	Number of HUC8s intersecting ASD
Arizona	AZ480	Pacific West	42
California	CA651	Pacific West	38
	CA680	Pacific West	40
	CA640	Pacific West	32
	CA650	Pacific West	28
Colorado	CO880	Plains	15
Florida	FL1280	Southeast	19
	FL1250	Southeast	18
Georgia	GA1370	Southeast	13
Idaho	ID1690	Pacific West	40
	ID1670	Pacific West	30
	ID1680	Pacific West	16
Maine	ME2310	Northeast	9
Michigan	MI2650	Midwest	9
	MI2680	Midwest	12
Minnesota	MN2790	Midwest	12
	MN2780	Midwest	13
	MN2740	Midwest	16
	MN2750	Midwest	17
New York	NY3640	Northeast	9
North Dakota	ND3830	Plains	11
Oregon	OR4110	Pacific West	28
	OR4130	Pacific West	17
Texas	TX4897	Plains	4
Washington	WA5320	Pacific West	26
	WA5350	Pacific West	12
	WA5310	Pacific West	41
	WA5390	Pacific West	11
Wisconsin	WI5560	Midwest	9
	WI5530	Midwest	9
	WI5550	Midwest	7

1.1.2. Objectives

Changing trends in temperature and precipitation signify that impacts of global climate change in specific agricultural regions needs to be addressed. This study focuses on the water availability for irrigation in the five regions containing these ASDs as well as water supply stress from irrigation demand over time. The objectives of this study include:

1) assessing water available for irrigation use in the five regions at historical, near future, and far future conditions, and
2) determining water supply stress in the five regions at historical, near future, and far future conditions

1.1.3. Hypotheses to be tested

The focus of this research was to evaluate potential water available for irrigation use and to quantify water supply stress through time in the five Agricultural Research Service (ARS) regions containing the 31 ASDs. Many projections of rainfall and water availability have been made over the past ten years for the CONUS, but no studies have evaluated predicted competing demands at the watershed (HUC8) scale within ASDs or the ARS regions.

Combinations of regions and climate scenarios were chosen for analysis based on the results of the ANOVA tests. (see Section 3.1.1). The ANOVA tests were necessary for finding significant differences between the historical time period and the future scenarios and as such, not every combination of each region and scenario was chosen for analysis. The following hypotheses were tested to see if the projected water available for irrigation use will not show a decreasing trend in these regions.

$H(0)_1$: Projected water available for irrigation use will not show a decreasing trend in the five regions of the US in the near future scenarios.

$H(0)_2$: Projected water available for irrigation use will not show a decreasing trend in the five regions of the US in the far future scenarios.

1.1.4 Modeling irrigation water supply stress index under climate change scenarios

This second group of hypotheses evaluates whether the water supply stress index due to irrigation needs alone will have a statistically significant difference in the five regions when comparing the historical period to the future scenarios.

$H(0)_3$: Water supply stress due to irrigation demand will not increase from the baseline scenario to the near future scenarios in the five regions of the US.

$H(0)_4$: Water supply stress due to irrigation demand will not increase from the baseline scenario to the far future scenarios in the five regions of the US.

1.2. Literature Review

It is important to provide a sufficient background related research and modeling methods being utilized. It is important to have an understanding as to the origins of climate change research leading into present day studies that examine the impact of climate change on water resources. Some of the first research on climate change started over a century again. In 1824, Joseph Fourier discovered the greenhouse effect (AIP, 2018). In 1862, John Tyndall showed that carbon dioxide had a strong greenhouse effect (AIP, 2018). Svante Arrhenius first showed how doubling atmospheric CO_2 in the atmosphere would warm surface temperature in 1896 (Arrhenius, 1896). There were scattered reports describing how greenhouse gases had an impact on the climate but it was not until 1988 that greenhouses gases were becoming a more forefront issue (Revkin, 2018). The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 and its first report on climate change was published in 1990. This report showed how small changes in temperature and precipitation could have a significant impact on runoff (Shiklomanov et al., 1990). In 1977 the impact of climate change on water resources and its effects on the world was explored in *Climate, climatic change, and water supply (*Wallis, 1977). Gleick (1987) used a water balance model for the Sacramento Basin for climate impact assessment, which was one of the first studies using hydrologic modeling under a changing climate. As early as 1968, large-scale water use projections in the U.S. were made by the Senate Select Committee on National Water Resources (Brown, 1999). A national water-use compilation in the U.S. has been conducted by the United States Geological Survey (USGS) every five years since 1950 under the National Water Census. These reports show consumptive-use estimates for thermoelectric power and irrigation water use as well as estimates of public supply and domestic use (National Water Census). Climate change and water resource science resource has come a long way since these studies. While the concerns identified in the hypotheses for this study are not new, the methods for assessment are more advanced than previous investigations. It is crucial to build upon previous studies but also improve upon previous hydroclimatological models by looking at the critical issue of water availability in major fruit and vegetable production regions.

1.2.1. Fruit, vegetables, and irrigation

All eight of the fruit and vegetable crops in this study require some level of irrigation; however, there was not national data available to show irrigation water use estimates for each of these crops. It is still important to understand where these crops are being grown, their economic value, and to see where crop irrigation in general is taking place in the U.S.

In 2018 the total area harvested for carrots in the U.S. was 79,800 with a value of 731,504,000 dollars. The largest producers are California, Michigan, Texas, Washington, and

Wisconsin. The total area harvested for sweet corn was 473,100 acres with a value of 858,862,000 dollars. The largest producers are California, Florida, Washington, New York, and Georgia. The largest producers of spinach are California, Arizona, New Jersey, and Texas with a total area harvested of 61,450 acres and a value of 422,879,000 dollars. Idaho and Washington are the largest producers of potatoes. The total area harvested for potatoes was 1,014,800 acres with a value of 4,006,340,000 dollars. California and Florida are the largest producers of green beans, oranges, tomatoes, and strawberries. The total areas harvested in 2018 for green beans, and tomatoes were 221,500 acres and 321,900 acres with respective values of 363,506,000 dollars and 1,856,280,000 dollars. Three million eight hundred seventy-five thousand tons of oranges were produced with a value of 1,704,399,000 dollars and 1,428,895 tons of strawberries were produced with a value of 2,670,523,000 dollars (National Agricultural Statistics Service, 2019).

In 2012, the majority of crop irrigation occurred in five principal regions: The Mississippi Delta, the High Plains Ogallala region, the California Central Valley, the Columbia River Basin of the Pacific Northwest, and the Snake River Basin of the Pacific Northwest. Vegetables accounted for seven percent of the irrigated acres in the 17 Western States and 12.5% of the irrigated acres in the 31 Eastern States in 2012 (USDA ERS, 2019). It is important to note that sources of irrigation differ on a farm by farm basis. One farm in California growing tomatoes may rely on a groundwater source while another may be using surface water. This is an important consideration for this study as only surface water availability for irrigation was analyzed.

1.2.2 Climate change and water resources

There is a multitude of studies exploring the link between climate change and water resource vulnerability. Roy et al. (2012) modeled water withdrawal projections in the U.S. through the year 2050 and demonstrated that future water resources could be affected by population growth and climate change. This study builds upon his research by assessing how water resources are at risk from climate change and population growth in fruit and vegetable production regions. Higher temperatures will turn snowfall into rainfall and the time of snowmelt will occur earlier in the year (Dahlman, 2018). As a result, the timing and volume of the spring flood will drastically change. This change in the timing of spring flooding adds uncertainty to this project due to the model operating at the annual time scale which cannot account for seasonal fluxes in water availability. Tavernia et al. (2013) showed that the number of watersheds in the Northeastern and Midwestern U.S. experiencing severe water stress was projected to increase under most climate change scenarios between 2010 and 2060 using the Water Supply Stress Index (WaSSI) model. Additionally, some watersheds were projected to develop severe stress under several scenarios. These findings are noteworthy as watersheds were modeled in specific fruit and vegetable production regions in the Northeast and Midwest using the same model. Duan et al. (2016) found that future climate change may result in reduced water yield in the 170 National Forests and Grasslands (NFs) in the U.S. under 20 General Circulation Models (GCMs) of the Coupled Model Intercomparison Project phase five (CMIP5). These GCMs are the most current future climate projections. A subset of these GCMs were used in this project using similar methods. Water yield is projected to decrease by 18 ~ 31 mm per year by 2100 due to a rise in air temperature and precipitation. In addition to understanding of regional water resources are impacted by climate change it is important to present information on water use given that irrigation water use is a major focus of this project.

1.2.3. Overview of water use

Globally, agricultural consumption makes up 90% of water usage (Rost et al., 2008). In the U.S., agriculture makes up the largest sector of consumptive water use by 80.7% of the total (Moore et al., 2015). According to the Economic Research Service branch of the United States Department of Agriculture (USDA), agriculture accounts for over 90 percent of consumptive use for ground and surface water in many western states (USDA ERS , 2019). Agriculture is extremely important in this region of the country which is why it was essential to include major fruit and vegetable production areas in the Pacific West for this study. Water use for irrigation has stayed within a narrow range or has declined slightly from 1970-2005 (Roy et al., 2012). In the USGS data set, the water use per unit area known as irrigation intensity, did not show a clear correlation with climatic drivers like average precipitation and potential evapotranspiration (Roy et al., 2012). Brown et al. (2013) investigated USGS water use data from 1960-2015 and found that water use efficiency has improved in most sectors. Domestic, public, and irrigation withdrawals in most regions of the western U.S. have started to decrease. If these trends continue and with the absence of further climate change, withdrawals in the U.S. will be expected to stay within 3% of the 2005 levels. Including the effects of future climate change significantly increases the projection in water withdrawals. Modeling the effects of future climate change on water withdrawals and water supply has been accomplished in many studies through the WaSSI model.

1.2.4. Review of studies using the WaSSI model

Sun et al. (2008) conducted a study using two General Circulation Models (GCMs), one land use change model, and one human population model to evaluate water stress conditions in the 13 southeastern states across their 666 HUC8s. Future water supply stress was projected in 2020. The study found that climate changes had the most significant impact on water supply in Western Texas. Population increases contributed mainly to higher water supply stress in metropolitan areas in Florida and the Piedmont region. Future changes in precipitation patterns were found to be uncertain, mainly in the eastern U.S. Tavernia et al. (2013) used WaSSI to evaluate changes in the Northeast and Midwestern regions between 2010 and 2060. The study examined anthropogenically induced water stress in watersheds. Six scenarios of land-use change, climate change, and population change were used. The results indicated that severe stress would increase for most of the scenarios. In the future scenarios, the changes were averaged across the HUCs. This project also adapted his method and averaged water stress values across HUCs. As seen in previous studies, precipitation did not show a consistent direction of change. Half of the future scenarios projected increases in precipitation and half showed decreases. The average WaSSI value increased for HUCs in the Midwest and Northeast for all the scenarios. Averyt et al. (2013) assessed the influences of different demand sectors on water stress using WaSSI. Agriculture is the principal demand-side contributor to water stress overall in the U.S. Their results imply that water resources in the Southwest region are at risk. This project explores water resources in the Southwest region in major fruit and vegetable production regions adding to the body of research for this region. Total surface water supplies in the Northwest are projected to increase and a 10% decrease in runoff is projected in the Southwest when comparing the periods of 1900-1970 to 2041-2060. Duan et al. (2017) used historical records and 20 CMIP5 models through WaSSI and found that precipitation has been the primary driver of runoff variation; however, temperature's role will outweigh that of precipitation's in most regions if future climate change follows projections. Precipitation is expected to be the principal driver in runoff increases across the Southwest and Pacific Coast. Severe runoff depletion is predicted to occur in the central U.S. due to temperature increases. This runoff depletion may play a role in available water for irrigation use in this region. A wetter future is a possibility in the Eastern U.S. due to increasing humidity and precipitation which could also impact water available for irrigation but it is unknown of this precipitation will vary through specific fruit and vegetable growing seasons.

Water scarcity increases during the summer months where crop production is the highest. Since data was analyzed over a large time period, annual data was used instead of monthly data for this project. The WaSSI dataset contains monthly data for all the factors analyzed but for a general sense of water stress in major fruit and vegetable production areas annual data was sufficient. According to a five-year, county-scale water study done by Moore et al. (2015), 13.7% of the county is considered water scarce at the annual scale but increases to 17.3% in the summer months. Approximately 15% of the basins modeled that were classified as "unstressed" contained water scarce areas around 10% during the summer months. This information should be considered for future studies done on fruit and vegetable producing areas that incorporate water use. Further diving into some of these studies it is important to understand how water withdrawals are modeled.

1.2.5. Projection modeling

The overall approach in modeling water withdrawals under climate change scenarios that Brown et al. (2013) took was to create projections instead of forecasts. The intent of projections is to show the effects of what happens when past trends are extended into the future rather than trying to predict future trends. Oki et al. (2006) state that the objectives of future-oriented water resource studies should show what can happen if water resources are managed the way they presently are. Scenarios influenced by past decisions and trends are used for future projections on the water demand side. Averyt et al. (2013) also kept present-day water demands constant due to uncertainty in predicting future water demands. This provides a rationale for why water demand is projected rather than predicted in future water resource assessments. This same approach was used for this project to stay consistent with these studies. With the knowledge of climate change research, resulting water resource issues, similar studies utilizing WaSSI, and water withdrawal projection methodology it is important to set forth certain limitations and gaps in knowledge in the modeling deployed in this project. On top of the limitation of accounting for water fluctuations during crop growing seasons, these limitations include environmental water requirements, interbasin transfer (IBT), and groundwater data.

1.2.6. Environmental water requirements

Studies on water availability, stress, and use have often failed to consider the water requirements of aquatic systems. Smakhtin et al. (2004) developed the first pilot global assessment of total water volumes needed for maintaining freshwater ecosystems in world river basins. In the report, the water volumes are referred to as environmental water requirements (EWR), which is commonly referred to as environmental flow. The necessary EWR to sustain fair conditions globally in freshwater systems ranges from 20 to 50% of the mean annual river flow. Caissie et al. (2014) define EWR as the idea of environmental flow or environmental water requirements related to the volume of water required in freshwater systems needed to maintain an acceptable level of life of aquatic organisms throughout their life cycles. Kendy et al. (2012)

developed a guide for environmental flows for nine cases studies while acknowledging that site specific EWR criteria have not been developed across the whole U.S. For North Carolina water bodies, a percentage of flow strategy was developed to address EWR. This approach uses 80-90% of the ambient modeled flow that remains in streams as EWR (*Recommendations for Estimating Flows to Maintain Ecological Integrity in Streams and Rivers in North Carolina*, 2013). There are no universal criteria for EWR because it is site specific and continues to be quantified with further research.

1.2.7. Interbasin Transfer

When using the WaSSI model, it is common to find modeled WaSSI values greater than 1.0 in certain watersheds. Since WaSSI values greater than 1.0 mean that the local demand exceeds the available supply in the watershed, water transfer from an adjacent HUC is necessary. This transfer of water constitutes interbasin transfer (IBT). The WaSSI model does not account for IBT. This means that water supply stress is being calculated under no basin transfer conditions. Southern California is an example of an area where IBTs play a crucial role in water resource management. In this area, water demand is not being met by the local supply (WaSSI>1.0). This region depends on bringing water in from both northern California and the Colorado River to increase the local supply. Although water demands are generally met there, the region may be at risk if water supplies from the Colorado River and northern California decrease, or if the infrastructure that stores and transports the water to California is affected. With all of this in mind it is important to consider the research done on IBTs in the U.S.

The most recent work identifying interbasin transfers in the U.S. was done by Kerim et al. (2017). The purpose of this work was to identify the number of interbasin transfers that exist in the U.S. and to examine the distribution of them along with potential impacts related to any clusters of IBTs. The most recent national studies of IBTs were done by the USGS in 1985 and 1986 using the HUC definitions of basins. The USGS studies used HUC4 boundaries. For the study done by Kerim et al. (2017) the HUC6 boundaries were used and so an IBT was defined as a water transfer across HUC6 boundaries. They found that a total of 2,161 man-made waterways cross these boundaries in the U.S. They are mainly concentrated in Florida, Texas, and North Carolina accounting for over 50% of the IBTs. North Carolina does not contain any of this project's ASDs and the ASD in Texas does not have recorded IBTs based on historical data, so this knowledge is helpful in determining the validity of the data in these areas. Unfortunately, volumetric flow data is not available through the National Hydrography Dataset (NHD) which the authors used to identify the IBTs. This means that quantifying the impact of each IBT on the basins is difficult. The national inventory by the USGS included volumetric flow data and magnitudes of the IBTs between 1973 and 1982 (Mooty and Jeffcoat 1986, Petsch 1985). This data was utilized in the very first study to both use WaSSI and include IBT data downscaled to the HUC8 level by Emanuel et al. (2015). This study found that supplying and receiving drainage basins have hydroclimatological conditions in common with each other. This suggests that climatological drivers of water shortages in receiving basins have similar effects on the supplying basins. Human water demand as well as engineering constraints influence the distribution of IBTs across the continent while the hydrological characteristics of the basins do not seem to be a driving factor. This work is important in understanding how IBTs affect the HUC8 basins involved and emphasizes the need for updated national inventories and analyses to better understand IBTs in a hydrological sense. This lack of data adds an assumed limitation to this project since IBTs affects water used for irrigation in many areas.

1.2.8. Groundwater

The WaSSI model does not account for the physical volumes of available groundwater that can exist in the same geographic boundaries that freshwater reside in. The model assumes an unlimited groundwater supply. For example, the entire region that uses the Ogallala Aquifer shows no current water stress through WaSSI modeling, yet the aquifer is overdrawn.

Two important assumptions in the WaSSI calculation noted in (Averyt et al., 2013) are that water is supplied by local natural sources (i.e. stream flow) and that the available groundwater is unlimited. This second assumption means that groundwater withdrawals will continue at their current rates despite the implied impacts and overdrafts. Groundwater supplies are not unlimited and are in fact declining in many places because of withdrawals, but there is a lack of quality assessments on availability (Dennehy, Reilly, & Cunningham, 2015). Since there is no national dataset for groundwater use at the HUC8 scale or ASD scale, the options regarding groundwater are to assume it is infinitely available or completely unavailable. Oki & Kanae (2006) state that approximately half of the world's population depends on groundwater as a source for drinking water as well as for other uses. In terms of groundwater demand, changes in the seasonal pattern have not been quantified globally.

1.2.9. WaSSI model calibration and validation

One of the most important aspects to the WaSSI model is that it does not require calibration. This is not a common feature in similar models. WaSSI was created to include crucial ecohydrological processes that influence water balance with standardized input datasets without the need for calibration. Schwalm et al. (2014) found that WaSSI exceeded the customary Nash-Sutcliffe efficiency (NSE) for a "good" model-data agreement. Comparing modeled runoff values to observed USGS measurements for the 18 Water Resource Regions

(WRRs) in the CONUS, WaSSI had a 0.89 NSE value. A score of 1.0 indicates that the modeled data perfectly matches the observed data. Caldwell et al. (2015) found that simple, regional-scale models like WaSSI, have comparable performance to more complex, fine-scale models at a monthly time step. WaSSI had a comparable error in predicting observed streamflows at a monthly time step as more complex models such as HSPF, PRMS, SWATG, and WaterFALL. Caldwell et al. (2015) found that the uncalibrated WaSSI model predictions were considered good for five sites and very good at one site in the Southeastern U.S.

Bagsta et al. (2018) compared results between InVEST models and WaSSI using land cover data at 30 and 300-meter resolution. The study found that the models were insensitive to the choice of spatial resolution and that six out of nine ecosystem service variables gave similar predictions for at least two different land cover datasets. Results can be robust to data and models in both simple models and national scale analyses. Caldwell et al. (2012) validated WaSSI using monthly observed runoff data between 1961 and 2007 at outlets of 10 sites that are a part of the USGS Hydro-Climate Data Network. It performed well in showing annual and monthly runoff patterns at the sites. Duan et al. (2017) performed additional validation of the model to verify this result. Annual runoff was simulated using monthly precipitation and temperature from the PRISM dataset and was compared to USGS measurements across the entire CONUS and in the 18 WRRs from 1961-2010. The R-squared value was shown to be 0.91 and 0.95 for these two scales and the root mean squared error (RMSE) was 29 and 555 mm/yr, respectively. Based on these studies, WaSSI is believed to be the best model for accomplishing the goals of this project due to its ease of use for regional modeling.

Chapter 2- Materials and methods

2.1. Study area

This study analyzed watersheds within 31 Agricultural Statistics Districts (ASD) in the CONUS. The ASDs are groupings of counties defined by climate, cropping practices, and geography in each state. The geographic features include terrain, elevation, and soil type. The components of climate are annual precipitation, length of growing season, and mean temperature. These variables impact the need to conserve soil moisture, crops grown, and irrigation use (National Agricultural Statistics Service). In turn, the ASDs were grouped within their Agricultural Research Service Region (ARS). In the hydrologic unit system created by the U.S. Geologic Survey (USGS), the U.S. is divided into six levels of hydrologic units. Each unit has a unique hydrologic unit code (HUC) made up of 2-12 digits. The level of classification used in this study is the HUC8 sub basin level. The sub basin level is comparable to medium-sized river basins (about 2200 nationwide at the time the WaSSI simulations were run). This level of classification is also referred to as watershed in this study. Climate and water supply variations at the resolution of the HUC8 watershed were simulated and upscaled to the ASD and ARS scale. The different spatial resolutions modeled are shown in Figure 2.

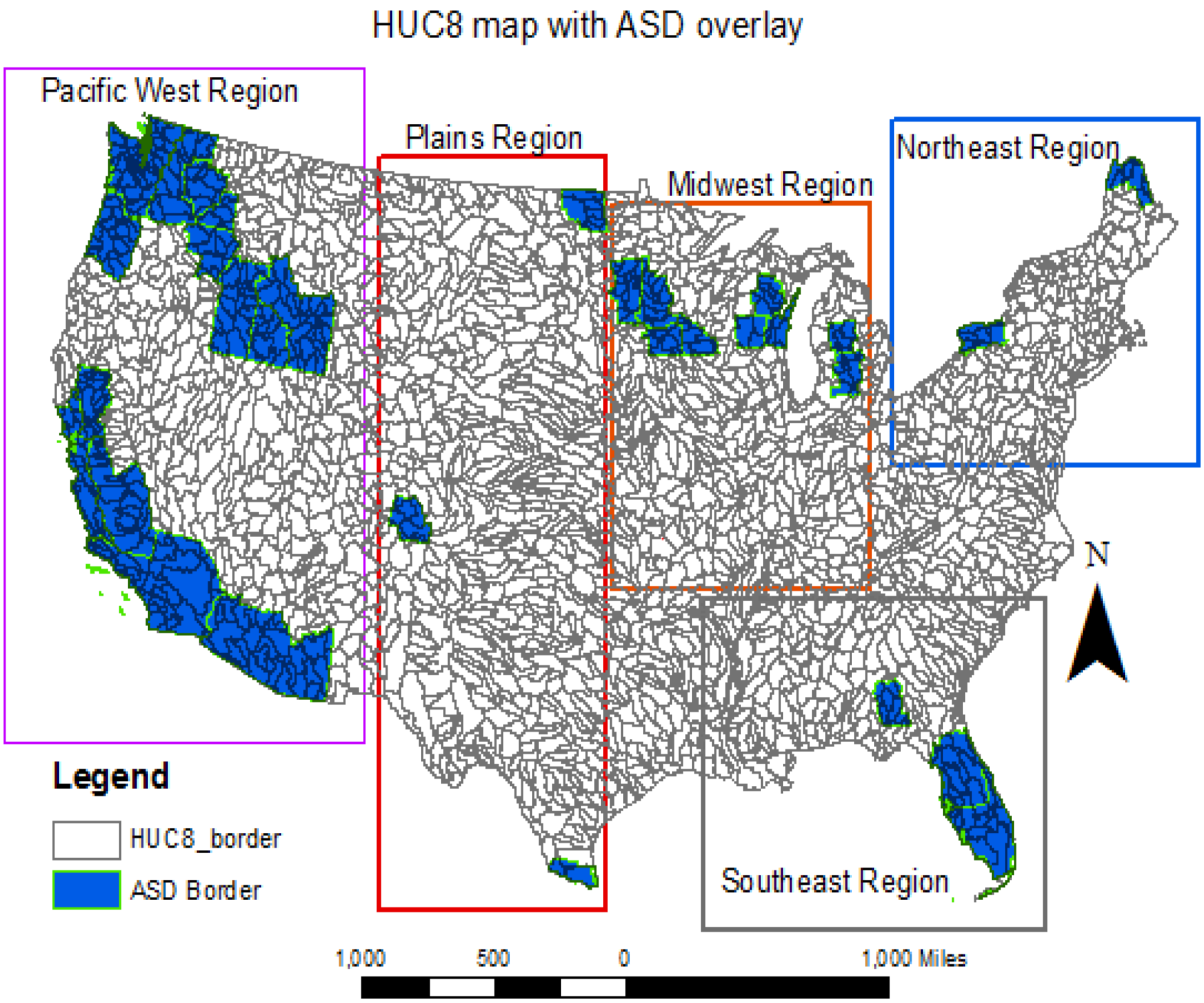

Figure 2. HUC8 map of the CONUS with ASD overlay and ARS region groupings

2.2. Climate change scenarios

Two climate datasets were used to provide inputs to the WaSSI model. The first contains monthly temperature and precipitation for the historical period of 1981-2010 from the Parameter-elevation Relationships on Independent Slopes Model (PRISM) dataset. This data came with the WaSSI model and was used as the baseline scenario. The second dataset contains monthly precipitation, solar radiation, wind speed, specific humidity, maximum temperature, and minimum temperature from the Multivariate Adaptive Constructed Analogs (MACA) datasets (MACAv2-LIVNEH dataset). Only the temperature and the precipitation data were needed from this dataset. The downscaling from the larger grid spatial resolution to HUC8 was done by (Duan et al., 2017). The five General Circulation Models (GCMs) of the fifth phase of the Coupled Model Inter-comparison Project (CMIP5) were used. The five GCMs are: GFDL-ESM2M(GCM1), HadGEM2-ES365(GCM2), IPSL-CM5A-LR(GCM3), MIROC-ESM-CHEM(GCM4), and NorESM1-M(GCM5). Representative Concentration Pathways (RCP)4.5 and RCP8.5 were used for each of the GCMs. These RCPs correspond to climate forcings such as aerosols and greenhouse gas emissions projected into a future where radiative forcing reaches 4.5 and 8.5 W/m^2 in the year 2100 (Moss et al., 2010; IPCC, 2014). The two future time periods are 2021-2050 for near future, and 2040-2070 for far future for the study scenarios.

2.3. Population scenarios

The population scenarios used are the A1 and the A2 scenarios. The A1 scenario came with the WaSSI Fortran model. It is considered the “as is” scenario. This data is based on county resolution IPCC SRES A1 projections (Zarnoch et al., 2010). This is equivalent to what was the current official U.S. Bureau of Census national projection in 2010. This scenario was previously downscaled from county resolution to the HUC8 level by the WaSSI model developers. The annual population estimates were calculated through linear interpolation between the decadal data by the same researchers. After the year 2060, the population for that year is kept constant for simulations that go beyond it because of a lack of data that goes beyond that year and because of difficulties rewriting the Fortran code to allow for the population to be read beyond 2060. The A2 population scenario was provided by Dr. Kai Duan and contains data from 2006 to 2099. This scenario is a higher population growth future. This scenario’s data was not in a format that could be read by the Fortran model and had to be converted to match the format in the A1 scenario by using the MATLAB programming language.

2.4. Model background

The model used to simulate water supply variables for this project is the Water Supply Stress Index (WaSSI) model. WaSSI is a process-based model that can project the effects of climate change, forest land change, and water withdrawals on water supply stress, river flows, and carbon dynamics across the conterminous U.S., Rwanda, Burundi, and Mexico (U.S Forest Service). The core of this model is a water balance module that is sensitive to land cover and climate. It operates on a monthly time step at the 8-digit HUC watershed scale across the U.S. Annual USGS water demand estimates are adjusted to the population, disaggregated to the monthly time step, and compared to the surface and groundwater supply to assess stress on the water supply. Consumptive use is subtracted from stream flow in the river network. The model algorithms were developed by USDA Forest Service scientists from the Eastern Forest Environmental Threat Assessment Center. The web application version was created by a partnership between Praecipio Consulting, Photo Science Inc, and the Eastern Forest Environmental Threat Assessment Center and the USDA Forest Service International Programs.

The principal element of the model that was used for this project is the water balance module. The water balance module contains the predicted precipitation data for each of watersheds within the selected ASDs which is a critical driving force behind predicting water availability. The WaSSI water balance module computes the water balance separately for each of the different land cover classes in each watershed. Evapotranspiration (ET), infiltration, snow accumulation, snow melt, soil storage, surface runoff, and base flow is accounted for within each basin as shown in Figure 3 below. The required inputs for each watershed include monthly precipitation (PPT), mean monthly leaf area index (LAI), and temperature(T) for each land cover class, impervious cover fraction by land cover, soil properties, and land cover distribution.

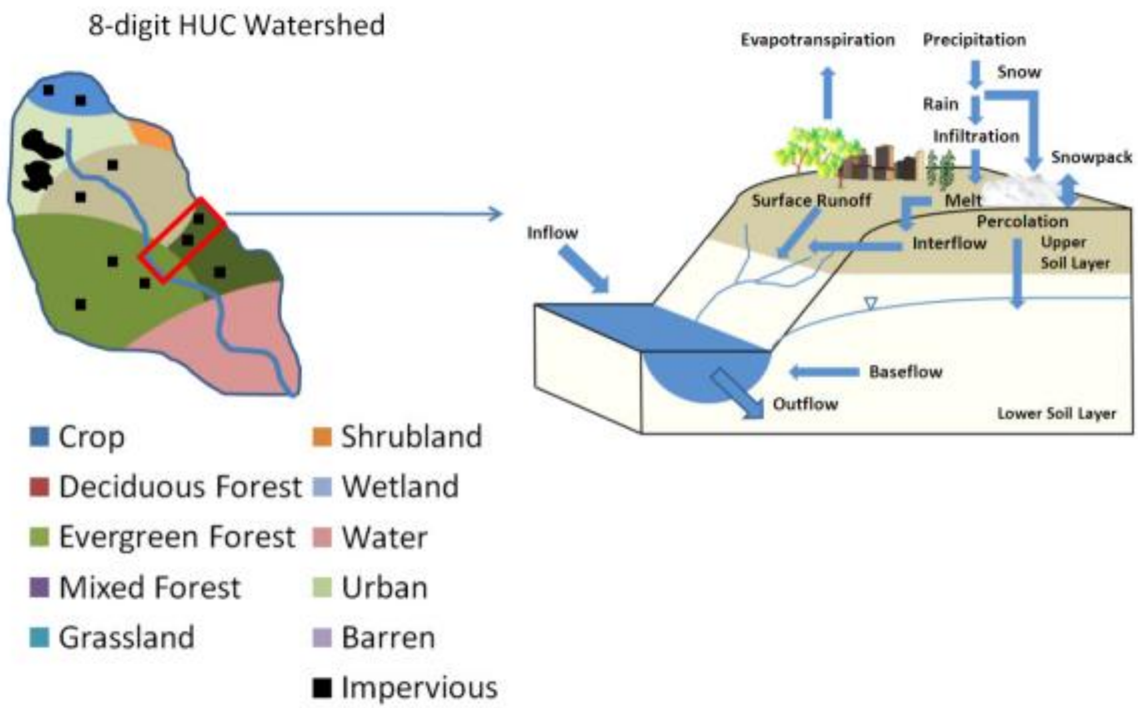

Figure 3. Land cover classes and hydrologic processes simulated by the WaSSI Model. Reprinted with permission from WaSSI Services Model User Guide v1.2 by P. Caldwell and G. Sun et al., 2019 USDA

The water supply/demand module is the other component of the model that was used for this project. This module can perform three functions:

1. Calculate the total monthly water demand, groundwater withdrawals, and return flows across the domestic, industrial, thermoelectric, irrigation, livestock, public supply, aquaculture, and mining sectors in each watershed based on the 2005 county-level USGS water use estimates scaled to HUC8;

2. Accumulate and route the water yield generated in each watershed through the river network at a monthly time step, subtracting consumptive use which is withdrawals minus return flows from river flows at the watershed outlets; and

3. Compute the Water Supply Stress Index (WaSSI) for each watershed at a monthly time step.

WaSSI is computed as D/S. Total freshwater withdrawals, WD_{SW+GW}(MGD) is the total freshwater withdrawals from groundwater and surface water (SW+GW) is as follows:

$$WD_{SW+GW} = total\ freshwater\ withdrawals\ from\ groundwater\ and\ surface\ water$$

Equation 1

The total water demand(D) for a HUC8 in WaSSI is the sum of total freshwater withdrawals from groundwater and surface water and is shown by:

$$D = \Sigma WD_{SW+GW}$$

Equation 2

The total water supply(S) in a HUC8 is given by

$$S = Q_S + \Sigma WD_{GW}$$

Equation 3

Where Q_S is the surface water supply (MGD) for a HUC8 and ΣWD_{GW} is the sum of groundwater withdrawals for a HUC8.

The 2005 USGS water use data was replaced with the 2010 USGS water use data for this project to simulate more accurate projections for future water use. The code used to run the model was obtained by the developers of WaSSI who work with the U.S. Forest Service (Dr. Ge Sun, Dr. Peter Caldwell, Erika Mack). The data was simulated through a Fortran-backed version of the model and produced output at the watershed level.

2.5. Surface water supply validation

The variables generated from the water balance within the WaSSI model were not all directly used in projecting surface water supply for the stress analysis section. Instead, processes within the model was recreated using the equations in the WaSSI User Guide (Peter Caldwell et al., 2013). This was done because certain processes within the model had to be manipulated to project water availability for irrigation use in ASDs and ARS regions rather than project water availability at the HUC8 scale. The surface water supply produced from the WaSSI model was compared to the surface water supply calculated in Equation 4.

$$CalculatedSWS_w(MGD) = \Sigma Q_{in}(MGD)_w + ConvertedRunoff(MGD)_w$$

Equation 4

$\Sigma Q_{in}(MGD)_w$ is the sum of flows from upstream watersheds if present and the derivation of it is elaborated on in more detail in Section 2.7. First, the runoff values from WaSSI were converted from mm to Mm^3/year and is shown by

$$ConvertedRunoff\left(\frac{Mm^3}{year}\right) = RUNOFF(mm) * Area\ of\ \frac{HUC(m^2)}{1000} /1{,}000{,}000$$

Equation 5

Next, the newly converted runoff needed to be converted from Mm^3/year to MGD.

$$ConvertedRunoff(MGD) = ConvertedRunoff\left(\frac{Mm^3}{year}\right) * 0.724\frac{MGD}{Mm^3}/year$$

Equation 6

Q_{in} was then converted from Mm^3/year to MG/year and is as follows

$$\text{Qin}\left(\frac{MG}{year}\right) = \text{Qin}\left(\frac{Mm^3}{year}\right) * 264.17\ MG/Mm^3$$

Equation 7

Another conversion of the flow in had to take place in order to get the water supply values in the same units as water demand for irrigation (MGD) which was needed for the stress analyses. The Q_{in} in MG/year was converted to MGD and is as follows

$$Flow\ in\ (MGD) = \frac{Flow\ in\left(\frac{MG}{year}\right)}{365\ days}$$

Equation 8

There were some mismatches between the values from the WaSSI simulations and the numbers manually calculated. The same routing table was used to calculate the surface water supply manually that the model uses, and the runoff values were also the same. It is not believed that the errors have a huge impact on the water availability analysis for the ASDs based on the overall percent differences between the surface water values. In comparing the values, the percent difference was used since the values compared are both from models and therefore are values obtained from experimentation which fits the criteria for using the percent difference formula. The equation used to find the percent difference is

$$\%\ Difference = \left(\left(\frac{\frac{|WaSSI_{SWS} - Calculated_{SWS}|}{WaSSI_{SWS} + Calculated_{SWS}}}{2}\right)\right) * 100$$

Equation 9

Where $WaSSI_{SWS}$ = the surface water supply for a HUC8 in MGD generated from the WaSSI simulation; $Calculated_{SWS}$= the surface water supply for a HUC8 in MGD calculated manually fromEquation 9.

The average percent difference was 0.15% and the maximum value was 9.28% using WaSSI simulation output utilizing historical data. All but two of the watersheds in the 31 ASDs had a percent difference under 5.00%. ASD 680 contains a watershed with the largest percent difference in surface water supply. 18100204 which is an isolated watershed, had a percent difference of -8.273%. The value calculated from the WaSSI equations is a larger value than the value produced from the model-simulation.

2.6. Routing

In order to accurately project surface water supply in the ASDs using output from WaSSI, the same routing data between HUC8s needed to be used that the WaSSI model uses. Routing in this case is the physical relationship between each HUC8 in terms of how one watershed outlet empties into another watershed. The format of the routing matrix in the WaSSI model is seen in Table 2. Each number in the three columns corresponds to an ID number. An ID number represents a specific HUC8. The -9999 values are blank values that do not correspond to a HUC and are just placeholders that allow the Fortran code to read the table.

Table 2. Screen capture of routing data read by Fortran code. Entire Matrix is 1245 rows X 33 columns

1	2	-9999
1	3	-9999
4	-9999	-9999
5	-9999	-9999
16	-9999	-9999
17	10	6
-9999	10	8
-9999	10	9
-9999	13	12
18	13	11
18	15	14
19	-9999	-9999
20	-9999	-9999
21	-9999	-9999
23	-9999	-9999
27	22	-9999
27	24	-9999
27	25	-9999
27	26	-9999

The ID numbers were replaced with the 8-digit HUC codes to give a table like that shown in the first column of Table 3.

Table 3. Three transformations of the routing matrix shown in each column

Transformation 1

1010001	1010002		
1010001	1010003		
1010004			
1010005			
1050001			
1050002	1020005	1020001	1020002
	1020005	1020003	
	1020005	1020004	
	1030003	1030002	
1050003	1030003	1030001	
1050003	1040002	1040001	
1060001			
1060002			
1060003			
1070002			
1070006	1070001		
1070006	1070003		
1070006	1070004		
1070006	1070005		
		1080106	1080105
		1080106	1080107
	1080201	1080202	
	1080201	1080203	

Transformation 2

18100203	18100204
18100100	18100204
18090208	18070203
18090202	18090203
18070304	18070305
18070202	18070203
18070105	18070106
18070104	18070106
18070102	0
18070102	0
18060012	18060006
18060007	18060008
18050004	18050002
18050001	0
18050001	0
18030010	18030012
18030009	18030012
18030007	18030012
18030006	18030012
18030005	18030012
18030004	18030012
18030003	18030012
18010211	18010209
18010210	18010209
18010206	0
18010206	0
18010206	0

Transformation 3

FROM	TO
18100204	None
12040101	12040104
11080003	11080006
11140306	11140304
5030104	5030101
12070101	12070104
6010107	6010201
15020014	15020013
14070004	14070001
12100303	12100204
14080106	14080105
9030004	9030008
15020018	15020016
18100100	18100204
16060002	None
16060012	None
8010202	8010100
9010003	None
15080102	None
2080203	2080205
16020306	None
3060103	3060106
15080101	None

The table in the first column is an example of the first transformation that took place. In this table, the columns are read from right to left with headwater HUC8s starting on the right and ocean or international boundaries in the leftmost column. Each column of the table was then pasted in reverse order to give a mirror image of the data so that the data could be read from left to right. This is seen in the second column of Table 3 above. In this second transformation, the column all the way on the right corresponds to HUCs flowing into oceans or international boundaries. The third transformation is the table in the final column. Table headers of ‘FROM’ and ‘TO’ were added to the table. The ‘FROM’ column corresponds to the HUC that has water traveling to separate downstream HUC. The ‘TO’ column corresponds to the HUC that is receiving water from the separate upstream HUC (if applicable).

If there is a none in the ‘TO’ column it means that the HUC is not contributing any flow downstream to another HUC. After this final table was created all duplicate routing pairs needed to be removed. For example, 18010206 to zero is shown three times when it only needs to be counted once. After removing all duplicates, the resulting table represents the same routing data used for the coterminous U.S. that the WaSSI Model. The resulting table was formatted as an Excel file that the developed code in R could use to process data. This table was used to find all flow out values (water leaving the outlet of the HUC) for the HUCs.

The next steps for determining projected water available for irrigation involved ArcMap. The Agricultural Statistics Districts borders were added from a shapefile obtained from the USDA National Agricultural Library (“NASS - Quick Stats | National Agricultural Library,” 2017). Using the ASD borders and HUC8 border in ArcMap, the percent area of each HUC in each ASD was found using the ‘Tabulate Area’ tool. In order to avoid having shared flows between HUCs crossing two or more ASD borders, the ASD borders were redefined based on watershed boundaries. If the majority of a HUC was contained in an ASD it was counted towards the new border. The new ASD borders based on HUCs are called ASD Watershed Borders. An example of this new type of boundary is shown below.

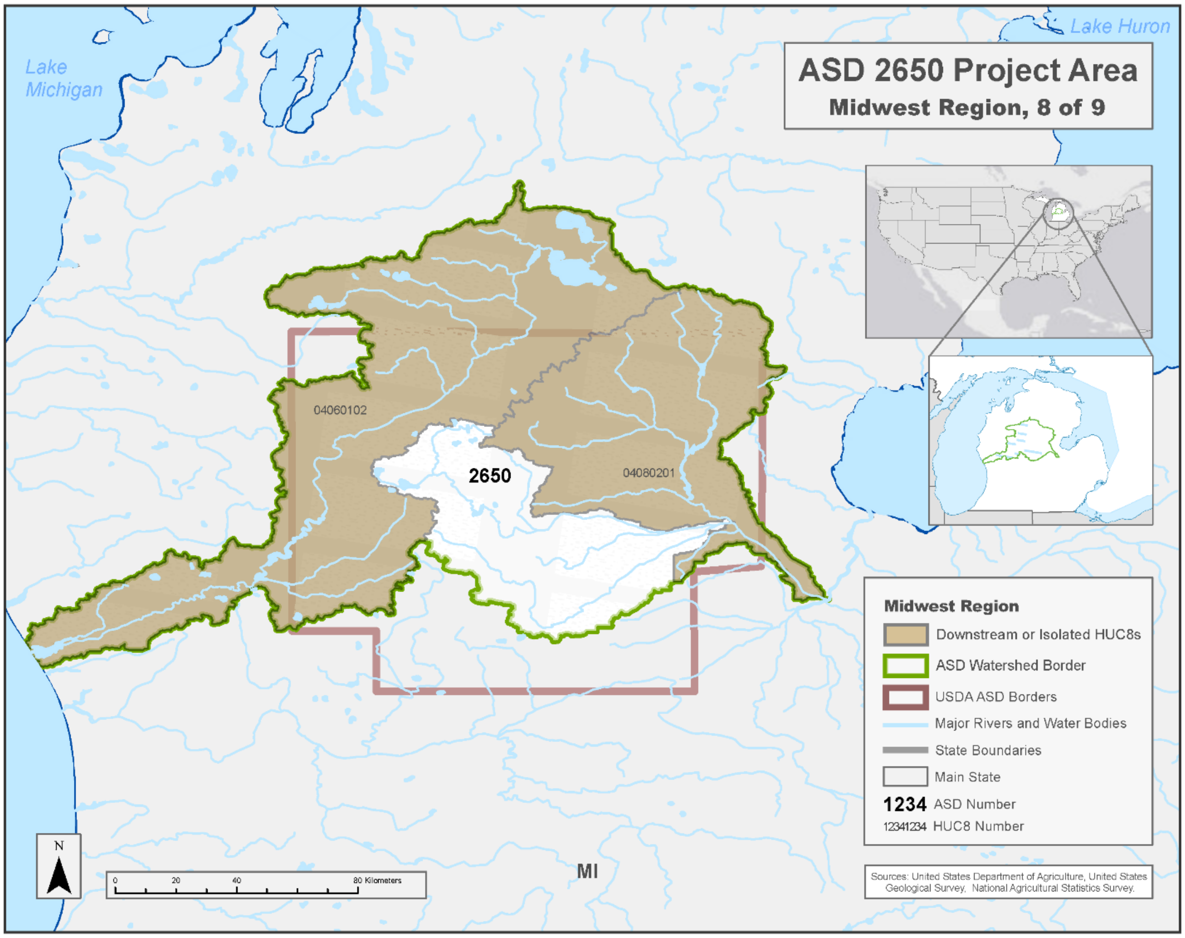

Figure 4. Example of an ASD Watershed Border boundary. ASD 2650 in the Midwest is shown.

2.6.1. Flow Classification

After creating the HUC8 routing table for the entire U.S., a routing table for the 31 ASDs was created was created using the ASD Watershed Borders which changed the number of HUCs assigned to each ASD. Based on the ASD routing data, flow classifications were assigned to each HUC8. Each HUC was assigned a flow classification value of one or two. A value of one means that the HUC is either ‘isolated’ or ‘downstream’. An isolated HUC does not receive flow from an upstream HUC or contribute flow to a downstream HUC. A downstream HUC means that the HUC is receiving flow from an upstream HUC in the ASD but not contributing flow to a downstream HUC in the ASD. A HUC with a flow classification of two is a ‘flow-through’ watershed. A flow-through watershed both receives flow and contributes flow to other watersheds. Water in a HUC with a flow classification of two is not considered available to the ASD in this upscaling approach since its outlet streamflow is counted in each downstream watershed. Ensuring that flow through HUCs are not counted towards the overall ASD water availability negates possible over accounting of water that is represented downstream.

2.7. Projecting surface water available for irrigation

Determining the water available for irrigation use in the future was accomplished through the R programming language. Microsoft Excel was used to separately check the calculations done in R. Each of the scenarios used in projecting water available for irrigation use is seen in Table 44. Each scenario has water supply data in WaSSI that is determined by whether the climate variables come from PRISM, RCP 8.5, or RCP 4.5 for the respective GCM. In WaSSI, the domestic water demand sector is the only water demand sector that is being simulated through time and is dependent on the population scenario. All other water demand sectors are kept constant from USGS data in the model. The irrigation water use estimates come from 2010 USGS data. F1 scenarios correspond to near future (2021-2050), and F2 scenarios correspond to far future (2040-2070). All scenario results are the average of the five GCMs results with the exception of the historical scenario.

Table 4. Summary of historical (1981-2010) and future (2021-2050,2040-2070) scenarios of irrigation water supply stress and projected irrigation water availability

Scenario	Water Supply	Water Demand Domestic	Irrigation
Historical	PRISM Climate	USGS County Level Census	2010 USGS Data
High Stress AF1	RCP 8.5 Climate	Population under SRES A2	2010 USGS Data
High Stress BF1	RCP 8.5 Climate	Population under SRES A1	2010 USGS Data
Intermediate Stress AF1	RCP 4.5 Climate	Population under SRES A2	2010 USGS Data
Intermediate Stress BF1	RCP 4.5 Climate	Population under SRES A1	2010 USGS Data
High Stress AF2	RCP 8.5 Climate	Population under SRES A2	2010 USGS Data
High Stress BF2	RCP 8.5 Climate	Population under SRES A1	2010 USGS Data
Intermediate Stress AF2	RCP 4.5 Climate	Population under SRES A2	2010 USGS Data
Intermediate Stress BF2	RCP 4.5 Climate	Population under SRES A1	2010 USGS Data

For each scenario, routing data for the ASDs was referenced to derive the correct flow out values for each HUC8 in million meters cubed per year.

$$Q_{out} = \Sigma Q_{in} + Y - \Sigma CU$$

Equation 10

The variable Y inEquation 10 refers to the water yield/runoff generated in a HUC. ΣCU is the sum of consumptive water use in all watersheds across all water use categories. For this analysis, irrigation was set to zero in the water use and return flow files that the model uses since water available for irrigation use was being modeled. Therefore, irrigation was not being accounted for in the consumptive use variable.

$$\Sigma Q_{in} = sum\ of\ flows\ from\ upstream\ watersheds\ if\ present$$

Equation 11

Flow in was not a variable present as WaSSI output. Through a lookup function, the flow out of a given HUC that was being routed to another HUC is counted as Flow in. All Flow out values from a HUC going to another HUC were summed to give an overall Flow in value for a

HUC. Q_{out} and Q_{in} values change for each scenario. Next, the water left in the downstream or isolated HUC for EWR was calculated. The EWR constant is determined by the user and was set to be a constant 0.20 (20%).

$$EWR\ constant = 0.20$$

Equation 12

The AvailableFlowOut is the flow out of an isolated or downstream HUC in the ASD. This value was directly simulated from WaSSI.

$$EWR = AvailableFlowOut\left(\frac{Mm^3}{year}\right) * EWR\ constant$$

Equation 13

The water available for irrigation after EWR is subtracted from the AvailableFlowOut is given by

$$ProjectedWaterAvailable\left(\frac{Mm^3}{year}\right) = AvailableFlowOut - EWR$$

Equation 14

ProjectedWaterAvailable($\frac{Mm^3}{year}$) was aggregated from HUC to each ASD for every simulation year to give an overall value for each ASD called ASDIrrigationWater($\frac{Mm^3}{year}$) and is given by

$$ASDIrrigationWater\left(\frac{Mm^3}{year}\right) = \sum_{i=1}^{n} ProjectedWaterAvailable\left(\frac{Mm^3}{year}\right)$$

Equation 15

The variable *n* corresponds to each watershed and *i* corresponds to each year of simulation so that the projected water available is summed for each year in a watershed for every watershed making up the ASD to show results at the ASD scale. The water availability values were each year were averaged across ASDs in a region to give an average value for each region. Statistical analyses were then run on each region's results.

2.7.1 ANOVA

The first statistical test performed was a one-way Analysis of Variance (ANOVA) test using Microsoft Excel. The significance level of 0.05 was used. This test compared each projected future scenario to the historical time period simulation to assess whether there was a statistically significant difference between the datasets.

2.7.2 Mann-Kendall

The next statistical test used was the Mann-Kendall test. The Mann-Kendall rank statistic test is one of the most widely used tests for analyzing climatological time series trends and in hydrologic time series (Mavromatis & Stathis, 2011; Yue & Wang, 2004). It is a non-parametric test that does not require normally distributed data. It is most generally a test to see if Y values tend to increase or decrease with time. The package 'Kendall' in R was used for calculating Kendall's S statistic (score) and Kendall's tau (*Package "Kendall,"* 2015). Tau assesses the strength of the relationship between the x and y variables. It is resistant to effects from a small number of skewed data points and is rank based. Tau is typically lower than the traditional correlation coefficient r when compared to linear relationships of the same caliber.

When the score is a large positive number, the values measured later in time are larger than values measured earlier in time which indicates an upward trend in the data. If tau is positive, this also indicates an upward trend. The null hypothesis of no trend is rejected when the score is significantly different from zero (Helsel & Hirsch, 2002). The alternative hypothesis assumes there is a trend. Kendall's tau is expressed as

$$\tau = S/D \text{ where } S = \Sigma_{i=1}^{n-1} \Sigma_{j=i+1}^{n} sign T_j - T_i \text{ and } D = n(n-1)/2$$

Where T_j and T_i are annual values in years j and i, and j is great than i. S is the score and D, the denominator. D is the largest possible value S can be.

2.8. Irrigation surface water supply stress evaluation

2.8.1. Stress classification

Calculating the water supply stress index due to irrigation demand was modeled after the method done by Averyt et al. (2013). One key difference; however, is that only surface water supply stress was calculated for this project. Knowing the routing connections between each HUC in the ASDs allowed for calculating the surface water supply for each HUC using the runoff and the flow in (Q_{in}).

The water supply stress by the irrigation sector *i* at the watershed scale *w* was calculated through Equation 16, where $WD_{w,i}(MGD)$ is the water demand for irrigation in 2010 for each watershed and $CalculatedSWS_w(MGD)$ is the calculated surface water supply for each watershed found in Equation 4.

$$WaSSI_{w,i} = WD_{w,i}\ (MGD)\ /CalculatedSWS_w(MGD)$$

Equation 16

The stress indices used for this analysis originate from Oki et al. (2001) and are seen in Table 5.

Table 5. Watershed level stress indices ranging from low stress to high stress

Classification of WaSSI values	
Category	*Index*
Low	<0.1
Moderate	0.1-0.2
Medium	0.2-0.4
High	>0.4

The higher the WaSSI value, the greater the water supply stress to the watershed. Groundwater supplies are not taken into account due to the lack of quality data surrounding this topic (Dennehy et al., 2015). One assumption in the WaSSI calculation was that the water was being supplied by local sources. Interbasin transfer was not considered. A watershed may have a WaSSI value greater than 1.0 but this may be an overestimate due to demands being met by infrastructure such as reservoirs, groundwater pumping, recycled water, reclaimed water, and interbasin transfers. EWR was not considered for the stress analysis to remain consistent with previous studies looking at watershed stress induced by specific demand sectors and given that the stress value may already be an overestimate in certain areas due to the above-mentioned reasons.

Annual surface water supply ($CalculatedSWS_w$) for each of the scenarios in Table 4 was calculated using the modified WaSSI model developed for this project. Irrigation water demands were estimated by projecting 2010 USGS water use data into the future. This was done in order to see the possible effects on water supply stress if present water use in this sector was projected into the future under a range of climate and population scenarios. Each simulation year into the future used the 2010 irrigation values. Present water use equated to the 2010 USGS values because that was the most recent data available. Only the HSAF1, HSAF2, ISAF1, and ISAF2 scenarios were analyzed for this section because the B scenarios used a different population scenario. Since the only water use sector used for calculated WaSSI was irrigation, the population did not impact the resulting data.

Chapter 3- Results and discussion

3.1. Results and statistical analyses

The results for projected surface water available for irrigation use in million meters cubed per year (Mm^3/year) are shown in Appendix G and in the proceeding graphs. These results are shown for each year for the Historical, HSAF1, HSBF1, ISAF1, ISBF1, HSAF2, HSBF2, ISAF2, and ISBF2 scenarios. These represent the full range of scenarios chosen across the two warming scenarios (RCP 4.5 and 8.5), two population scenarios (A1 and A2), historical period from 1981-2010, near future period from 2021-2050, and far future period from 2040-2070. Figure 5 shows the results for each of the five regions for the historical time period from 1981-2010. Overall, the Pacific West has the most water available for irrigation use over time, followed by the Southeast, Northeast, Midwest, and Plains. The Pacific West and Southeast also appear to have the greatest fluctuations in water availability. This coincides with extreme precipitation and temperature events in these regions. Figure 6, Figure 7, Figure 8, and Figure 9 shows the results for the near future scenarios (2021-2050) which follow similar trends as the Historical scenario. Figure 10, Figure 11, Figure 12, and Figure 13 show the water availability for each region for the far future scenarios (2040-2070). In these scenarios, the noticeable difference in water availability is the switch from the Southeast to the Northeast having the second most available water. This data is more comprehensively analyzed through the ANOVA and Mann-Kendall tests.

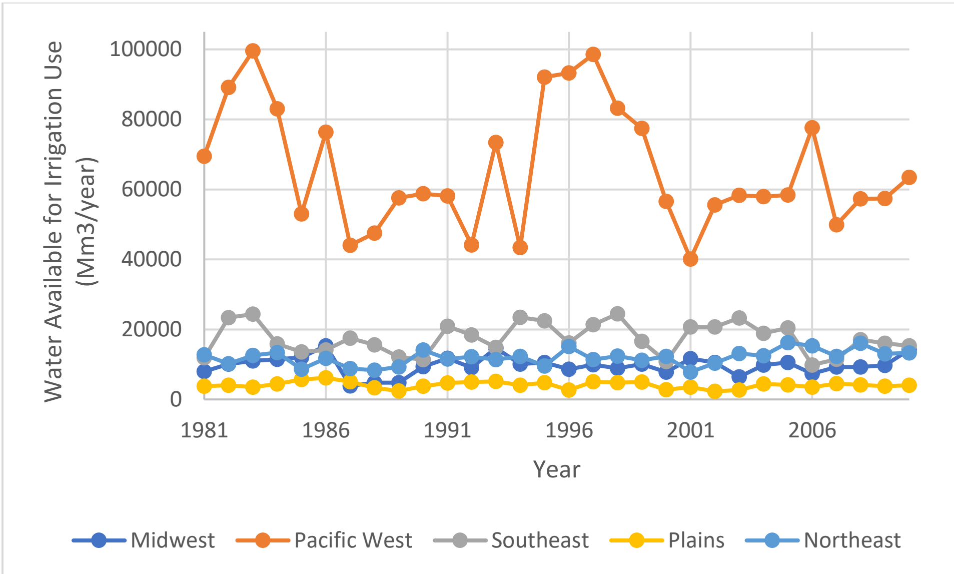

Figure 5. Projected surface water available for irrigation use over time in the Historical scenario

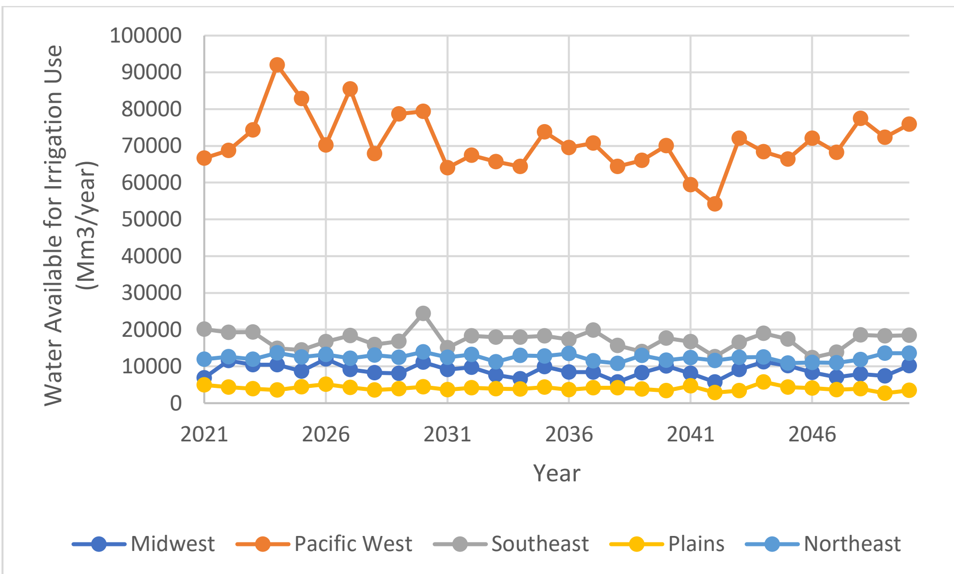

Figure 6. Projected surface water available for irrigatoin use over time in the High Stress High Population Near Future (HSAF1) scenario

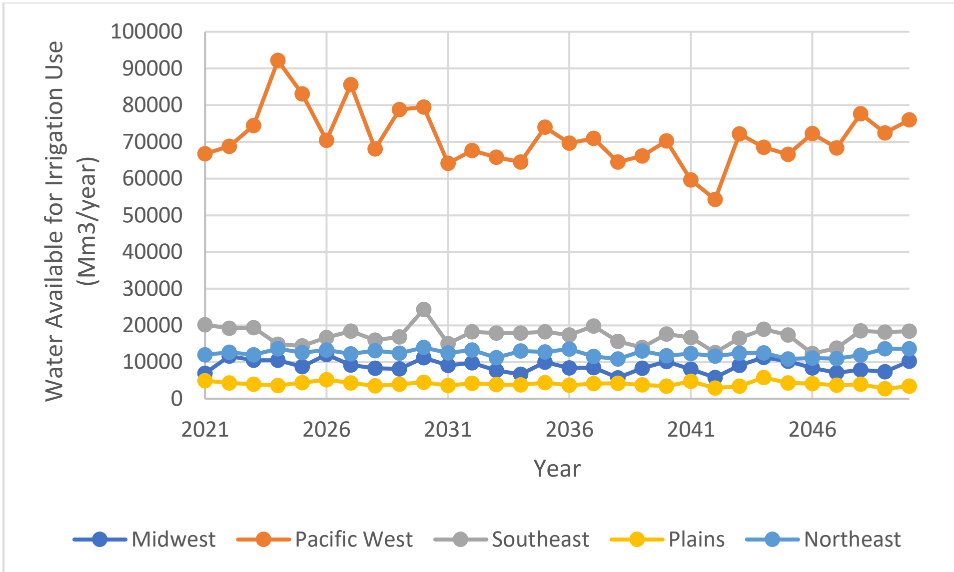

Figure 7. Projected surface water available for irrigation use over time in the High Stress Normal Population Near Future (HSBF1) scenario

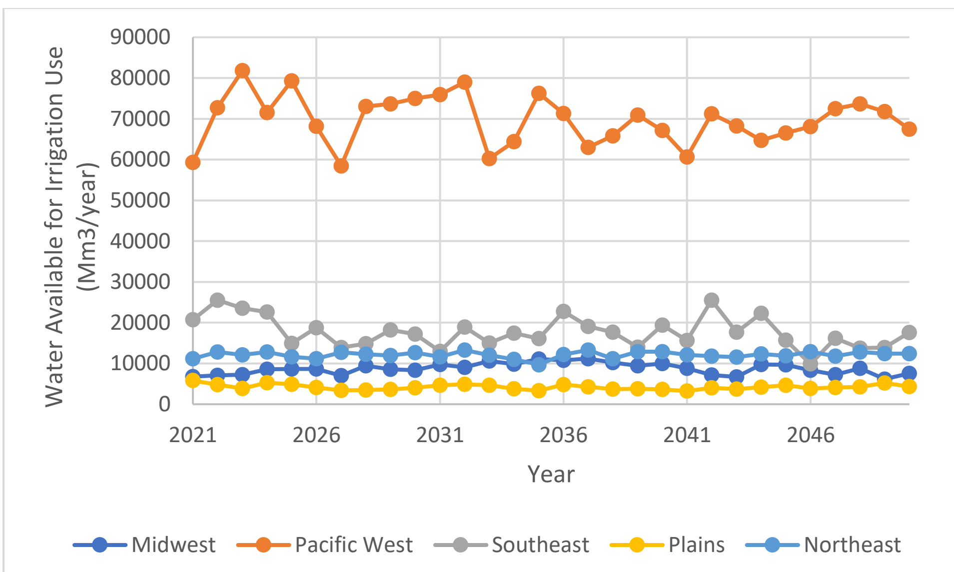

Figure 8. Projected surface water available for irrigation use over time in the Intermediate Stress High Population Near Future (ISAF1) scenario

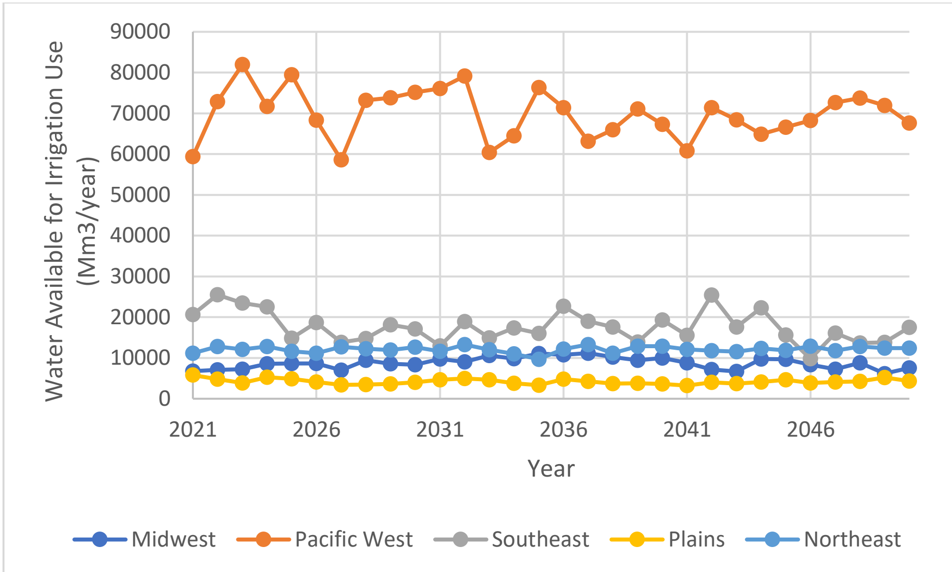

Figure 9. Projected surface water available for irrigation use over time in the Intermediate Stress Normal Population Near Future (ISBF1) scenario

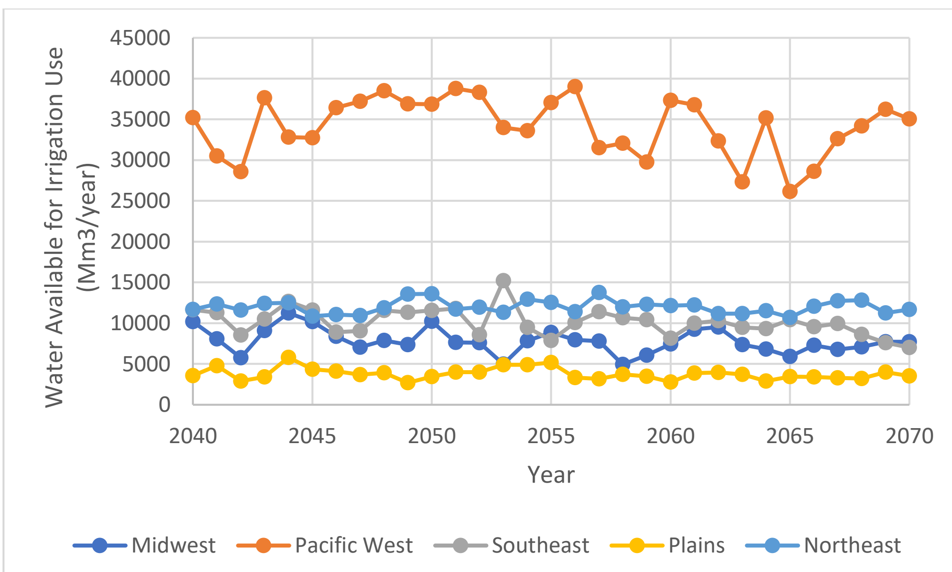

Figure 10. Projected surface water available for irrigation use over time in the High Stress High Population Far Future (HSAF2) scenario

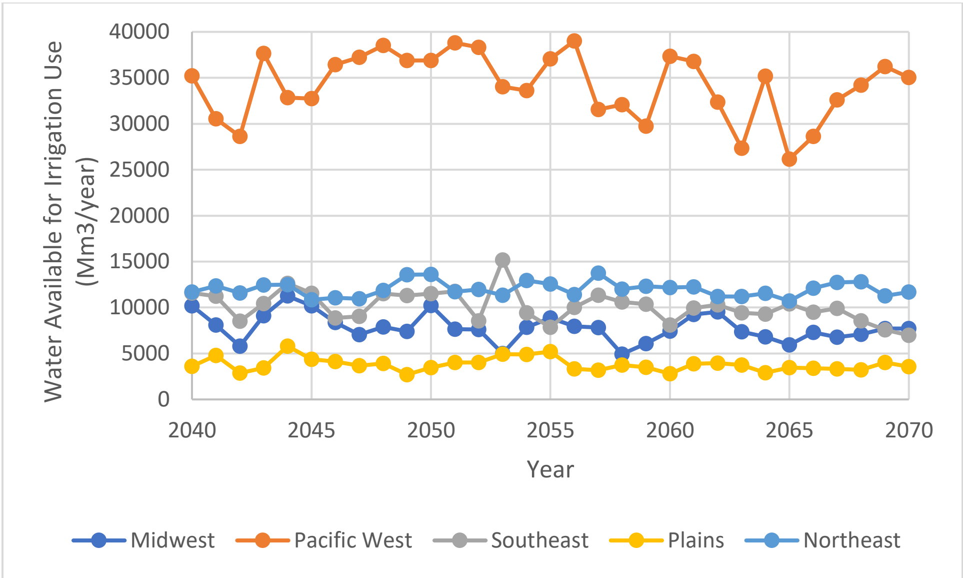

Figure 11. Projected surface water available for irrigation use over time in the High Stress Normal Population Far Future (HSBF2) scenario

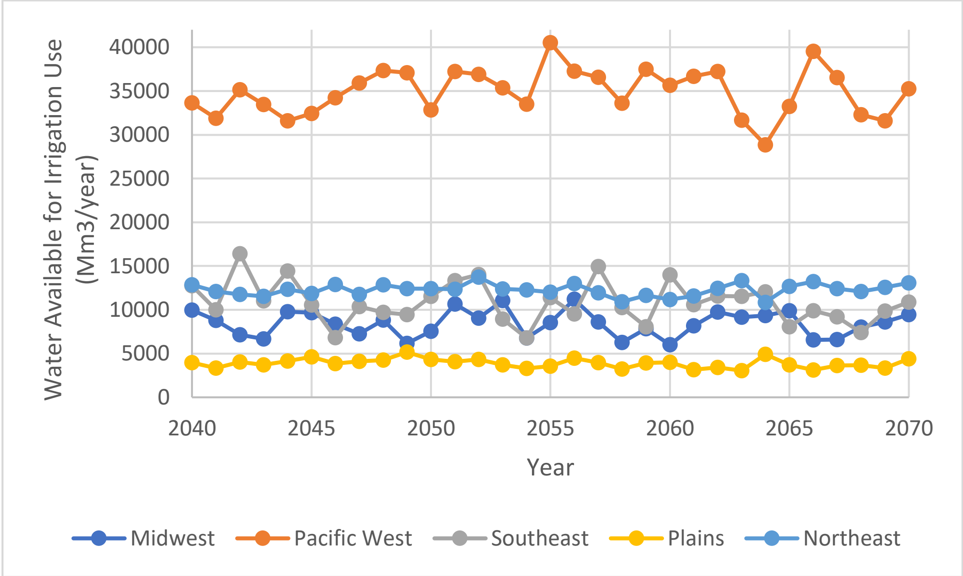

Figure 12. Projected surface water available for irrigation use over time in the Intermediate Stress High Population Far Future (ISAF2) scenario

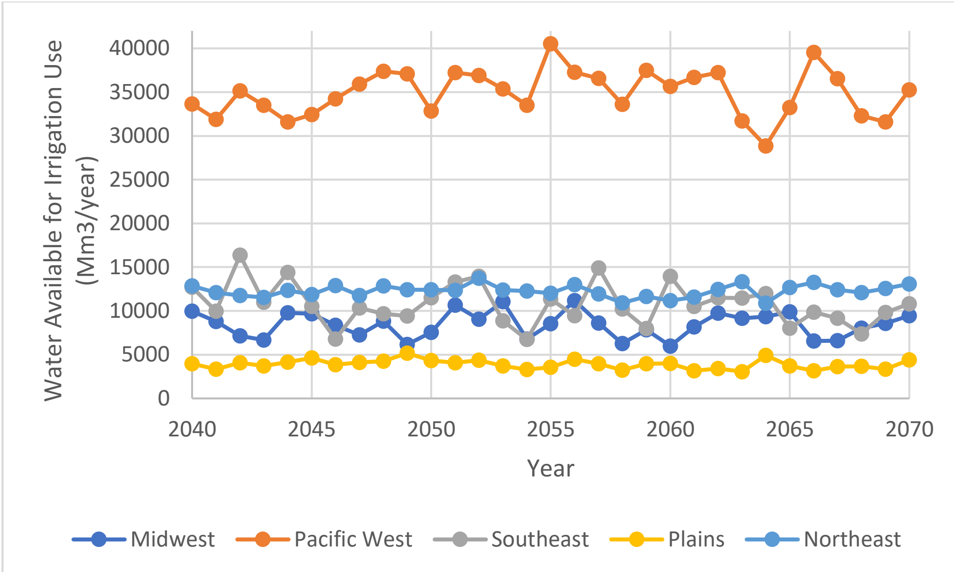

Figure 13. Projected surface water available for irrigation use over time in the Intermediate Stress Normal Population Far Future (ISBF2) scenario

3.1.1. ANOVA results

Each scenario's projections for surface water available for irrigation use had ANOVA tests performed on them. The mean of the historical water availability scenario's regional results generated from measured precipitation and temperature was compared to the mean of each projected future water availability scenario's regional results. If the ANOVA test output shows that the P value is less than 0.05, the means between the historical and the future values are significantly different (Significant). The ANOVA test did not indicate whether a projected future scenario has more or less water compared to the historical values, rather it provided a metric to determine which scenarios required trend testing to determine the positive or negative trend of water availability. Given that there were nine different scenarios for each of the 31 different ASDs the data needed to be consolidated since there would be hundreds of tables to look at with further tests needing to be run. The 31 ASDs were grouped into their respective ARS regions to allow for these analyses. Each table in this section shows the average projected water available for irrigation use for each scenario, the p-value, the alpha level, and the interpretation of the

ANOVA results. The historical scenario for each region shows ‘NA’ for the p-value, alpha, and Test Interpretation because the historical data was what the ANOVA test measured the means against for each future scenario. The historical scenario itself was not interpreted for significance as it was the baseline needed for the comparison of means in ANOVA.

Table 6. Summary of ANOVA results for Midwest Region at alpha = 0.05

Water Availability Scenarios	Average	p-value	Test Interpretation
Historical	9713	NA	NA
HSAF1	8878	0.15	Non-Significant
HSBF1	8881	0.15	Non-Significant
ISAF1	8745	0.08	Non-Significant
ISBF1	8748	0.08	Non-Significant
HSAF2	7813	0.001	Significant
HSBF2	7813	0.001	Significant
ISAF2	8445	0.02	Significant
ISBF2	8444	0.02	Significant

Table 6 above shows that for the Midwest Region there was no Statistical Significance for the HSAF1, HSBF1, ISAF1, and ISBF1 scenarios. There was Statistical Significance in the HSAF2, HSBF2, ISAF2, and ISBF2 scenarios. These same results are seen for the Pacific West and Southeast Regions in Table 7, and Table *8.* Summary of ANOVA results for Southeast Region at alpha = 0.08 below.

Table 7. Summary of ANOVA results for Pacific West Region at alpha = 0.05

Water Availability Scenarios	Average	p-value	Test Interpretation
Historical	65819	NA	NA
HSAF1	65819	0.14	Non-Significant
HSBF1	71106	0.13	Non-Significant
ISAF1	69736	0.25	Non-Significant
ISBF1	69876	0.23	Non-Significant
HSAF2	34171	3.64E-14	Significant
HSBF2	34180	3.68E-14	Significant
ISAF2	34919	6.20E-14	Significant

ISBF2	34927	6.25E-14	Significant

Table 8. Summary of ANOVA results for Southeast Region at alpha = 0.05

Water Availability Scenarios	Average	p-value	Test Interpretation
Historical	17430	NA	NA
HSAF1	17215	0.82	Non-Significant
HSBF1	17162	0.08	Non-Significant
ISAF1	17430	0.79	Non-Significant
ISBF1	17665	0.83	Non-Significant
HSAF2	10153	6.82E-12	Significant
HSBF2	10105	5.49E-12	Significant
ISAF2	10819	8.22E-10	Significant
ISBF2	10770	6.65E-10	Significant

Table *9.* Summary of ANOVA results for Plains Region at alpha = 0.059 and

Table 10. Summary of ANOVA results for Northeast Region at alpha = 0.0510 show that there was no Statistical Significance found in any of the future scenarios for the Plains and Northeast Regions based on the results of the ANOVA tests.

Table 9. Summary of ANOVA results for Plains Region at alpha = 0.05

Water Availability Scenarios	Average	p-value	Test Interpretation
Historical	4107	NA	NA
HSAF1	4018	0.67	Non-Significant
HSBF1	4026	0.70	Non-Significant

ISAF1	4202	0.65	Non-Significant
ISBF1	4210	0.63	Non-Significant
HSAF2	3791	0.15	Non-Significant
HSBF2	3799	0.16	Non-Significant
ISAF2	3886	0.27	Non-Significant
ISBF2	3894	0.28	Non-Significant

Table 10. Summary of ANOVA results for Northeast Region at alpha = 0.05

Water Availability Scenarios	Average	p-value	Test Interpretation
Historical	11964	NA	NA
HSAF1	12388	0.33	Non-Significant
HSBF1	12390	0.33	Non-Significant
ISAF1	12111	0.73	Non-Significant
ISBF1	12112	0.73	Non-Significant
HSAF2	12001	0.93	Non-Significant
HSBF2	12003	0.93	Non-Significant
ISAF2	12275	0.46	Non-Significant
ISBF2	12278	0.45	Non-Significant

In the Midwest, Pacific West, and Southeast Regions the results of these ANOVA tests showed that there was a statistically significant difference in the means of the historical scenario to the ISAF2, HSAF2, ISBF2, and HSBF2 scenario. This means that the projected water available for irrigation use averaged across ASDs in this region differed enough between historical period from 1981-2010 and projected data from 2040-2070. This applied to the moderate warming RCP 4.5 and high warming RCP 8.5 scenarios for both the normal A1 population scenario and the high A2 population scenario. These scenarios represent four of the eight projected future scenarios. The near future period from 2021-2050 and its different scenarios did not show statistically significant differences compared to the historical period meaning these scenarios were not analyzed through trend testing. It is worth noting that these results do not mean that there is not a change in projected water availability in the near future but using averaged results across specific ASDs at the annual scale there was not a statistically significant difference.

The Northeast and Plains Regions did not show statistically significant difference in the means between the historical period from 1981-2020 to any of the projected future scenarios. This means that for the ASDs in these regions, the average results do not show statistical significance for the scenarios modeled. This does not necessarily mean there is no change in water availability which is important to note. The ANOVA test was used to determine which scenarios and regions would require more testing and since there was no statistical significance found for the Northeast and Plains, they were not analyzed using the Mann-Kendall trend test. These results imply that precipitation and temperature do not have a large enough change in these two regions using the selected ASDS at the annual time scale. Specific watersheds and crops may still be heavily affected by a changing climate in the regions and scenarios that did not show statistical significance.

3.1.2. Trend Testing Results

This section presents the results of the Mann-Kendall trend tests which were run on the scenarios with significant differences between the means of the historical scenario compared to a future scenario through the ANOVA test. These scenarios were analyzed using this trend test to indicate which direction the water availability is trending towards throughout the scenario's timespan. The test showed whether the trend was positive or negative over the selected time period.

When the score (S) was a large positive number, later measured projected water available for irrigation use values were larger than earlier measured values (positive trend). If tau was positive, this also indicated an upward or positive trend. The trend test is comparing later measured water available for irrigation use to earlier measured water available for irrigation use.

Table 11. Mann-Kendall Trend Test Results for each scenario by region

Scenario	Score	Var	Denominator	tau	Test Interpretation
Midwest					
Historical	-9	3141.67	435.00	-0.02	Negative Trend
HSAF2	-129	3461.67	465.00	-0.28	Negative Trend
HSBF2	-129	3461.67	465.00	-0.28	Negative Trend
ISAF2	-11	3461.67	465.00	-0.02	Negative Trend
ISBF2	-11	3461.66	465.00	-0.02	Negative Trend
Pacific West					
Historical	-49	3141.67	435.00	-0.11	Negative Trend
HSAF2	-67	3461.67	465.00	-0.14	Negative Trend
HSBF2	-67	3461.67	465.00	-0.14	Negative Trend
ISAF2	21	3461.67	465.00	0.05	Positive Trend
ISBF2	21	3461.67	465.00	0.05	Positive Trend
Southeast					
Historical	-11	3141.67	435.00	-0.03	Negative Trend
HSAF2	-161	3461.67	465.00	-0.35	Negative Trend
HSBF2	-161	3461.67	465.00	-0.35	Negative Trend
ISAF2	-77	3461.67	465.00	-0.17	Negative Trend
ISBF2	-77	3461.67	465.00	-0.17	Negative Trend

Table 11. Mann-Kendall Trend Test Results for each scenario by region

above shows the Mann-Kendall trend test results for each of the scenarios that had significant differences between the means of the historical and future scenarios. The first region analyzed was the Midwest region. The historically projected water available for irrigation on average for the selected ASDs trended towards decreased water availability over time for the period of 1981 through 2010 as evidenced by the score of -9 and the tau of -0.02. HSAF2 scenario values trended towards decreased water availability over time for the near far future period from 2040-2070 shown by the score of -129 and the tau of -0.28. The HSBF2 scenario also trended negative with the same score and tau as the HSAF2 scenario. Both the ISAF2 and ISBF2 water availability scenarios trended towards decreased availability from 2040-2070 as evidenced by the score of -11 and the tau of -0.20. There was an overall decreasing trend when comparing later measured projected water available for irrigation use values to the earlier measured values in the Midwest scenarios.

The next region analyzed was the Pacific West region. Historically, the ASDs in this region trended towards decreased water available for irrigation use over time on average. This trend is shown by the score of -49 and the tau of -0.11. In the HSAF2 and HSBF2 scenarios, the values trended towards decreased water availability over time for the period of 2040-2070 as evidenced by the score of -67 and the tau of -0.14. There was a decreasing or negative trend when comparing the later measured values to the earlier measured values in the HSAF2 and HSBF2 scenarios.

The ISAF2 scenario showed increasing water availability from 2040-2070 on average for the ASDs in the Pacific West. This is shown by the score of 21 and the tau of 0.05. The ISBF2 scenario also showed a positive trend for this same time period. Its score of 21 and tau of 0.05 demonstrated this. For both of these scenarios there was a small positive trend in the data.

The final region analyzed through the Mann-Kendall test was the Southeast region. Historically, the region trended towards decreased projected water available for irrigation use from 1981-2010 seen by the score of -11 and tau of -0.03. The HSAF2 scenario had a negative trend in water availability from 2040-2070 with a score of -161 and tau of -0.35. availability over time for the period of 2040 through 2070 as evidenced by the score of -161 and the tau of -0.35. Projected water availability in the HSBF2 scenario trended negative for this same time period. The score and tau for this scenario were -161 and -0.35. The ISAF2 and ISBF2 scenarios both trended towards decreased water availability from 2040-2070. Both IS scenarios had a score of -77 and tau of -0.17.

All four scenarios analyzed for the Midwest region had downward trends in water availability. This means that in the far future period being analyzed across both population and warming scenarios, the projected water available for irrigation use was declining on average for the ASDs in this region at the annual time step. The high warming, higher population scenario (HSAF2) showed the largest decrease in water availability followed by the high warming, normal population scenario (HSBF2). The intermediate warming scenarios with both a high population growth scenario (ISAF2) and normal population growth scenario (ISBF2) both showed a negative trend as well albeit not as large the projected drop in the higher warming scenarios.

In the Pacific West, a negative trend was seen in both high warming scenarios (HSAF2 & HSBF2). The moderate warming scenarios; however, showed a small positive trend in projected water availability. The ISAF2 and ISBF2 scenarios were the only scenarios analyzed that showed increased water availability over time. The score and tau values were small so the trend towards increased water availability is not strong, but it does exist. This implies that in the selected ASDs in the Pacific West, from 2040-2070, there may be more water available annually with a moderate warming climate scenario. This does not necessarily correlate to more water being available for irrigation use for the specific fruit and vegetable crops during the growing season and does not account for possible flood risks from increased precipitation. It could imply anything ranging all the way from more water available during the growing season, increased flooding, to an earlier snow melt.

All four future scenarios trended towards decreased water availability in the Southeast region. This applied to the moderate warming scenarios with a high population growth rate and a normal population growth rate (ISAF2 & ISBF2) as well as the two high warming scenarios with both population scenarios (HSAF2 & HSBF2). The largest drop in projected water availability was seen in the HSBF2 scenario followed by the HSAF2 scenario. The lowest change was seen in the ISAF2 scenario followed by the ISBF2 scenario. These results imply that less water may be available annually when higher warming occurs in the selected ASDs in the Southeast region.

Water resources are being affected in an unequal manner depending on which region of the country is being modeled as well as the amount of warming occurring. This finding is further corroborated in the water stress results. Next, the results of the surface water supply stress index induced by irrigation demand are presented for each region.

3.2. Irrigation surface water supply stress results

3.2.1. Midwest

The results show that for the Midwestern ASDs, the average watershed WaSSI for the historical scenario was about 0.008 which indicates no stress. For the future scenarios, the average watershed WaSSI was about 0.01 which also indicates no stress. The lowest percent change was seen in the HSAF1 scenario at 14.07%. The next lowest was the ISAF1 scenario at 19.6%. The two highest percent changes are seen in the HSAF2 scenario and ISAF2 scenario at

43.4% and 36.19% respectively. (see Appendix F for visual percent change maps for each scenario)

The four future scenarios all showed a projected average increase in water supply stress at the watershed scale. The two far future scenarios had a higher increase than the near future scenarios. The intermediate stress near future scenario (ISAF1) had a higher percent increase than the high stress near future scenario for the Midwest while the intermediate stress far future scenario (ISAF2) had a lower percent increase than the high stress future scenario (HSAF2). Tavernia et al. (2013) showed that Northeast and Midwestern regions would show increased stress between 2010-2060 which backs up the finding of increased stress from these scenarios.

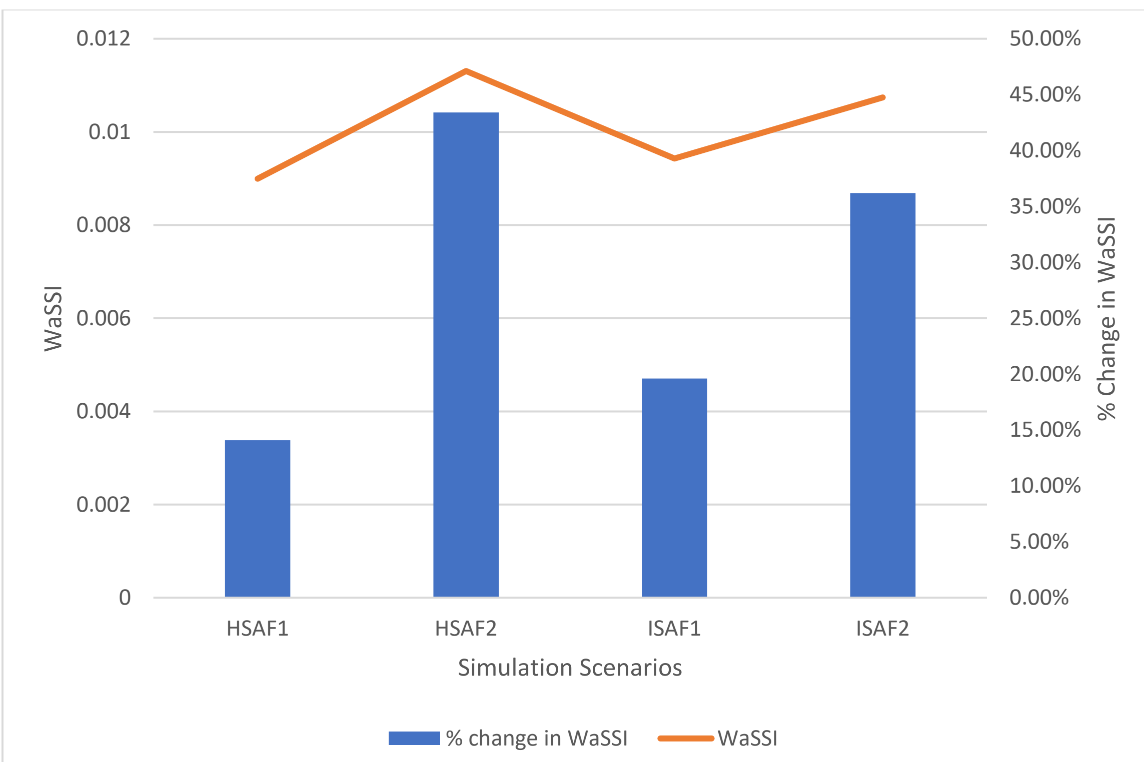

Figure 14. Impacts from climate scenarios on water supply stress in the Midwest region with percent change in WaSSI and average WaSSI

3.2.2. Northeast

Contrary to other regions, the Northeast showed no water stress historically. On average the WaSSI was 0.001. Projecting forward to the future scenarios the water stress did not vary significantly and stated at approximately 0.001. The percent change for the HSAF1 scenario was 1.49% followed by a change of 3.92% for the ISAF1 scenario. The change for the HSAF2 and ISAF2 scenarios was 6.82% and 3.68%. On average all the future scenarios had increased water supply stress at the watershed scale. The highest change was seen in the high stress far future scenario (HSAF2) and the intermediate stress near future scenario (ISAF1). The lowest percent change in stress was seen in the high stress near future scenario (HSAF1).

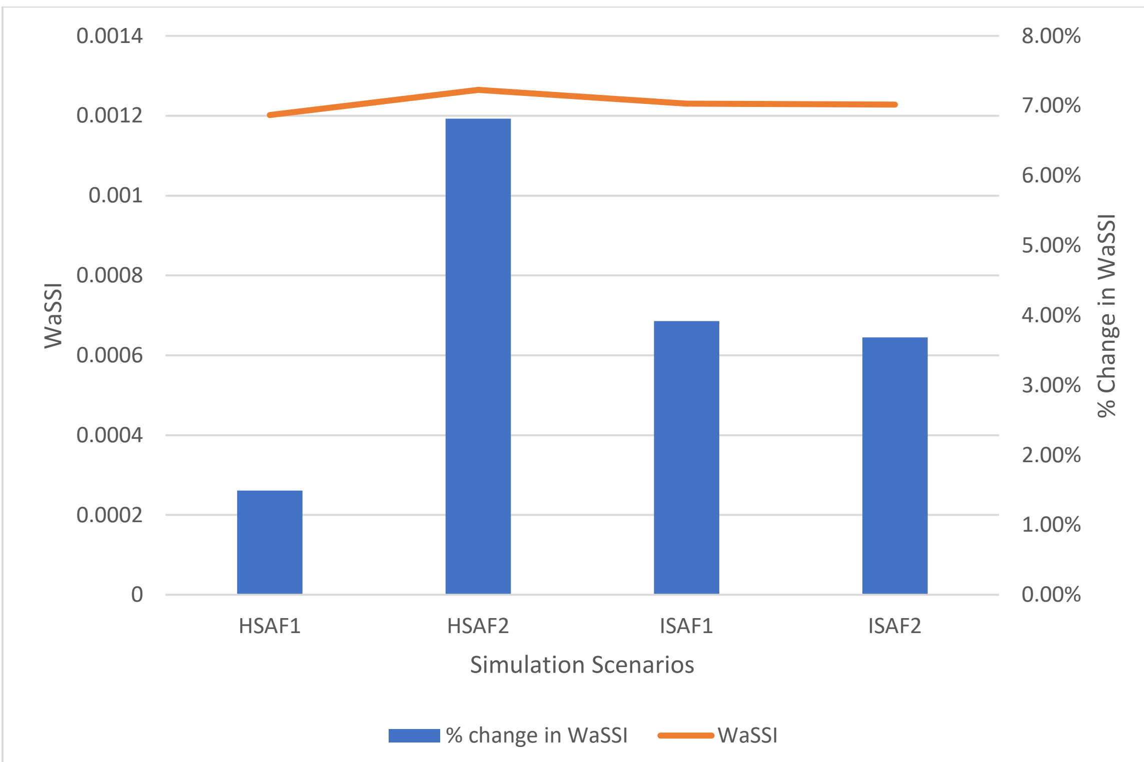

Figure 15. Impacts from climate scenarios on water supply stress in the Northeast region with percent change in WaSSI and average WaSSI

3.2.3. Pacific West

In the historically stressed region of the Pacifc West, the average watershed WaSSI for the historical scenario was about 5.31. This aligns with what is known about this region in that many watersheds experience very high water stress. For the future scenarios, the average watershed WaSSI was about 5.21 which also indicates very high stress. The percent change for the HSAF1 scenario was -7.5%. For the ISAF1 scenario the change was -4.87%. The change was 10.58% and -5.65% for the HSAF2 and ISAF2 scenarios. This region showed some markedly different results from the Northeast and Midwest regions in that the average water supply stress decreased for three of the four scenarios. The reduction in surface water supply stress does coincide with the projected increase in total surface water supplies in this region. A reduction in water supply stress across the selected ASDs does not mean that water stress is improving across the entire region or during specific growing seasons. It means that with the data analyzed the water stress reduced on average across watersheds in the specific ASDs. It is important not to use this finding to state watershed water supplies improving in a historically stressed region. The high average annual water supply stress values (WaSSI > 1.0) for this region indicate that that this region must be dependent on transferred, groundwater, or stored water to meet local demands since a WaSSI value greater than 1.0 means the local water demand is exceeding the local surface water supply. Duan et al. (2017) demonstrated that runoff would increase across the Pacific coast and Southwest and that this increase would be driven by precipitation. An average annual precipitation increase coincides with an average annual reduction in water stress.

Figure 16. Impacts from climate scenarios on water supply stress in the Pacific West region with percent change in WaSSI and average WaSSI

3.2.4. Plains

High water stress was noted for the Plains region. Historically, the average watershed WaSSI was 0.65. The average watershed WaSSI for the future scenarios was about 0.76 which also indicates high water stress. This region contains many croplands and farms that rely on irrigation which could be an explanation for the high water stress. The percent change for the HSAF1 scenario was -3.19%. The change in the HSAF2 scenario was 35.77%. The change was -5.63% for the ISAF1 scenario. The percent change was 41.15% for the ISAF2 scenario. On average the water supply stress increased by 35.77% for the high stress far future scenario

(HSAF2) and 41.15% for the intermediate stress far future scenario (ISAF2). For both near future scenarios, the average water supply stress is decreasing. The average water supply stress is above the criteria for being considered high in all scenarios regardless of any decrease in supply stress. These findings are supported by Duan et al. (2017) drawing from the same GCMs. His study found that there will be severe runoff depletions in parts of the central U.S. due to temperature increases. This contributes to the understanding of why there is high water stress in the Plains region on average.

Figure 17. Impacts from climate scenarios on water supply stress in the Plains region with percent change in WaSSI and average WaSSI

3.2.5. Southeast

Historically, the Southeast ASDs showed an average watershed WaSSI of 0.06 which indicates unstressed watersheds. The projected average across future scenarios increased to 0.12 which means the watersheds experienced moderate water stress. This aligns with the the findings by Sun et al. (2008) in which they studies the impacts of climate change on watersheds in the Southeast. The percent change for the HSAF1 and ISAF1 scenarios was 76.59% and 36.40%. For the HSAF2 and ISAF2 scenarios the percent change was 140.82% and 79.14%. The ASDs in this region experienced the highest percent change in water supply stress out of all of the regions. In all four future scenarios there was a percent increase in water supply stress. The largest percent increases occurred in the two far future scenarios. The Southeast will experience great variability in precipitation under climate change scenarios and significant increases in air temperature. The high increases in air temperature coincide with the increased average water stress.

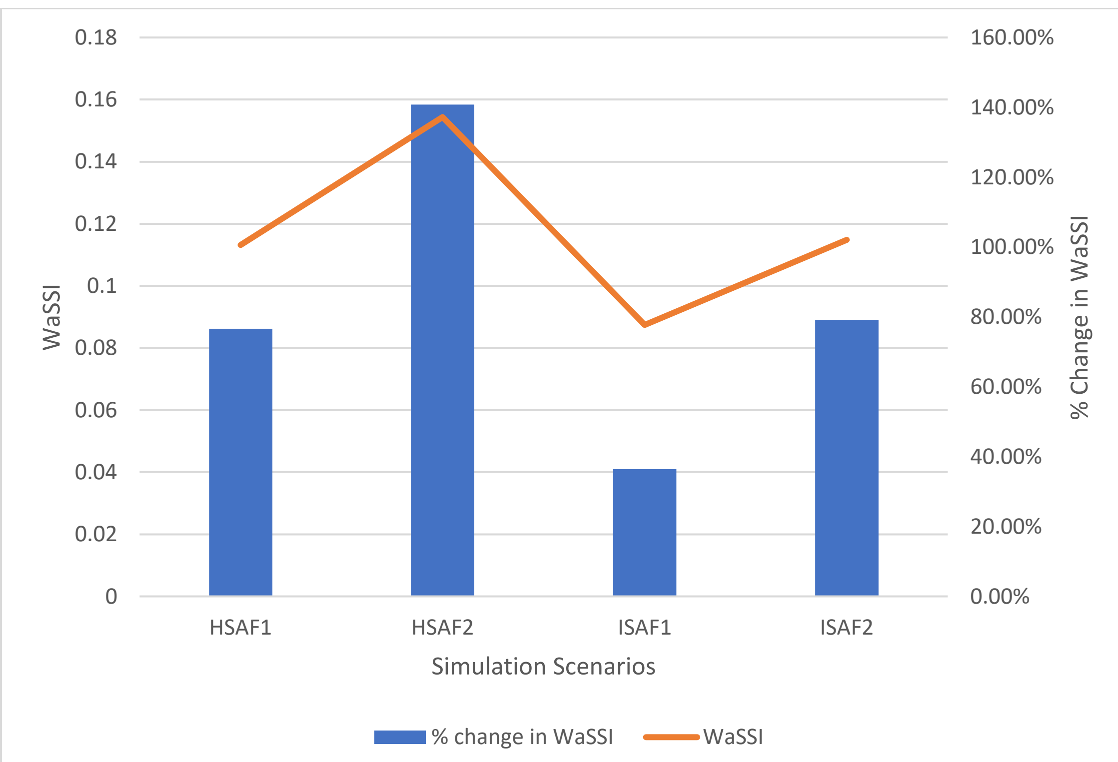

Figure 18. Impacts from climate scenarios on water supply stress in the Southeast region with percent change in WaSSI and average WaSSI

3.3. Model calibration and validation

While most hydroclimatological models require calibration, the WaSSI model does not require calibration and has been well-validated (Schwalm et al.,2014; Caldwell et al.,2015; Bagsta et al.,2018; Caldwell et al.,2012; Duan et al.,2017). The runoff output from the WaSSI model has been verifiably validated which directly relates to this project as runoff is a primary driver in water availability. Since the runoff output is used as a direct input to the model developed for this project it is reasonable to state that no further validation of this data is needed. WaSSI does not project water available for irrigation use. This projection is novel to this project it was built from validated data. To add more confidence to the projected surface water available for irrigation use data there are several recommendations. More research should be done to examine water demands from the eight fruit and vegetable crops in the modeled areas, assess the amount of water that has historically been used for these crops, quantify current irrigation use in these areas, find studies on how water use is predicted to change in these areas, and understand the trends in water use efficiency in the irrigation sector as related to these crops.

Chapter 4- Conclusions and recommendations

Global climate change has an impact on fruit and vegetable agriculture through the changing trends in temperature and precipitation. Temperature and precipitation patterns are key variables in fruit and vegetable production; therefore, the impact from climate change in specific agricultural regions needs to be addressed. The focus of this study was to understand the overall impact from a changing climate on surface water available for irrigation use in five regions containing 31 ASDs and the water supply stress from irrigation demand in HUC8s in these ASDs. The objectives for this study were to assess surface water available for irrigation use in the five regions at historical conditions, the near future period from 2021 to 2050, and the far future period from 2040 to 2070, and to determine water supply stress in the five regions at these same historical, near future, and far future conditions. No studies have investigated predicted competing demands at the watershed scale within the ASDs or ARS regions. It was important to research this topic to better understand the effects of climate change at different scales and how it can assist with decision making in these areas.

The approach to providing answers to the questions posed in the hypotheses involved using a modified version of an annual ecohydrological model (the Water Supply Stress Index model, WaSSI) utilizing historical climate data and future climate change scenarios derived from five Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models. Water supply data at the HUC8 scale was generated from WaSSI and upscaled to a newly created ASD Watershed Border. This ASD Watershed Border was defined by watershed boundaries within an ASD, and through flow routing information between watersheds, the available water could be scaled to this boundary to give an overall value for the ASD. The WaSSI model was also used to calculate surface water supply stress values induced by irrigation demand for watersheds in each of the ASDs at the average annual time scale. Each ASD was grouped into an ARS region to give values for five different regions across the U.S. Once model values were generated, upscaled to the 31 ASDs, and grouped to the five regions, the Analysis of Variance (ANOVA) and Mann-Kendall trend tests were run on the results to determine which direction the surface water available for irrigation use for future scenarios trended towards compared to historical conditions. The average watershed WaSSI value was compared between the historical scenario and different future climate scenarios to assess the change in surface water supply stress.

The near future scenarios did not show a significance level using the P value of 0.05 for the analysis of projected surface water available for irrigation use; therefore, the null hypothesis of not showing a decreasing trend cannot be rejected for $H(0)_1$. Projected surface water available for irrigation use trends towards an increase over time for the ISAF2 and ISBF2 scenarios for the Pacific West region. The HSAF2 and HSBF2 scenarios trend towards a decreased amount of surface water available for irrigation use over time. Since there is an increasing trend in two of the scenarios, the null hypothesis of no decreasing trend is rejected for $H(0)_2$.

The surface water supply stress decreased in the Pacific West and Plains regions for the near future scenarios; however, the surface water supply stress increased for the Southeast, Midwest, and Northeast. Therefore, the null hypothesis of no increase in water supply stress is rejected for $H(0)_3$. The increase in water supply stress for the Southeast may be related to a decrease in runoff in this region. Surface water supply stress increased on average in the Plains and Southeast regions for both far future scenarios, and in the Pacific West for the HSAF2 scenario. This result is consistent with increased ET due to the higher warming far future climate scenario. However, the stress index decreased in the Pacific West for the ISAF2 scenario. Water supply stress increased on average for both far future scenarios in the Northeast and Midwest regions. The null hypothesis is still rejected for $H(0)_4$ because there were increases in water supply stress in these regions for the far future scenarios.

A changing climate has the potential to differentially impact the country's surface water supply depending on the region. It is clear that water availability for irrigation use decreased at an annual scale in the far future in the Midwest, and Southeast for all combinations of population and warming scenarios. For the Pacific West, the availability decreased for both higher warming scenarios. This change occurred regardless of population change. The availability is increasing over time for the moderate warming scenarios at the annual scale for the selected ASDs. This result must strictly be interpreted to mean that on average, in the selected ASDs in the Pacific West, there was more surface water available annually.

Further research is needed to better the understanding of modeling water availability at the ASD scale. This is a new way of modeling water availability and therefore, the model needs to be adjusted to further quantify the results. The WaSSI model was validated to demonstrate its effectiveness when it was first developed and has been subsequentially validated in other studies as seen in the literature review of this paper. Any further validation of the results of this research would be pseudo-validation since the data to validate against is input data to the model. If more confidence in the validation is needed, more stream gages are required to cover more watersheds across the U.S. More historical streamflow data itself is needed in order to model across different decades to see how the validation numbers change. Additionally, more HUC8 specific information is needed to include IBT over time with the respective volumes of water both leaving and entering the HUC8 geographical area. Included in this HUC8 information should be the number of dams in a watershed and upstream of a watershed being modeled. More recent water use data should be incorporated into the WaSSI Model itself. Another recommendation for future studies would be to look at any ASDs with poor validation results and determine if there is a correlation with these results and the number of dams, interbasin transfers, upstream watershed alterations, and a significant change in water use over time. This would allow for better explanations of the results and create a better understanding of what is driving the water availability in these areas. More research needs to be done to understand the water sources for the eight crops in their principal production regions. The results of this study could be better utilized if the crops that rely more on surface water for irrigation in the selected ASDs can be identified as well as the watersheds that contribute the most to the major growing operations of these crops. To better the model as a whole, more GCMs should be used in the RCP 4.5 and 8.5 scenarios to expand upon the five GCMs that were used. A look into flood risks for specific

ASDs from specific WaSSI data would also be helpful for assessing the risks to fruit and vegetable infrastructure systems.

The results of this assessment suggest very specific areas, may experience a significant decrease in average annual water supply stress when compared to historical conditions, while other areas may have an increase in average annual water supply stress depending on the scenario. The average annual surface water supply stress increased for all future scenarios in the Midwest, Northeast, and Southeast regions. The water supply stress increased for both far future scenarios and decreased for the near future scenarios in the Plains. Three of the four future scenarios showed a decrease in stress in the Pacific West. More research is needed to understand what this decrease in stress translates to. It is an oversimplification to state that water supply stress is projected to decrease with climate change in the Pacific West. These results show that across watersheds in the Pacific West ASDs used in this study, on average, surface water supply stress induced by irrigation demand may decrease in the near future annually. The stress is still extremely high though when going by the metrics used in this study. Climate change affects water supply stress differently depending on the region, and modeled time period at the average annual basis.

Surface water supply stress is prominent in the Pacific West region of the U.S. where natural surface water supplies are not abundant enough to meet the local demand in many watersheds. In the areas where WaSSI > 1.0 under the current and projected supply and demand scenarios, the supplies are met by infrastructure such as reservoirs, groundwater systems, and water transfer systems. The ASDs in southern California are examples of where irrigation demands are not being met by local supply. This region depends on water from the Colorado River and northern California. Although water demands are being met, the analysis adds to one done by Averyt et al. (2013) in showing that the region is at risk if supplies from northern California and the Colorado were to diminish.

Another important consideration in this analysis is that the volume of groundwater is not considered. ASD 4897 in southern Texas and ASD 480 in Arizona are very reliant on groundwater supplies which could account for the high WaSSI values seen in these areas. Additionally, more research is needed on EWR in order to incorporate it into a study like this. EWR was left out of the water supply stress modeling to resemble past studies using the WaSSI model and given the uncertainty of EWR estimates across different geographical regions of the U.S., it was not included.

It is clear that further research needs to be done to identify more areas at risk and more information is needed to increase confidence in this type of new modeling methodology. This study was performed using an annual timestep. In many regions of the country there may be more water available at an annual scale due to more extreme precipitation events (i.e. flooding). This does not necessarily mean that there will be more water available for irrigation use in these ASDs. Without proper flood mitigation measures, and water storage systems, this volume of water may not be useable in the months that the fruit and vegetable crops need it most. Further research needs to be done to see how the water availability and water supply stress varies in the production months associated with the crops grown in these various ASDs and regions. Another consideration to note is that interbasin transfers were not incorporated into this study which has an impact on local water supply stress and overall water availability. Even though recent studies have been done incorporating IBT with the WaSSI Model, (Duan et al., 2019; Emanuel et al., 2015) I thought it was best not to use previously quantified IBT numbers for this study. The reason for this is because the original studies done on quantifying IBT volumes were done in the

1970s and at the HUC4 scale. Evenly distributing large water volumes from the larger geographical HUC4 to the HUC8 scale is poses the problem of having quantity inaccuracies since the water could be assigned to multiple HUC8s that have no water being transferred to or from them when spatially downscaling. Additionally, water supply can only be partially quantified in the future due to it largely being influenced by policies and laws of the water right system, and regulations of storage systems. (Duan, Sun, Caldwell, McNulty, & Zhang, 2018) Such complexities pose problems to the modeling approach employed here as they cannot be accurately represented.

In terms of modeling at the ASD scale, the watersheds were used as the system boundaries in order to take away unnecessary error. In a similar project an area weighting method was applied to the water from runoff in order to justify water availability within the ASD boundaries. ASDs have econometric data and agronomic commonality between them, but for hydrologic modeling at a watershed scale it is not justifiable to confide the water availability to these boundaries. These boundaries are compatible with econometric modeling, so the HUC8 unit of analysis was used for the USDA delineated ASD regions. There are still issues associated with modeling water availability in ASDs at the HUC8 scale due to there being shared watersheds between bordering ASDs. Due to this, the water available in one ASD will be partially dependent on the water available and being used by a bordering ASD. This is a dilemma encountered when modeling using artificially derived boundaries that do not follow the hydrological and geological characteristics that define a watershed.

An important conclusion is that there is a statistically significant change in surface water available for irrigation for specific regions in the United States when the ASDs are grouped into their respective regions. This is seen in the Midwest, Pacific West, and Southeast Regions.

Another important finding is that a warming climate is not affecting the Midwest, Pacific West, and Southeast regions uniformly. The ISAF2 and ISBF2 scenarios for the Pacific West region showed increased surface water available for irrigation use over time. An increase in water supply in certain areas is not necessarily positive for fruit and vegetable crops due implications that snow could be melting earlier in the year and not be available for use at the right time for irrigation. There is also the potential for higher flood risks to areas in the Pacific West if these warming scenarios prove true which could cause damage to fruit and vegetable production infrastructure.

There is a clear trend towards decreased surface water available for irrigation use projected in the far future scenarios. This is most evident in the Midwest, Pacific West, and Southeast Regions of the United States when looking at the specific ASDs that fall in those regions for this study going by the ANOVA and Mann-Kendall test results. Irrespective of whether the emission scenario is going towards 4.5 W m^{-2} or 8.5 W m^{-2} paired with either population scenario, the trend still shows that in these major agricultural production areas the surface water available for irrigation use from 2040-2070 is projected to be less than it was from 1981-2010. These findings could support the need to improve water use efficiency across all sectors but more importantly, cut down on global GHG emissions to reduce the projected radiative forcing posed by these scenarios to lessen the potential impact on the primary production systems for tomatoes, potatoes, oranges, green beans, carrots, spinach, strawberries, and sweet corn in the U.S.

Acknowledgements

The author would like to thank all providers of data and support for this project: Erika Cohen Mack, Dr. Ge Sun, Dr. Peter Caldwell, and Dr. Kai Duan with the U.S. Forest Service for providing data and technical expertise for the model they developed; the faculty and staff in the Biological and Agricultural Engineering Department for their continued support and advice. Special thanks are especially given to Jacob Hickman, Colby Reavis, and other graduate students both at the University of Arkansas and at other universities across the country for their advice, critiques, positivity, and friendship over the years. I also very much appreciate the support, guidance, and help my committee members Dr. Marty Matlock, Dr. Greg Thoma, Dr. Benjamin Runkle and Dr. Kieu Le gave me. Lastly, I would like to thank my family, friends in St. Louis, friends in Arkansas and elsewhere for their help and continued support which was greatly needed and appreciated.

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Appendix A- Midwest

Anova: Single Factor Midwest
SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	291379.6	9712.655	7047007
HSAF1WaterAvailability	30	266328.5	8877.615	2739431

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1E+07	1	10459358	2.137521	0.149131	4.006873
Within Groups	3E+08	58	4893219			
Total	3E+08	59				

Anova: Single Factor Midwest
SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	291379.6	9712.655	7047007
HSBF1WaterAvailability	30	266421.8	8880.727	2736775

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1E+07	1	10381557	2.122197	0.150571	4.006873
Within Groups	3E+08	58	4891891			
Total	3E+08	59				

Anova: Single Factor Midwest
SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	291379.6	9712.655	7047007
ISAF1WaterAvailability	30	262357.8	8745.26	1973304

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1E+07	1	14037778	3.112482	0.08296	4.006873
Within Groups	3E+08	58	4510156			
Total	3E+08	59				

Anova: Single Factor Midwest
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	291379.6	9712.655	7047007
ISBF1WaterAvailability	30	262443.1	8748.104	1972071

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E+07	1	13955355	3.09463	0.083825	4.006873
Within Groups	3E+08	58	4509539			
Total	3E+08	59				

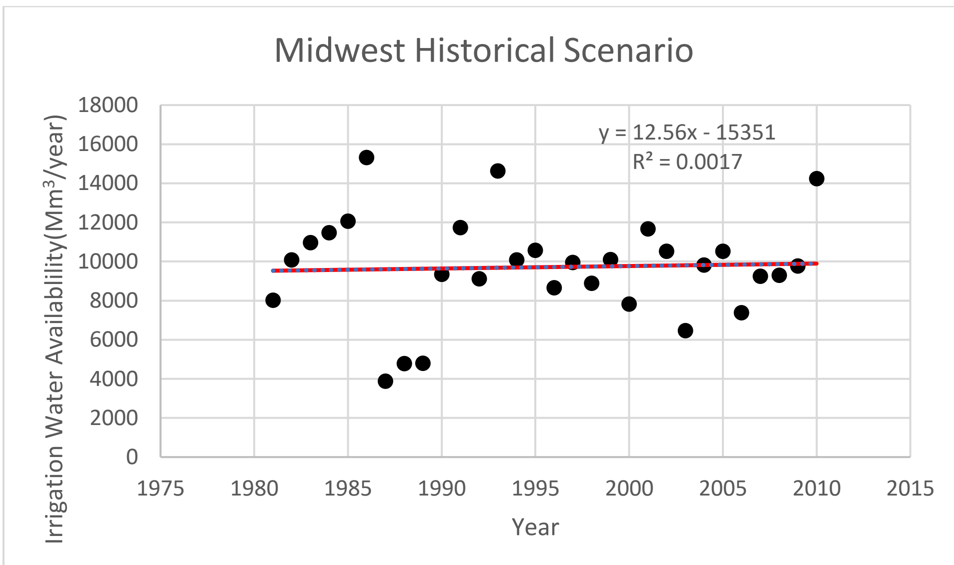

Figure A1. Mann-Kendall Trend Test results for Historical scenario in Midwest region with regression line

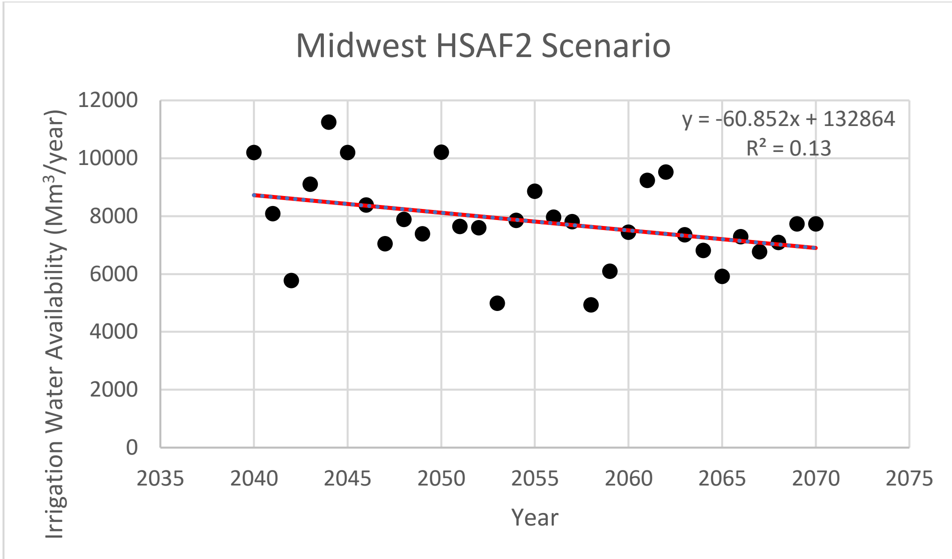

Figure A2. Mann-Kendall Trend Test results for HSAF2 scenario in Midwest region with regression line

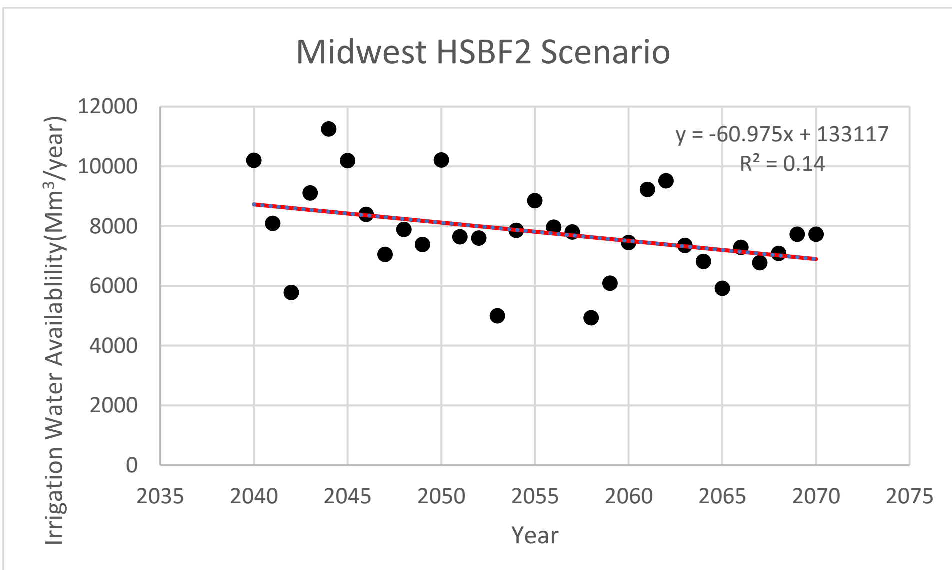

Figure A3. Mann-Kendall Trend Test results for HSBF2 scenario in Midwest region with regression line

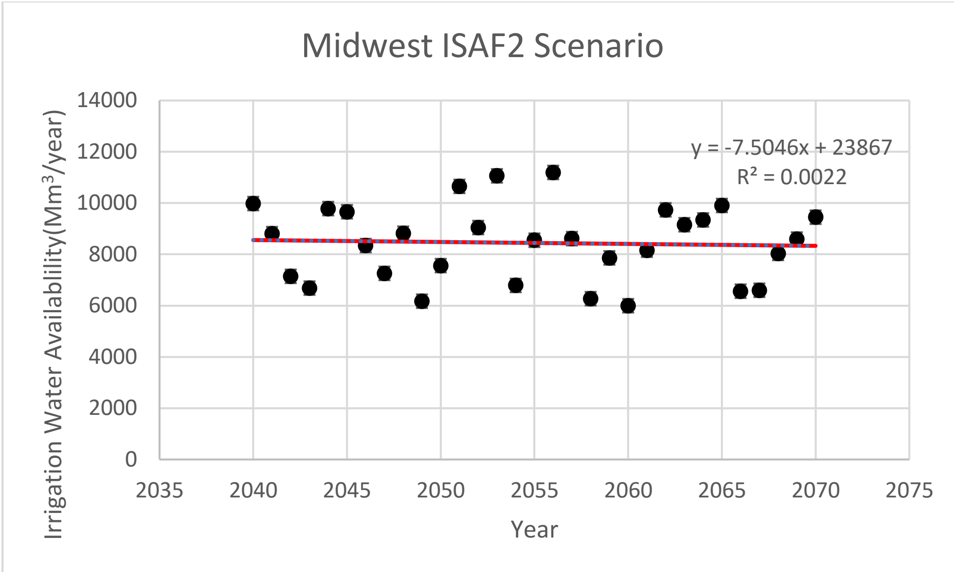

Figure A4. Mann-Kendall Trend Test results for ISAF2 scenario in Midwest region with regression line

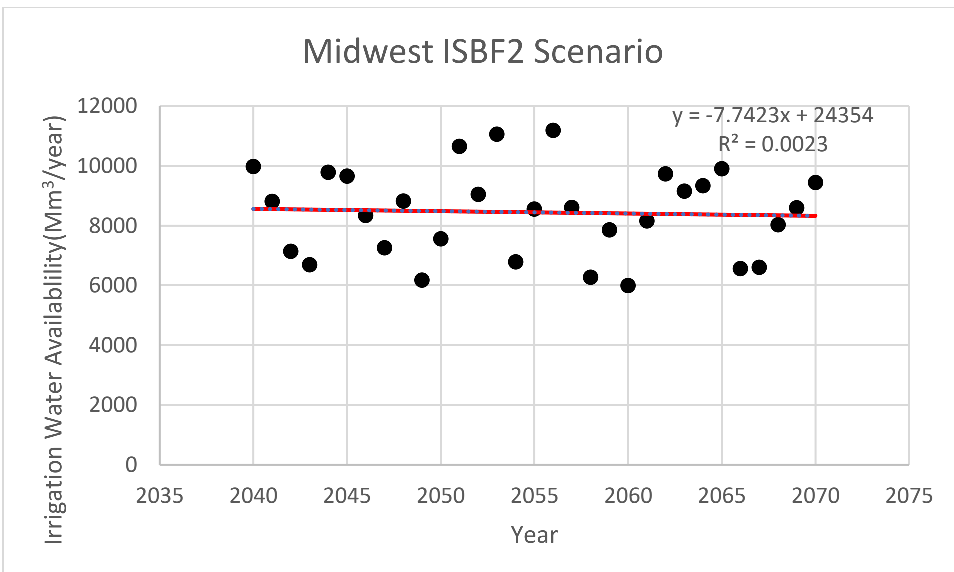

Figure A5. Mann-Kendall Trend Test results for ISBF2 scenario in Midwest region with regression line

Appendix B- Pacific West

Anova: Single Factor Pacific West
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	1974575	65819	3E+8
HSAF1WaterAvailability	30	2128994	70967	6E+7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E+8	1	4E+8	2.2	0.14	4.01
Within Groups	1E+10	58	1.8E+8			
Total	1E+10	59				

Anova: Single Factor Pacific West
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	1.98E+6	65819	3E+8
HSBF1WaterAvailability	30	2.13E+6	71106	587E+7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4E+8	1	4.19E+8	2.32	0.13	4.007
Within Groups	1E+10	58	1.81E+08			
Total	1E+10	59				

Anova: Single Factor Pacific West
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	1974575	65819	3.03E+8
ISAF1WaterAvailability	30	2092066	69736	3.64E+8

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E+8	1	2.3E+8	1.35	0.25	4.01
Within Groups	1E+10	58	1.7E+8			
Total	1E+10	59				

Anova: Single Factor Pacific West

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	1.97E+6	65819	3.03E+8
ISBF1WaterAvailability	30	2.1E+6	69876	364E+7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E+8	1	2.47E+8	1.45	0.23	4.007
Within Groups	1E+10	58	1.7E+8			
Total	1E+10	59				

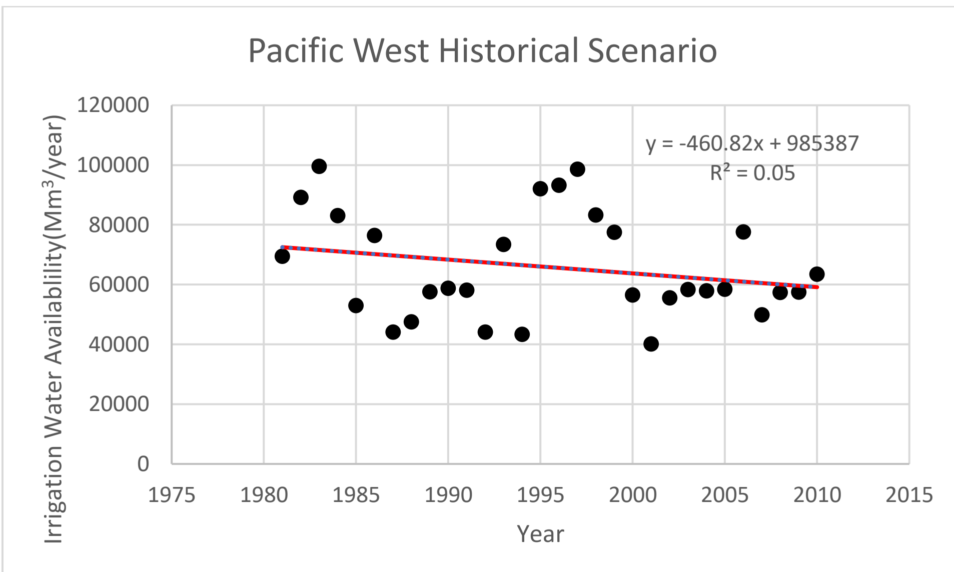

Figure B1. Mann-Kendall Trend Test results for Historical scenario in Pacific West region with regression line

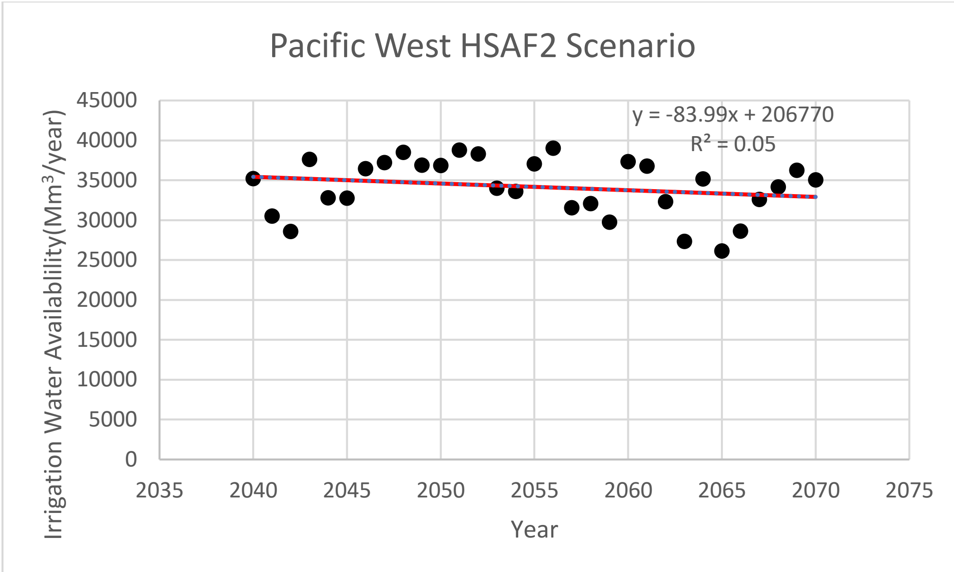

Figure B2. Mann-Kendall Trend Test results for HSAF2 scenario in Pacific West region with regression line

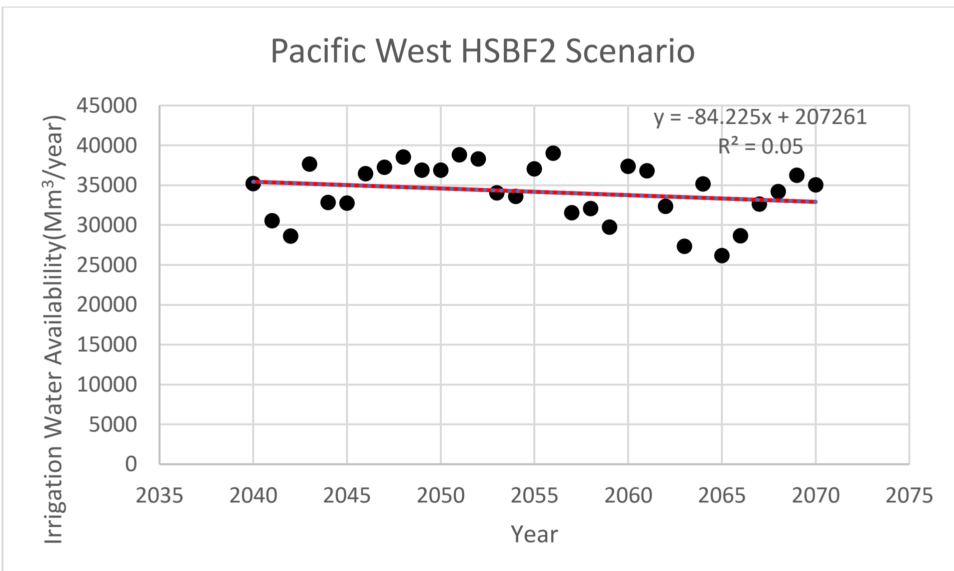

Figure B3. Mann-Kendall Trend Test results for HSBF2 scenario in Pacific West region with regression line

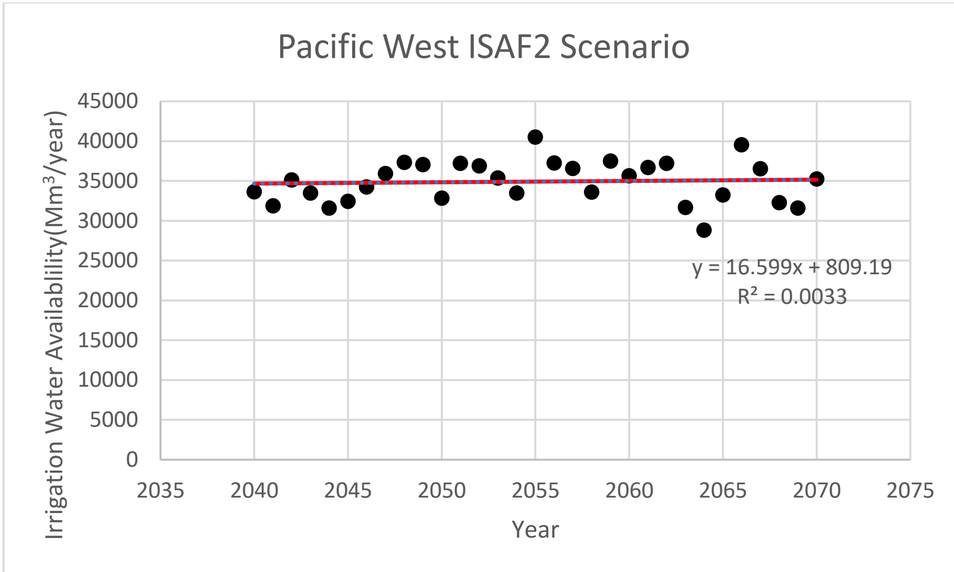

Figure B4. Mann-Kendall Trend Test results for ISAF2 scenario in Pacific West region with regression line

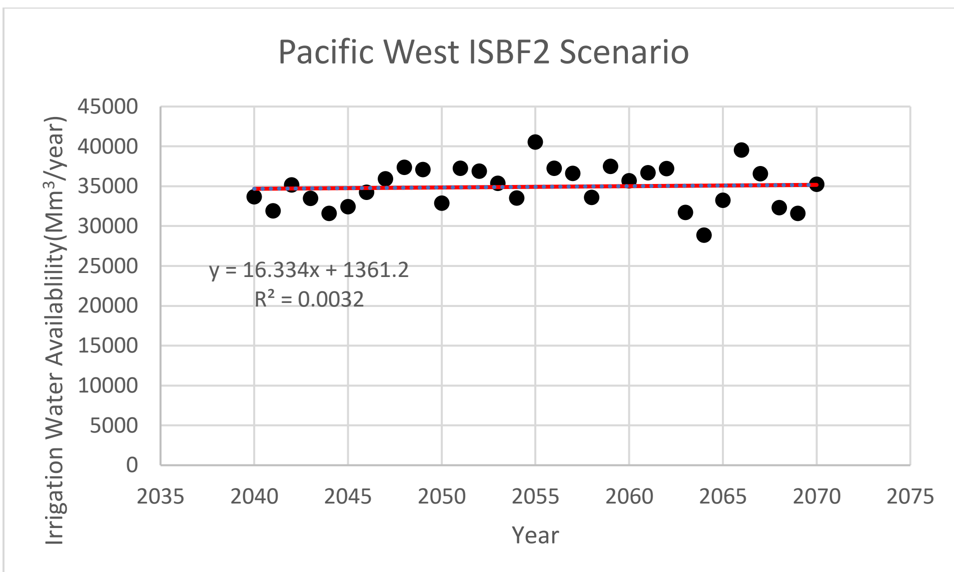

Figure B5. Mann-Kendall Trend Test results for ISBF2 scenario in Pacific West region with regression line

Appendix C- Southeast

Anova: Single Factor Southeast
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	522905	17430	19603113
HSAF1WaterAvailability	30	516445	17215	6123709

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7E+5	1	695402	0.054	0.817	4.007
Within Groups	7E+8	58	12863411			
Total	7E+8	59				

Anova: Single Factor Southeast
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	522905	17430	19603113
HSBF1WaterAvailability	30	514866	17162	6132305

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E+6	1	1076970	0.084	0.773	4.007
Within Groups	7E+8	58	12867709			
Total	7E+8	59				

Anova: Single Factor Southeast
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	522905	17430.15	19603113
ISAF1WaterAvailability	30	511527	17717.57	14545447

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E+6	1	1239112	0.073	0.7886	4.01
Within Groups	1E+9	58	17074280			
Total	1E+9	59				

Anova: Single Factor Southeast
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	522905	17430.15	19603113
ISBF1WaterAvailability	30	529951	17665.03	14566673

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	827480	1	827480.4	0.048	0.827	4.007
Within Groups	1E+9	58	17084893			
Total	1E+9	59				

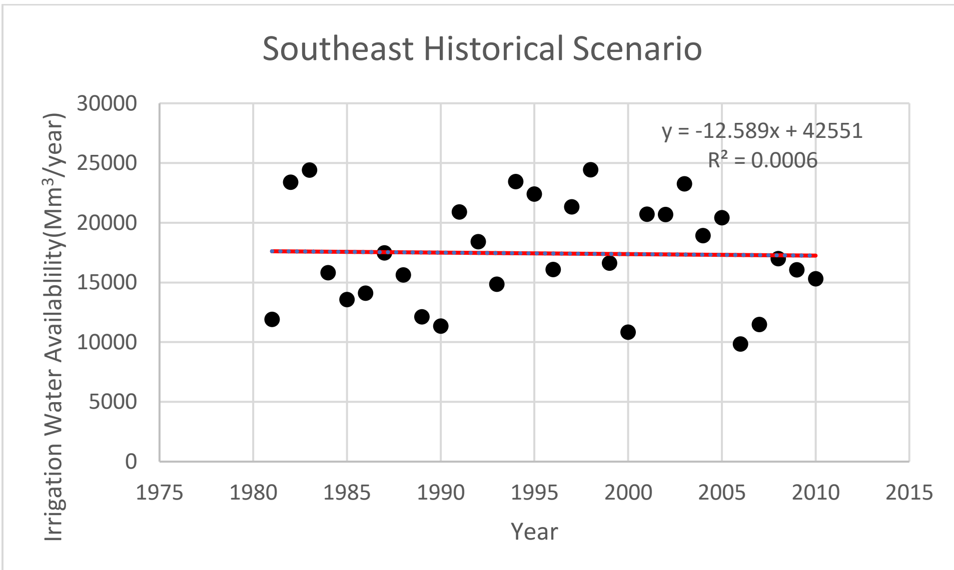

Figure C1. Mann-Kendall Trend Test results for Historical scenario in Southeast region with regression line

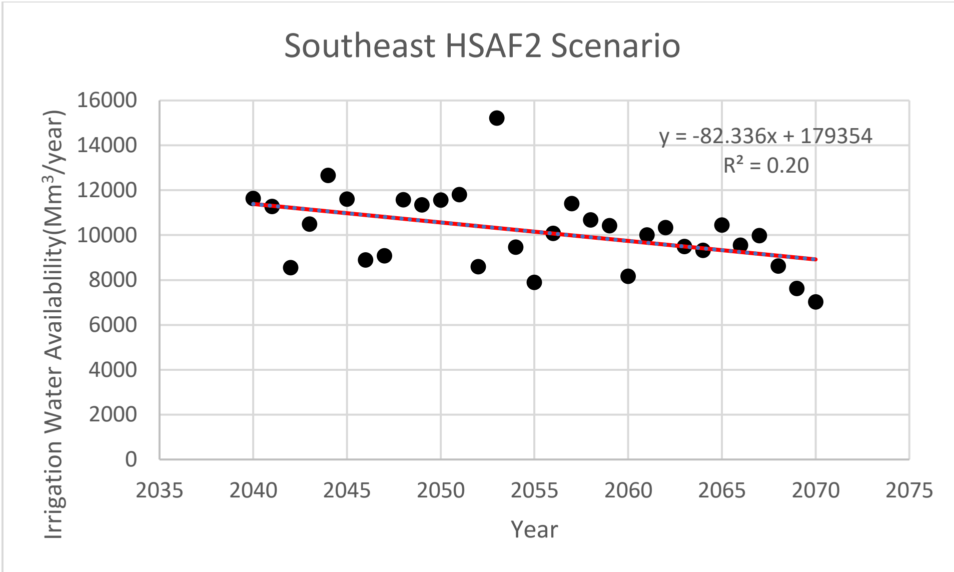

Figure C2. Mann-Kendall Trend Test results for HSAF2 scenario in Southeast region with regression line

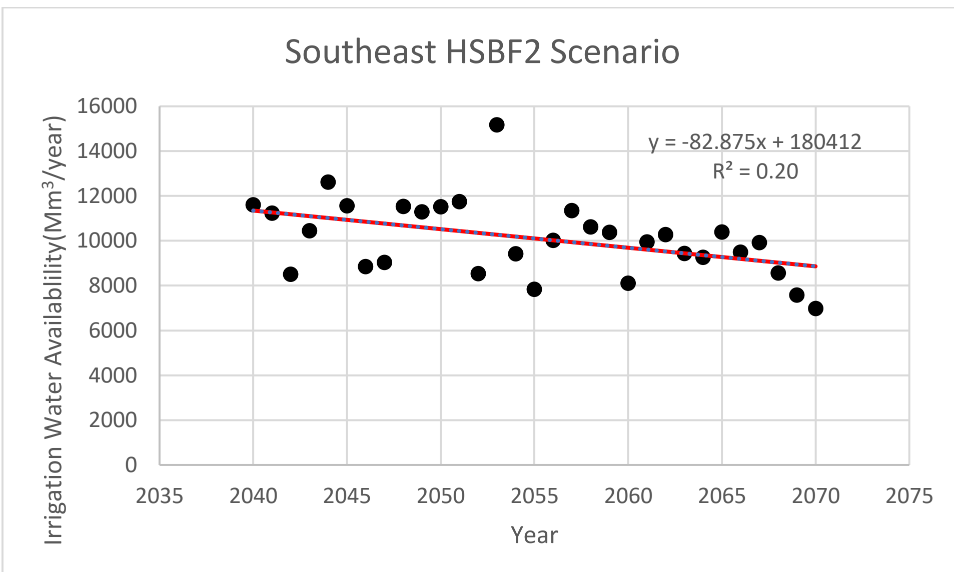

Figure C3. Mann-Kendall Trend Test results for HSBF2 scenario in Southeast region with regression line

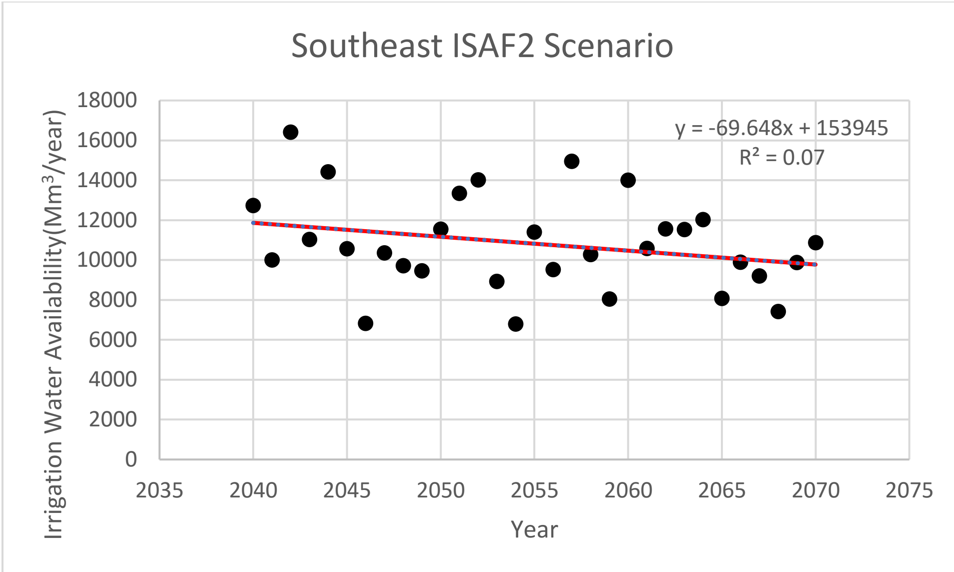

Figure C4. Mann-Kendall Trend Test results for ISAF2 scenario in Southeast region with regression line

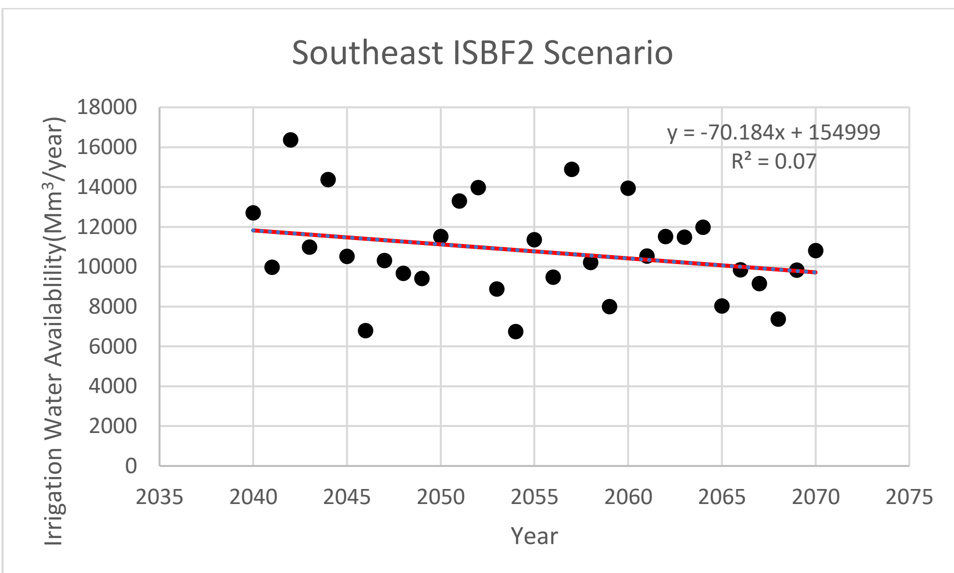

Figure C5. Mann-Kendall Trend Test results for ISBF2 scenario in Southeast region with regression line

Appendix D- Plains

Anova: Single Factor Plains
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214	4107	921431
HSAF1WaterAvailability	30	120547	4018	400849

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	118565	1	118565	0.179	0.674	4.0069
Within Groups	4E+7	58	661140			
Total	4E+7	59				

Anova: Single Factor Plains
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214	4107	921431
HSBF1WaterAvailability	30	120767	4026	399244

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	99804	1	99803.56	0.15114	0.698872	4.006873
Within Groups	4E+7	58	660337.4			
Total	4E+7	59				

Anova: Single Factor Plains
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123414.3	4107.14	921430.6
ISAF1WaterAvailability	30	126066.1	4202.03	402040.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	135548	1	135547.8	0.205	0.652	4.01
Within Groups	4E+7	58	661735.4			
Total	4E+7	59				

Anova: Single Factor Plains
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214.3	4107.142	921430.6
ISBF1WaterAvailability	30	126288	4209.598	402571.3

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	157459	1	157459	0.237853	0.627599	4.006873
Within Groups	4E+07	58	662000.9			
Total	4E+07	59				

Anova: Single Factor Plains
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214.3	4107.142	921430.6
HSAF2WaterAvailability	31	117532.5	3791.372	529803.1

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2E+06	1	1520179	2.104643	0.152149	4.003983
Within Groups	4E+07	59	722297.9			
Total	4E+07	60				

Anova: Single Factor Plains
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214.3	4107.142	921430.6
HSBF2WaterAvailability	31	117756.1	3798.583	528108.7

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E+06	1	1451547	2.012023	0.161318	4.003983
Within Groups	4E+07	59	721436.4			
Total	4E+07	60				

Anova: Single Factor Plains

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214.3	4107.142	921430.6
ISAF2WaterAvailability	31	120466.5	3886.016	274927.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	745476	1	745475.9	1.257763	0.266619	4.003983
Within Groups	3E+07	59	592700			
Total	4E+07	60				

Anova: Single Factor Plains

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	123214.3	4107.142	921430.6
ISBF2WaterAvailability	31	120701.1	3893.584	274697.9

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	695323	1	695322.7	1.173375	0.283116	4.003983
Within Groups	3E+07	59	592583.5			
Total	4E+07	60				

Appendix E- Northeast

Anova: Single Factor Northeast

SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
HSAF1WaterAvailability	30	371651.8	12388.39	822258.8

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3E+06	1	2698408	0.956558	0.332118	4.006873
Within Groups	2E+08	58	2820956			
Total	2E+08	59				

Anova: Single Factor Northeast

SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
HSBF1WaterAvailability	30	371701.3	12390.04	822059.5

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3E+06	1	2719442	0.964048	0.330247	4.006873
Within Groups	2E+08	58	2820856			
Total	2E+08	59				

Anova: Single Factor Northeast

SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
ISAF1WaterAvailability	30	363316.3	12110.54	621459

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	321017	1	321016.7	0.117997	0.73246	4.00687
Within Groups	2E+08	58	2720556			
Total	2E+08	59				

Anova: Single Factor Northeast
SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
ISBF1WaterAvailability	30	363365.8	12112.19	621364.4

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	328291	1	328291.3	0.120673	0.729563	4.006873
Within Groups	2E+08	58	2720508			
Total	2E+08	59				

Anova: Single Factor Northeast
SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
HSAF2WaterAvailability	31	372031.2	12001.01	650459.9

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	20594	1	20594.33	0.007628	0.930697	4.003983
Within Groups	2E+08	59	2699724			
Total	2E+08	60				

Anova: Single Factor Northeast
SUMMARY

Groups	Count	Sum	Average	Variance
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
HSBF2WaterAvailability	31	372103.6	12003.34	650296.5

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	23294	1	23293.58	0.008628	0.926306	4.003983
Within Groups	2E+08	59	2699641			
Total	2E+08	60				

Anova: Single Factor Northeast

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
ISAF2WaterAvailability	31	380535.3	12275.33	475565.5

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E+06	1	1475358	0.565099	0.455201	4.003983
Within Groups	2E+08	59	2610795			
Total	2E+08	60				

Anova: Single Factor Northeast

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HistoricalWaterAvailability	30	358927.6	11964.25	4819652
ISBF2WaterAvailability	31	380607.4	12277.66	475514

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1E+06	1	1497496	0.573584	0.451852	4.003983
Within Groups	2E+08	59	2610768			
Total	2E+08	60				

Appendix F- Irrigation Surface Water Supply Stress Graphics

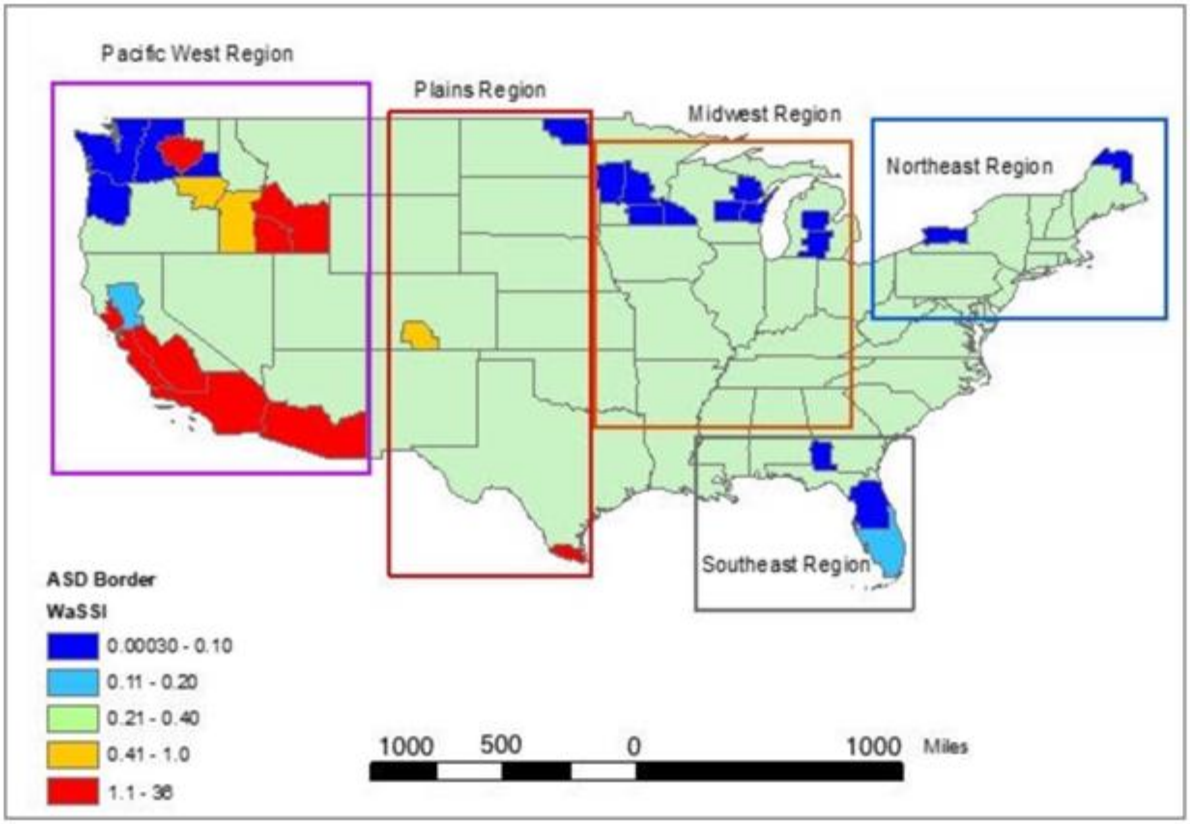

Figure F1. Average Annual WaSSI due to irrigation water use (1981-2010) Historical scenario

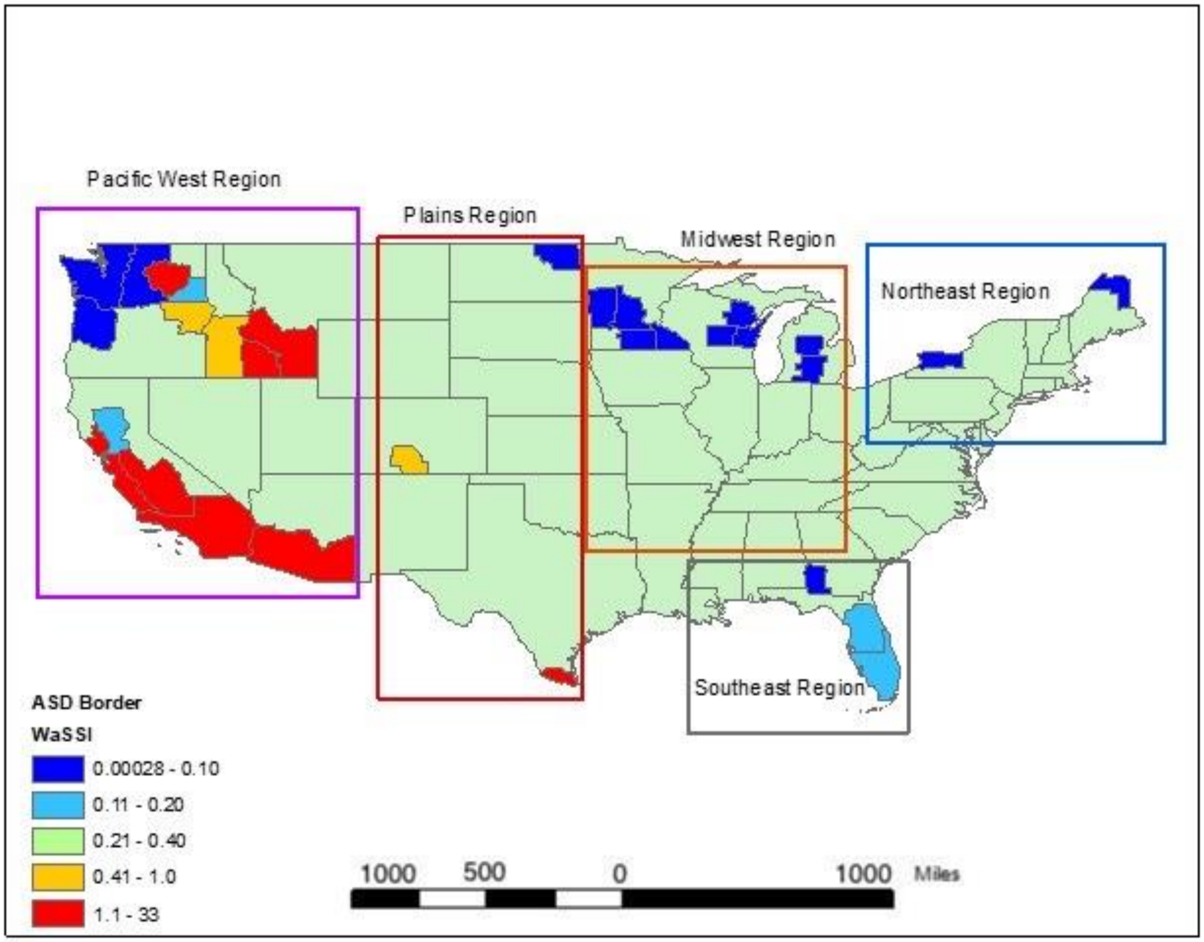

Figure F2. Average Annual WaSSI due to irrigation water use (2021-2050) scenario HSAF1

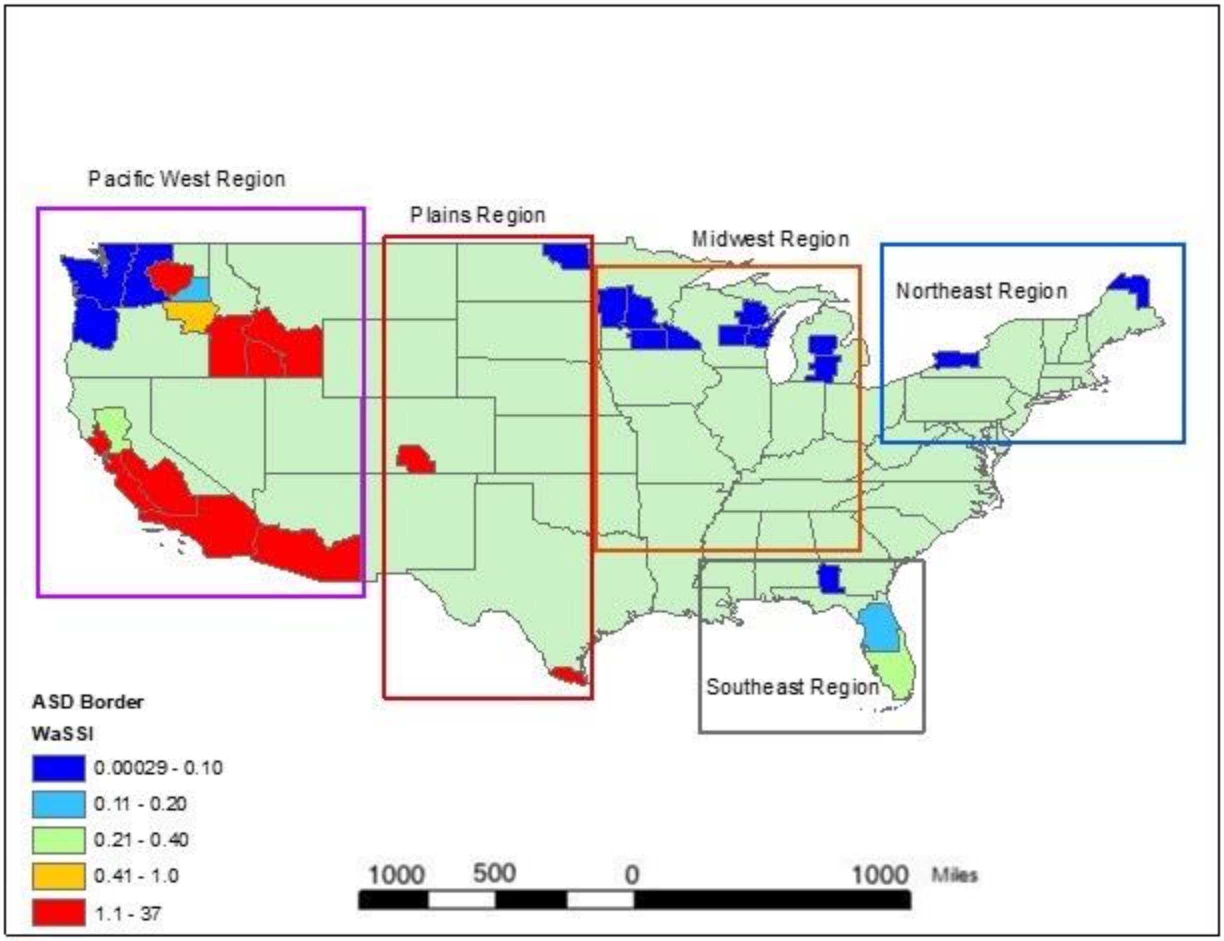

Figure F3. Average Annual WaSSI due to irrigation water use (2040-2070) scenario HSAF2

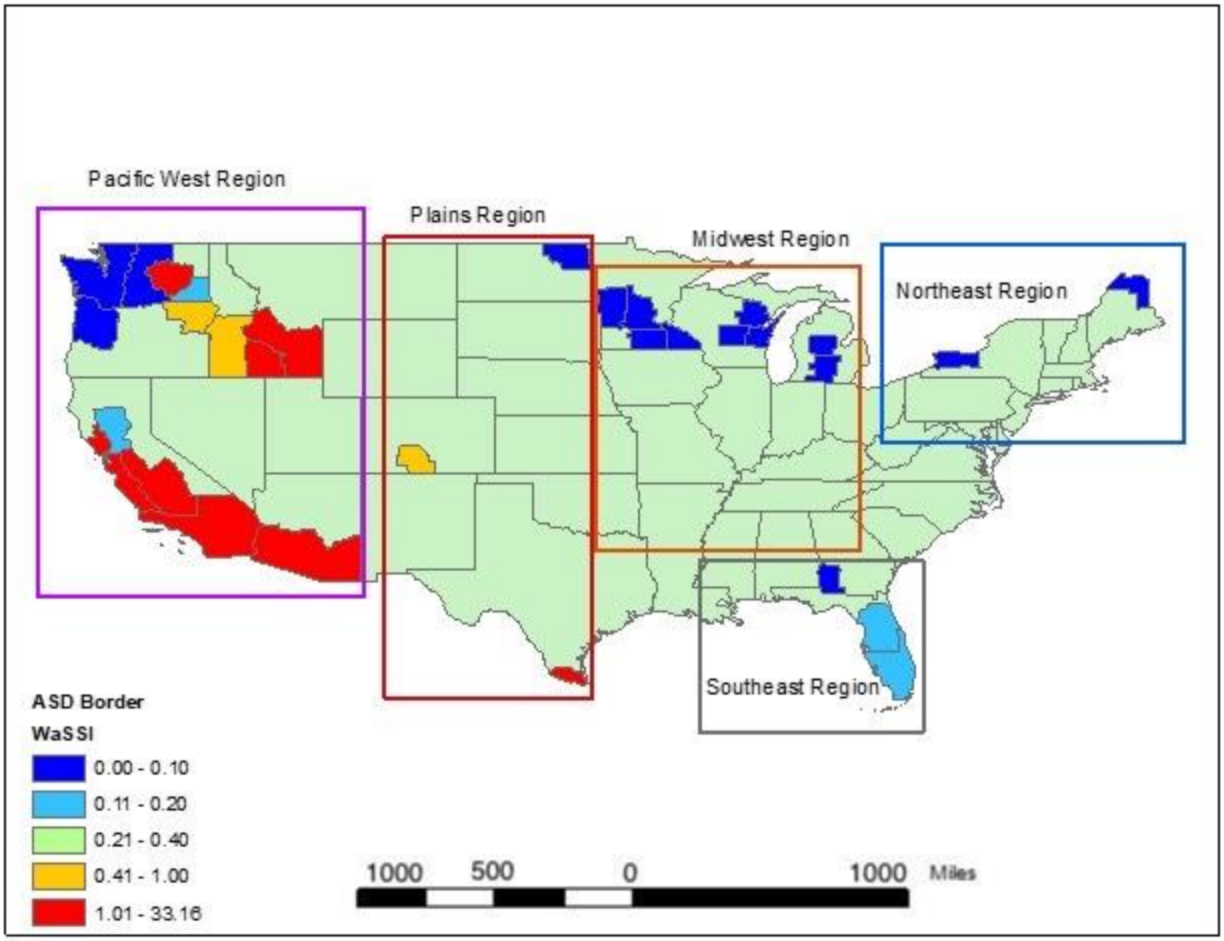

Figure F4. Average Annual WaSSI due to irrigation water use (2021-2050) scenario HSBF1

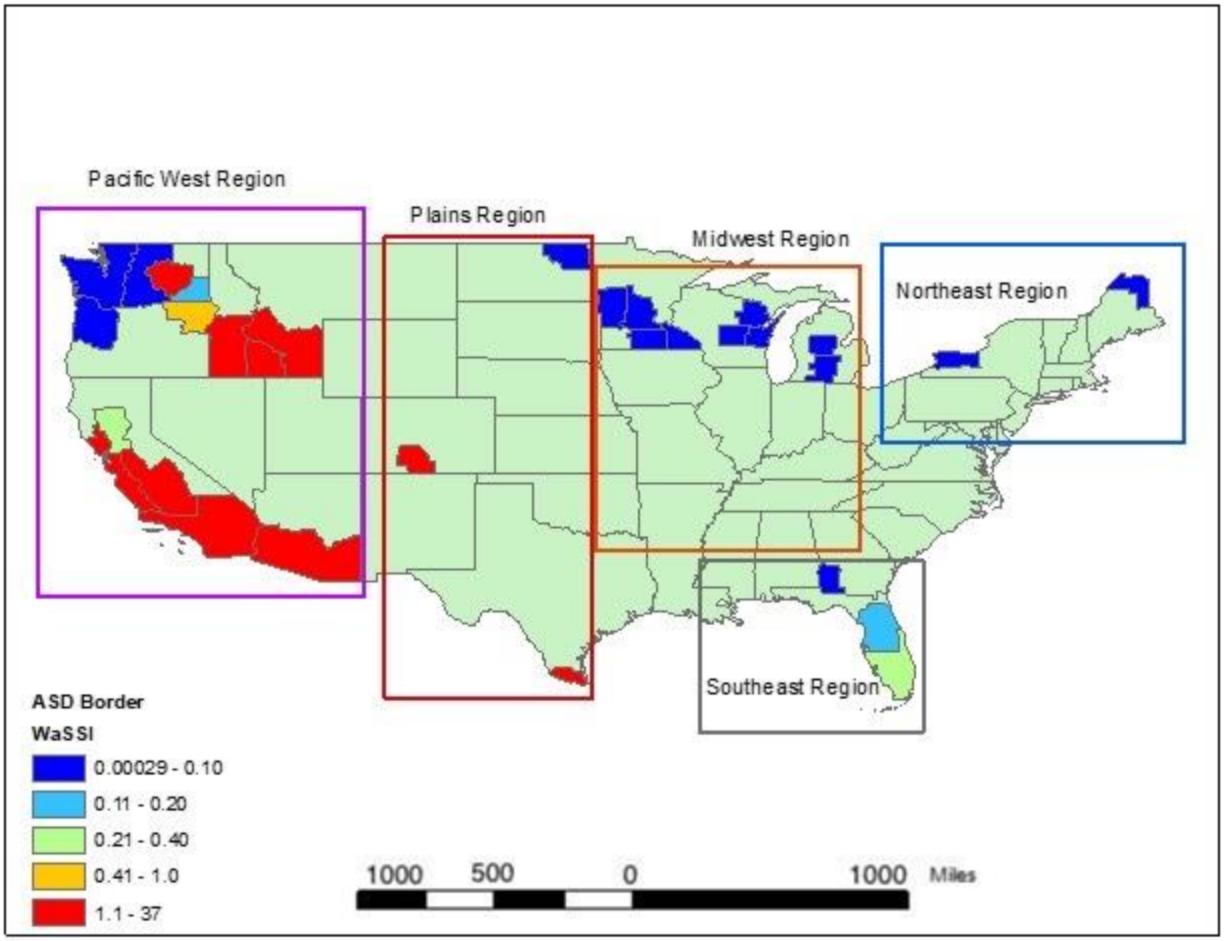

Figure F5. Average Annual WaSSI due to irrigation water use (2040-2070) scenario HSBF2

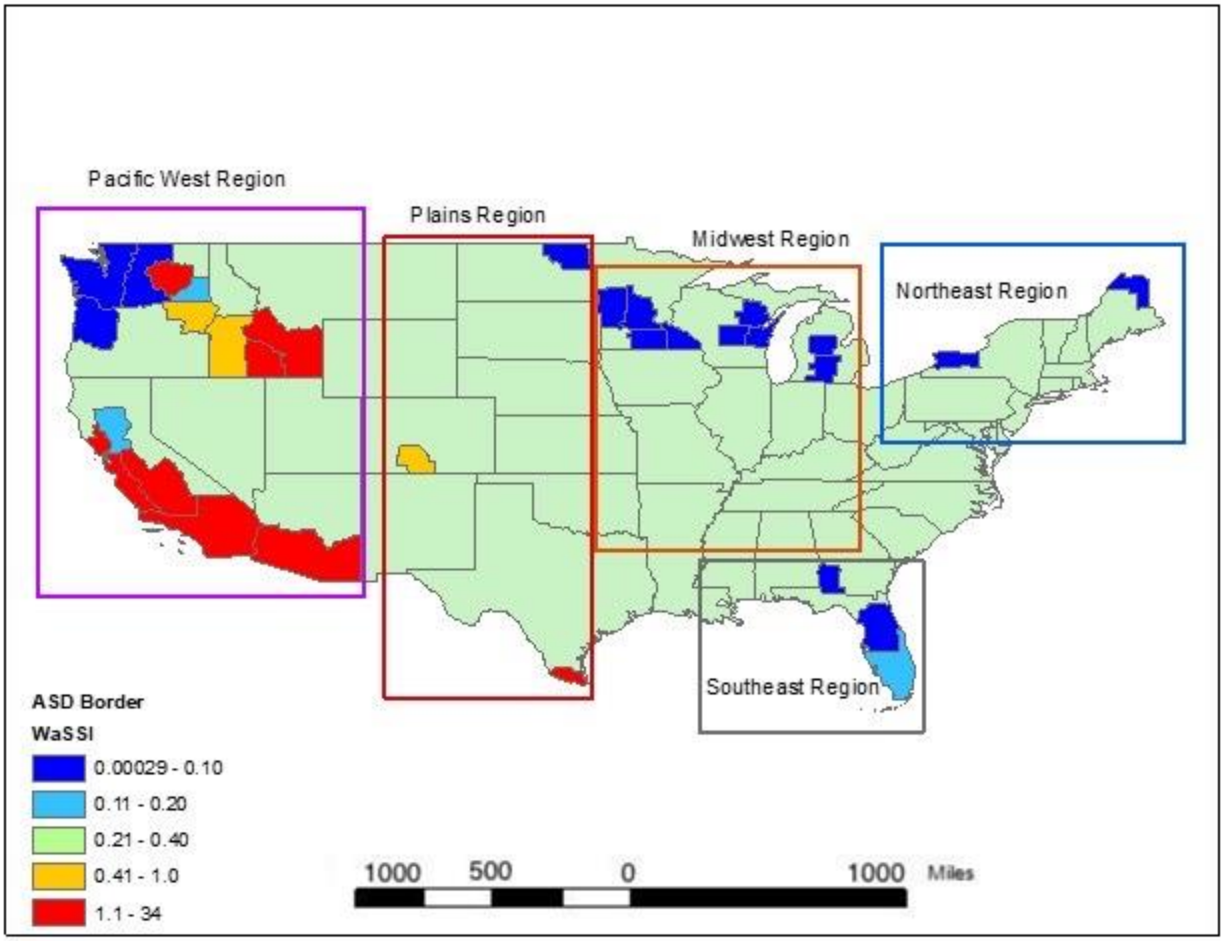

Figure F6. Average Annual WaSSI due to irrigation water use (2021-2050) scenario ISAF1

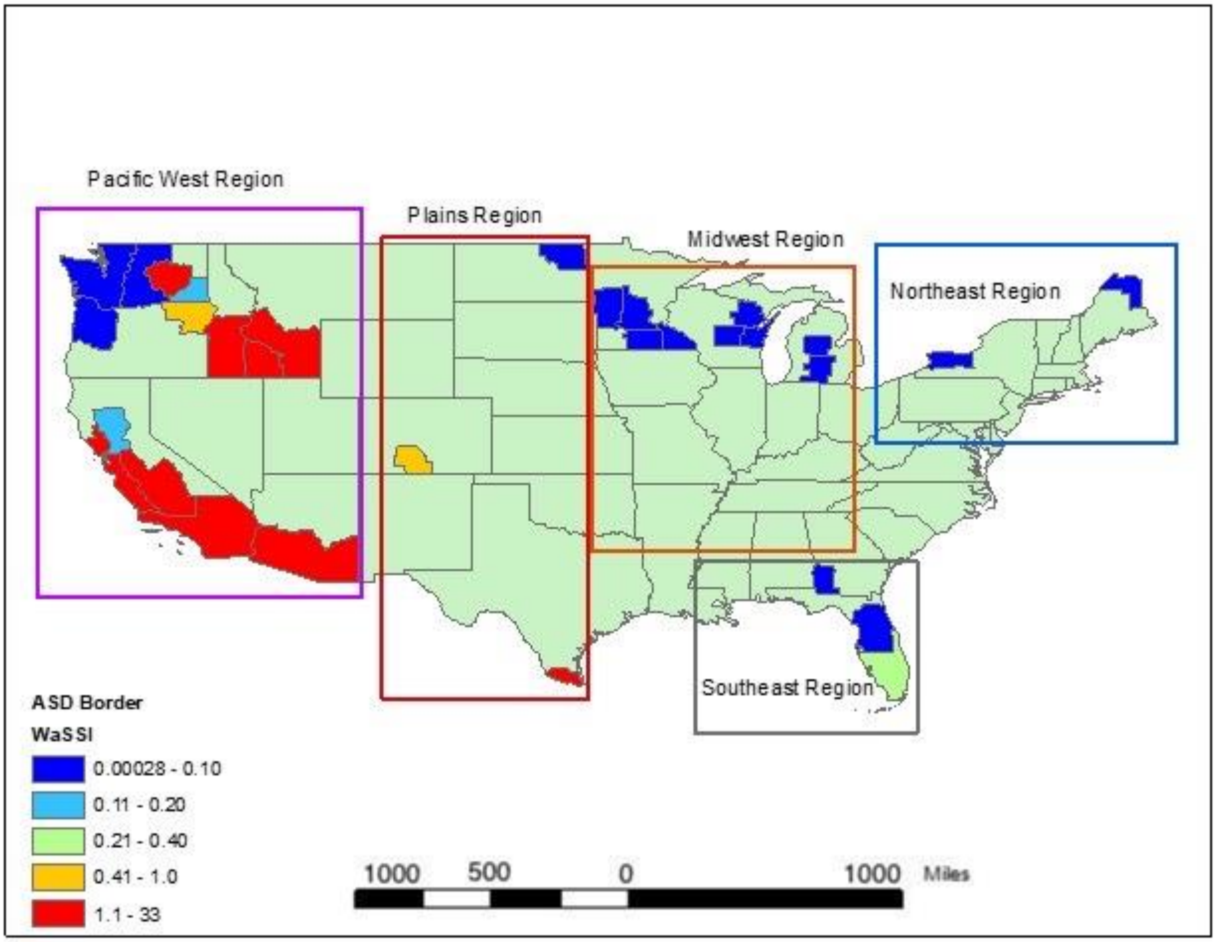

Figure F7. Average Annual WaSSI due to irrigation water use (2040-2070) scenario ISAF2

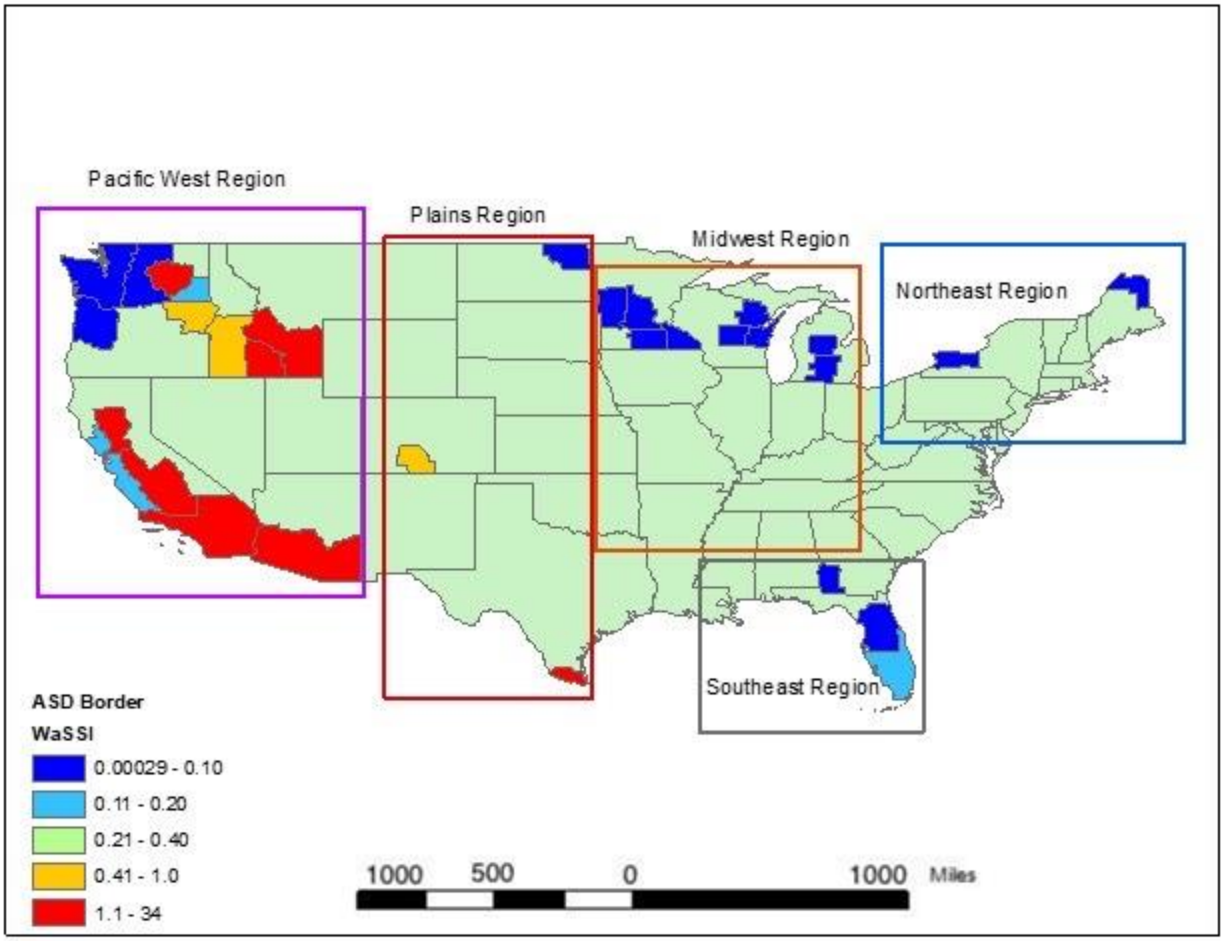

Figure F8. Average Annual WaSSI due to irrigation water use (2021-2050) scenario ISBF1

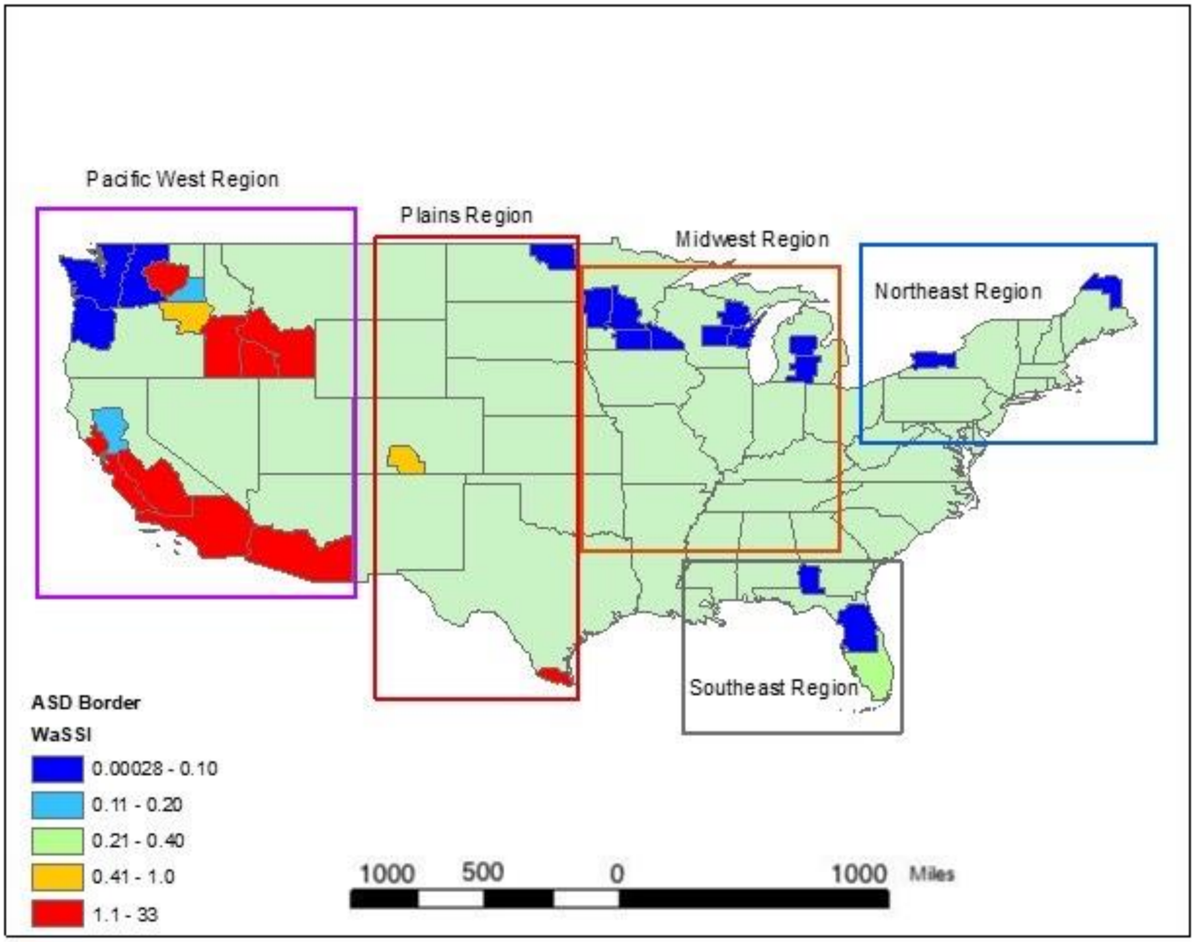

Figure F9. Average Annual WaSSI due to irrigation water use (2040-2070) scenario ISBF2

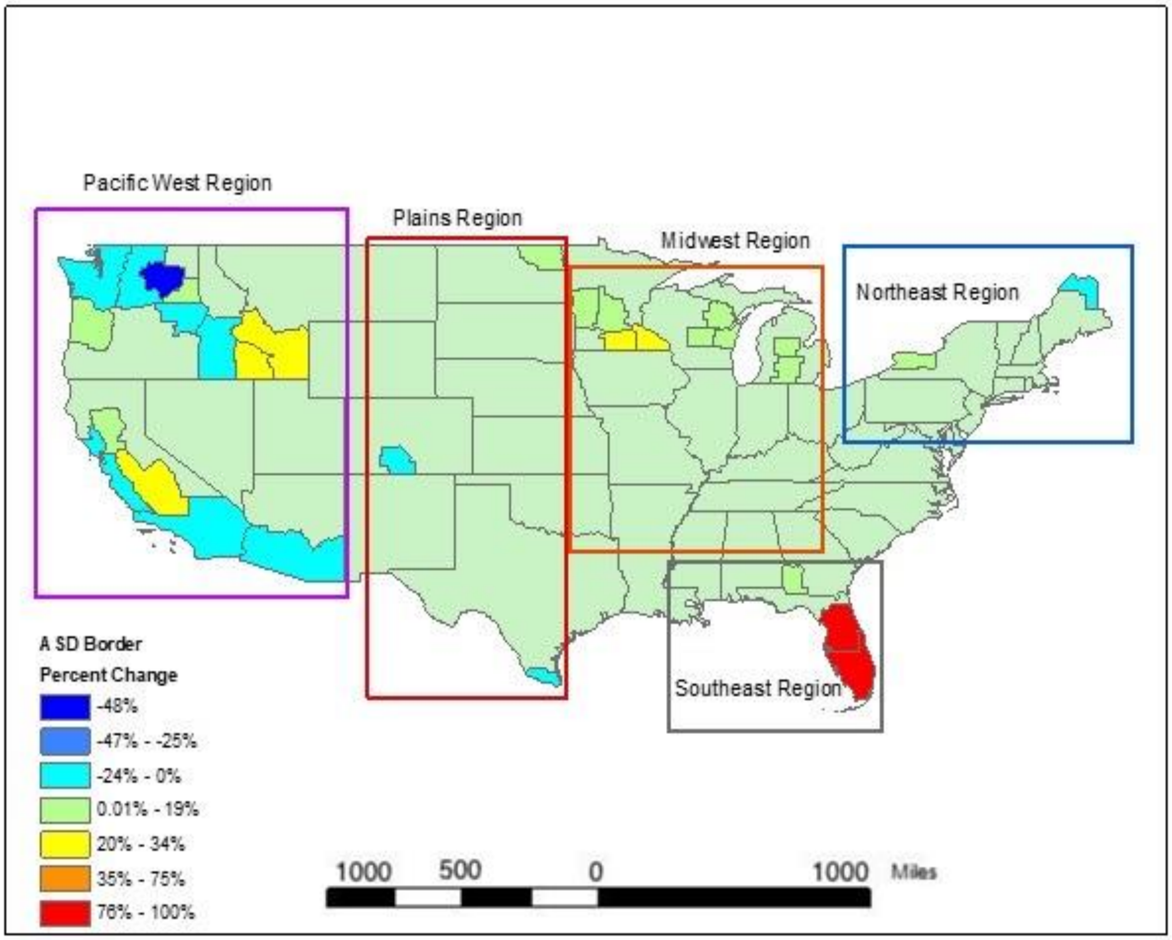

Figure F10. Percent Change in WaSSI from Baseline to HSAF1 scenario

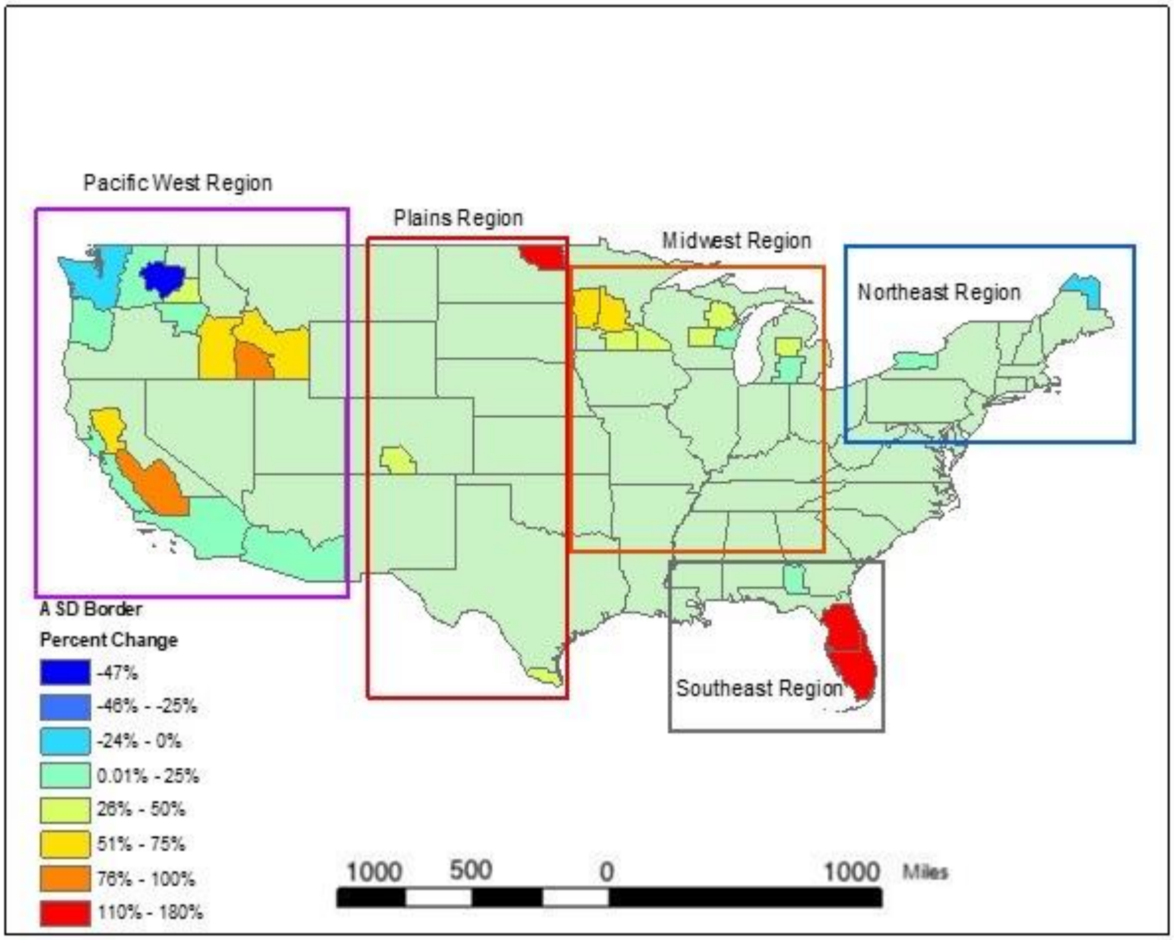

Figure F11. Percent Change in WaSSI from Baseline to HSAF2 scenario

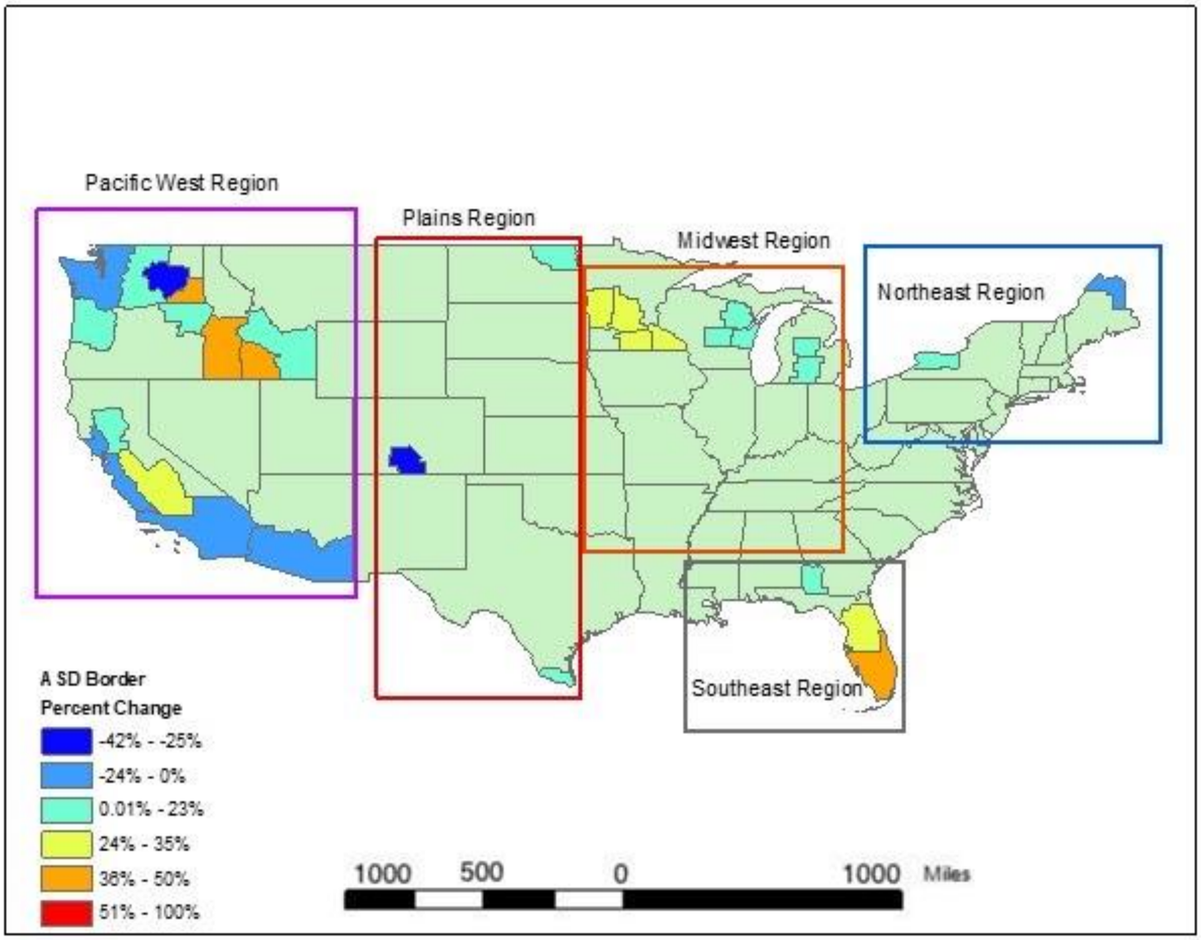

Figure F12. Percent Change in WaSSI from Baseline to ISAF1 scenario

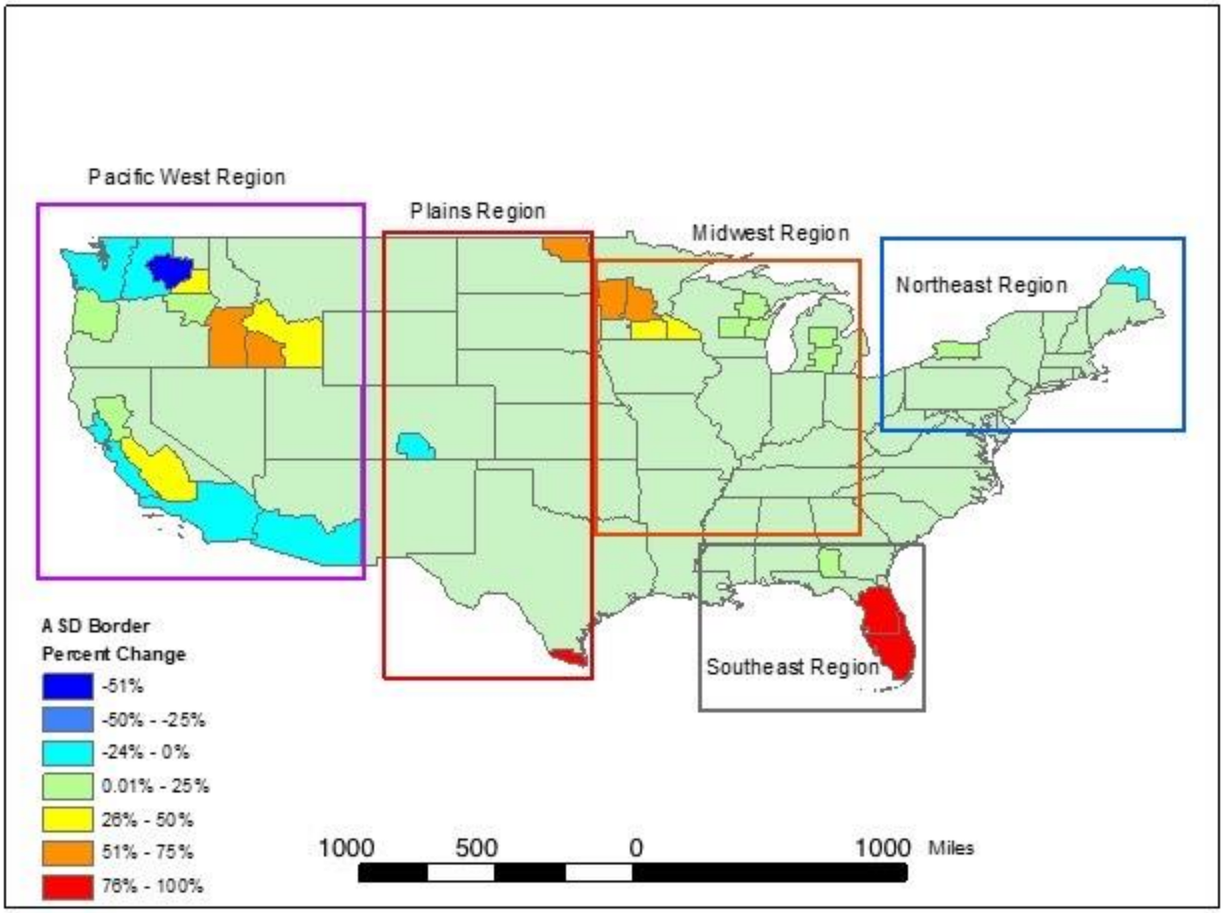

Figure F13. Percent Change in WaSSI from Baseline to ISAF2 scenario

Appendix G- Projected Surface Water Available for Irrigation Use Results

Table G1. Summary of historical projected water available for irrigation use

Historical Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
1981	8034	69473	11901	3775	12707
1982	10083	89134	23396	4077	10193
1983	10975	99529	24411	3535	12537
1984	11479	83009	15826	4385	13360
1985	12061	53015	13562	5676	8634
1986	15330	76375	14099	6158	11734
1987	3883	44080	17491	5101	8809
1988	4788	47492	15628	3289	8344
1989	4796	57554	12133	2401	9260
1990	9349	58780	11362	3786	14165
1991	11738	58156	20905	4710	11582
1992	9123	44124	18406	4969	12213
1993	14638	73394	14847	5147	11331
1994	10084	43353	23458	4082	12295
1995	10575	92040	22416	4781	9552
1996	8666	93226	16089	2704	15102
1997	9952	98588	21329	5066	11340
1998	8897	83234	24446	4760	12346
1999	10098	77435	16610	4984	11229
2000	7834	56546	10854	2769	12250
2001	11677	40124	20710	3492	7834
2002	10528	55589	20698	2317	10399
2003	6473	58325	23260	2683	13138
2004	9821	57931	18922	4424	12454
2005	10533	58422	20423	4171	16229
2006	7394	77585	9861	3494	15338
2007	9255	49863	11489	4479	12259
2008	9295	57315	17011	4178	16004
2009	9775	57439	16061	3770	13027
2010	14244	63447	15302	4052	13260

Table G2. Summary of HSAF1 projected water available for irrigation use

High Stress High Population Near Future (HSAF1) Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2021	6902	66685	20166	4946	11924
2022	11576	68710	19213	4333	12660
2023	10444	74356	19368	3952	11924
2024	10444	92010	14887	3584	13646
2025	8752	82883	14436	4411	12559
2026	12042	70259	16703	5117	13283
2027	9143	85445	18413	4269	12199
2028	8287	67918	15985	3528	13075
2029	8102	78689	16851	3913	12442
2030	11178	79364	24395	4450	13955
2031	9104	64034	15042	3621	12482
2032	9746	67482	18258	4203	13242
2033	7654	65659	17980	3879	11204
2034	6644	64424	17981	3796	12975
2035	9973	73843	18275	4349	12785
2036	8412	69518	17380	3690	13515
2037	8452	70790	19884	4148	11502
2038	5725	64360	15686	4192	10827
2039	8272	66038	14055	3806	12969
2040	10137	70090	17688	3382	11695
2041	8083	59465	16699	4732	12338
2042	5778	54183	12609	2875	11592
2043	9109	72043	16556	3410	12436
2044	11250	68388	18997	5780	12503
2045	10192	66413	17429	4342	10851
2046	8389	72100	12353	4131	11065
2047	7049	68197	13872	3670	10950
2048	7888	77476	18546	3904	11870
2049	7387	72295	18260	2691	13585
2050	10215	75877	18480	3441	13601

Table G3. Summary of HSBF1 projected water available for irrigation use

High Stress Normal Population Near Future (HSBF1) Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2021	6904	66780	20131	4950	11925
2022	11578	68803	19176	4337	12661
2023	10446	74452	19331	3964	11925
2024	10449	92183	14849	3595	13647
2025	8757	83060	14401	4420	12560
2026	12046	70429	16667	5128	13285
2027	9147	85608	18374	4279	12200
2028	8291	68059	15946	3537	13077
2029	8107	78837	16809	3923	12443
2030	11182	79496	24350	4459	13957
2031	9109	64173	14999	3630	12483
2032	9750	67629	18211	4212	13244
2033	7659	65794	17932	3888	11206
2034	6647	64538	17932	3804	12977
2035	9977	73979	18225	4358	12787
2036	8417	69652	17329	3698	13517
2037	8457	70913	19827	4156	11504
2038	5732	64518	15628	4199	10828
2039	8276	66200	13998	3813	12970
2040	10140	70243	17629	3387	11696
2041	8088	59595	16640	4735	12340
2042	5783	54316	12549	2878	11593
2043	9109	72183	16494	3412	12438
2044	11250	68548	18929	5779	12505
2045	10189	66570	17361	4342	10853
2046	8388	72232	12288	4130	11068
2047	7049	68312	13803	3681	10952
2048	7891	77626	18472	3916	11872
2049	7391	72432	18185	2704	13587
2050	10213	76032	18402	3452	13603

Table G4. Summary of ISAF1 projected water available for irrigation use

Intermediate Stress High Population Near Future (ISAF1) Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2021	6738	59308	20715	5788	11161
2022	7113	72752	25533	4808	12804
2023	7239	81842	23512	3890	12138
2024	8587	71553	22577	5278	12842
2025	8680	79292	14897	4862	11665
2026	8640	68207	18750	4090	11146
2027	6987	58475	13904	3413	12765
2028	9408	73035	14822	3480	12270
2029	8567	73683	18218	3616	11977
2030	8326	75014	17191	3990	12660
2031	9753	75932	12985	4676	11617
2032	9021	79006	18940	4922	13252
2033	10604	60265	15000	4634	12028
2034	9825	64383	17425	3776	10969
2035	11118	76238	16110	3313	9704
2036	10731	71285	22744	4801	12181
2037	11194	63032	19060	4249	13294
2038	10192	65829	17650	3680	11150
2039	9444	70945	13974	3796	12897
2040	9960	67184	19368	3628	12862
2041	8807	60673	15640	3219	12092
2042	7141	71249	25496	4031	11754
2043	6684	68233	17639	3680	11543
2044	9784	64683	22331	4143	12361
2045	9661	66492	15711	4621	11870
2046	8341	68082	9884	3857	12900
2047	7258	72506	16195	4091	11750
2048	8823	73634	13742	4240	12842
2049	6172	71778	13886	5161	12411
2050	7561	67478	17628	4333	12410

Table G5. Summary of ISBF1 projected water available for irrigation use

Intermediate Stress Normal Population Near Future (ISBF1) Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2021	6741	59403	20680	5792	11162
2022	7116	72844	25497	4812	12805
2023	7242	81937	23474	3902	12139
2024	8592	71719	22537	5290	12843
2025	8685	79473	14864	4873	11666
2026	8645	68358	18715	4101	11147
2027	6993	58607	13865	3423	12766
2028	9413	73185	14784	3490	12272
2029	8571	73829	18175	3624	11978
2030	8330	75165	17150	3999	12662
2031	9756	76081	12942	4684	11619
2032	9025	79165	18893	4930	13254
2033	10605	60404	14954	4642	12030
2034	9827	64499	17377	3784	10971
2035	11121	76362	16061	3322	9706
2036	10733	71406	22692	4809	12183
2037	11196	63153	19005	4257	13296
2038	10194	65987	17594	3687	11151
2039	9447	71114	13916	3802	12899
2040	9961	67335	19309	3634	12864
2041	8809	60821	15580	3225	12094
2042	7144	71411	25432	4033	11755
2043	6688	68377	17574	3681	11545
2044	9785	64843	22263	4144	12363
2045	9660	66644	15643	4622	11872
2046	8343	68219	9819	3855	12902
2047	7259	72669	16124	4102	11752
2048	8825	73761	13673	4254	12845
2049	6176	71915	13808	5171	12413
2050	7561	67590	17552	4344	12412

Table G6. Summary of HSAF2 projected water available for irrigation use

High Stress High Population (HSAF2) Far Future Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2040	10195	35193	11636	3583	11696
2041	8087	30523	11275	4800	12338
2042	5778	28601	8547	2883	11592
2043	9109	37628	10488	3416	12436
2044	11253	32815	12667	5802	12503
2045	10195	32743	11600	4358	10851
2046	8389	36436	8894	4132	11065
2047	7049	37213	9075	3670	10950
2048	7888	38517	11576	3904	11870
2049	7387	36881	11342	2692	13585
2050	10215	36867	11562	3441	13601
2051	7648	38784	11804	4005	11732
2052	7594	38294	8588	4017	11976
2053	4991	34009	15217	4918	11336
2054	7859	33604	9470	4891	12924
2055	8861	37038	7888	5179	12554
2056	7966	39020	10071	3317	11394
2057	7804	31537	11403	3159	13746
2058	4932	32065	10676	3735	11996
2059	6094	29744	10426	3484	12306
2060	7448	37339	8163	2775	12160
2061	9236	36786	10001	3881	12226
2062	9518	32337	10329	3941	11188
2063	7359	27320	9488	3719	11188
2064	6819	35164	9323	2902	11531
2065	5919	26154	10447	3451	10708
2066	7288	28631	9548	3392	12094
2067	6771	32605	9974	3306	12730
2068	7087	34181	8618	3219	12804
2069	7728	36232	7624	4012	11251
2070	7727	35051	7028	3547	11700

Table G712. Summary of HSBF2 projected water available for irrigation use

High Stress Normal Population (HSBF2) Far Future Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2040	10197	35202	11599	3587	11698
2041	8092	30532	11238	4804	12340
2042	5783	28613	8511	2886	11593
2043	9109	37641	10449	3418	12438
2044	11253	32827	12624	5801	12505
2045	10193	32756	11557	4358	10853
2046	8388	36448	8853	4130	11068
2047	7049	37226	9032	3681	10952
2048	7891	38529	11528	3916	11872
2049	7391	36893	11296	2705	13587
2050	10213	36877	11513	3452	13603
2051	7647	38793	11753	4017	11734
2052	7597	38301	8541	4028	11978
2053	4997	34014	15168	4928	11338
2054	7858	33611	9419	4899	12926
2055	8858	37044	7841	5189	12556
2056	7967	39024	10020	3327	11396
2057	7802	31542	11349	3169	13748
2058	4935	32073	10623	3741	11999
2059	6094	29752	10374	3488	12308
2060	7450	37345	8110	2784	12163
2061	9233	36792	9946	3890	12229
2062	9513	32341	10277	3949	11191
2063	7355	27327	9435	3727	11191
2064	6817	35171	9269	2912	11534
2065	5921	26160	10391	3459	10711
2066	7288	28638	9494	3399	12097
2067	6775	32612	9922	3313	12732
2068	7084	34187	8565	3227	12807
2069	7726	36238	7574	4018	11254
2070	7726	35056	6979	3555	11703

Table G8. Summary of ISAF2 projected water available for irrigation use

Intermediate Stress High Population (ISAF2) Far Future Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2040	9979	33647	12735	3951	12864
2041	8807	31885	10007	3354	12092
2042	7143	35142	16412	4055	11754
2043	6684	33477	11032	3692	11543
2044	9784	31587	14421	4147	12361
2045	9661	32420	10560	4635	11870
2046	8341	34234	6824	3859	12900
2047	7258	35912	10362	4093	11750
2048	8823	37348	9712	4241	12842
2049	6172	37074	9452	5162	12411
2050	7561	32839	11553	4333	12410
2051	10650	37230	13348	4066	12362
2052	9045	36884	14015	4345	13738
2053	11061	35353	8924	3701	12376
2054	6788	33491	6786	3311	12282
2055	8550	40516	11400	3551	12032
2056	11193	37258	9521	4462	13002
2057	8613	36578	14948	3966	11944
2058	6271	33601	10273	3240	10901
2059	7861	37489	8049	3943	11639
2060	5996	35659	13999	3988	11174
2061	8161	36689	10589	3154	11563
2062	9736	37212	11565	3399	12463
2063	9155	31681	11533	3050	13337
2064	9341	28838	12034	4907	10862
2065	9905	33244	8075	3697	12662
2066	6562	39531	9899	3139	13240
2067	6599	36539	9204	3628	12414
2068	8037	32291	7415	3663	12098
2069	8595	31597	9873	3342	12577
2070	9449	35251	10868	4394	13071

Table G9. Summary of ISBF2 projected water available for irrigation use

Intermediate Stress Normal Population (ISBF2) Far Future Water Availability (Mm^3/year)					
Year	Midwest	Pacific West	Southeast	Plains	Northeast
2040	9981	33656	12698	3956	12865
2041	8809	31894	9970	3359	12094
2042	7145	35153	16370	4057	11755
2043	6688	33490	10991	3692	11545
2044	9785	31600	14377	4148	12363
2045	9660	32431	10517	4635	11872
2046	8343	34246	6784	3857	12902
2047	7259	35924	10317	4104	11752
2048	8825	37360	9670	4254	12845
2049	6176	37085	9403	5172	12413
2050	7561	32850	11507	4344	12412
2051	10649	37239	13297	4078	12364
2052	9044	36892	13963	4357	13740
2053	11059	35359	8875	3712	12378
2054	6790	33499	6740	3322	12284
2055	8548	40521	11350	3561	12034
2056	11189	37263	9469	4470	13004
2057	8611	36583	14890	3975	11946
2058	6274	33609	10220	3248	10904
2059	7861	37495	7996	3950	11642
2060	5995	35664	13945	3996	11176
2061	8157	36695	10533	3164	11566
2062	9730	37217	11511	3409	12466
2063	9151	31687	11477	3060	13340
2064	9337	28845	11976	4914	10865
2065	9898	33249	8022	3703	12665
2066	6560	39535	9848	3147	13243
2067	6600	36544	9151	3634	12417
2068	8034	32297	7364	3669	12101
2069	8592	31603	9823	3351	12580
2070	9443	35256	10814	4402	13074