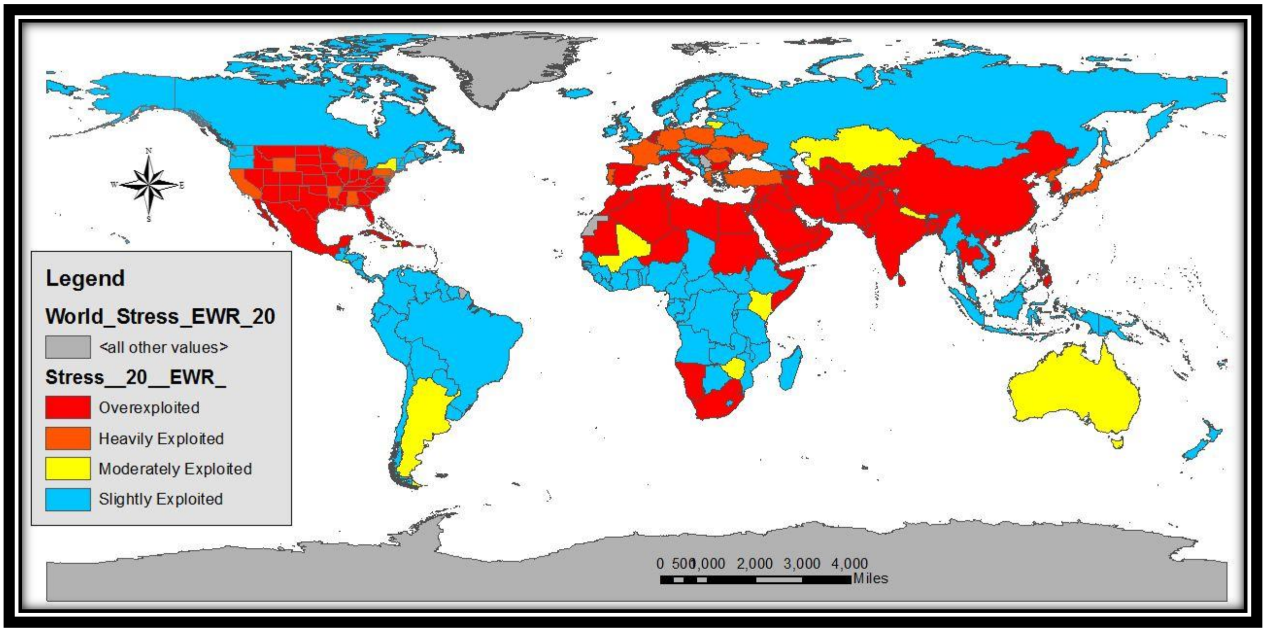
Mapping of Water Stress Indicators



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Abstract

Water stress indices are commonly used to visualize water resources vulnerability on a global scale. Since the introduction of the Falkenmark Indicator in 1989, a multitude of alternative water stress indices have emerged, each with their own unique set of assumptions and goals.[1] For this project the Falkenmark Indicator, based on population, was used as a preliminary assessment to be compared to Smakhtin's Water Stress Indicator (2005), based on water withdrawals. The decision to use these two indices resulted from their common presence in the literature. Additionally, the difference in parameters used (population vs. withdrawals) leads to valuable comparisons of which countries are completely stressed and which countries are stressed based only on one of the parameters.

The initial goal of this project was to improve understanding of the United States' water stresses as compared to the world's other countries, and this goal was completed by mapping each state's water stress and comparing these to each country's water stress. Further detail was added in the form of equalized stress indices, which allowed for a more detailed gradient of the country's and state's water stress levels. This ultimately informs which spatial regions require changes in terms of population and withdrawals in order to create an "ideal world" where water stress is identical in all countries throughout the world. Note that this "ideal world" will require different changes for each different water stress index that is used, and thus the idealization is not consistent between the Falkenmark Indicator and the Water Stress Indicator.

Introduction

The goal of this project was to explore the water stresses of the United States of America (US) as compared to other countries around the world. First, maps assessing the Falkenmark Indicator (FI) and Smakhtin's Water Stress Indicator (WSI) were created for the US, followed by similar maps for all countries around the world. By comparing the US maps to the global maps, a better understanding of each state's water stresses become apparent. These maps therefore improve assessments of water stresses within the US as they compare to the rest of the world (rather than comparing strictly to the US).

Further maps were then created to determine where change is necessary in order to more equally distribute water stresses throughout the world. This equalization was achieved by calculating a total FI and WSI for the whole world, and comparing these resultant stress indices with the previously calculated indices for each individual country and state. This comparison determined the changes in population and withdrawals required to equalize water stresses in all countries.

In the case of the FI, the model is reasonable but the means are not: shifting populations around the world based on water availability will not work. Regarding the WSI, though changing withdrawal habits is more reasonable than shifting populations, the model is not realistic: people living in deserts such as Arizona would have to experience an extreme shift in consumptive habits (there are simply too many people there to survive strictly on Arizonan water). These models function primarily as a means for identifying where change is needed; more detailed models must be devised in the future to better understand what methods of change can be implemented to improve (decrease) global water stress.

Models

Falkenmark Indicator

The Falkenmark Indicator is dependent on two variables: surface runoff (m^3/yr) and population.[2] Surface runoff in this case was set equal to Mean Annual Runoff values retrieved from the University of New Hampshire and the Global Runoff Data Centre (UNH/GRDC) Composite Runoff Fields V 1.0 (2002), while population data for countries was retrieved from the World Bank and state data from the US Census Bureau (for the retrieved runoff data, see figure A.1 in the appendix).[3,4,5] These data were then used to calculate FI values for every country and state using Equation 1.

$$FI = \frac{Surface\ Runoff}{Population} \qquad \text{(Equation 1)}$$

The results were then sorted into the four groupings proposed by Falkenmark, listed below in Table 1.

Table 1. Water stress index proposed by Falkenmark, 1989.

FI (m^3/capita/year)	Stress Level
> 1,700	No Stress
1,000-1,700	Stress
500-1,000	Scarcity
<500	Absolute Scarcity

It is important to note that the UNH/GRDC dataset has a spatial resolution of 0.5-degrees, meaning that each spatial cell has a resolution of roughly 3.1 billion square meters at the equator. Simply put, these are very large cells, and as such the correctness of the MAR data is debatable. However, the UNH/GRDC dataset is widely considered one of the better MAR datasets available, and calculating MAR for every state and country would have been an unreasonably large task for this term paper.

Another particularly important assumption in this paper is that the longitudinal metric distance equivalent of 0.5-degrees was assumed to be equal at the equator and at the poles. Technically speaking, this longitudinal length would decrease (quite significantly) as latitudes increased from 0° to 90° (or -90°). For example: longitudinal distance of 0.5-degrees at latitude 0° is ~55,600 meters, whereas the same 0.5-degree distance at latitude 45° is ~39,400 meters. Though this difference is substantial, this paper has assumed that the longitudinal distance remains constant at 55,600 meters for all latitudes. This absolutely creates a margin of error, but the simplicity allowed for more time to be invested in the actual subject at hand, and as such the simplification was considered reasonable.

Water Stress Indicator

Vladimir Smakhitn's Water Stress Indicator is defined as described in Equation 2.[6] Mean Annual Runoff (MAR) is a specified parameter, which again was retrieved from the UNH/GRDC dataset.[3] Withdrawal data was retrieved from the Food and Agriculture Organization's (FAO)

AQUASTAT database for each country, and the United States Geological Survey (USGS) for each state.[7,8] The USGS data was retrieved by US counties, and therefore required simplification into a new dataset organized by state.

$$WSI = \frac{Withdrawals}{MAR - EWR} \qquad \text{(Equation 2)}$$

The EWR term in the equation describes the "Environmental Water Requirements". Smakhtin argues that the environment requires a certain water volume for upkeep (EWR), and therefore not all water (measured as MAR) can be considered available for human consumption. This EWR term was determined by Smakhtin to typically be between 20 and 30% of MAR, and as such a 20% EWR has been used for calculating the standard WSI values throughout this paper. Additional maps using 0% EWR and 50% EWR were included in the appendix for trending purposes only. All values are measured in cubic meters per year.

The WSI has groupings of its own, listed below in Table 2. The four groupings technically describe water availability prior to EWR disruptions, though these details are not explained in this paper. The primary purpose here of using the WSI is to compare the difference between population (FI) and withdrawals (WSI) on water stress indices, and the primary purpose of calculating multiple WSI values (using different EWR assumptions) is to create visual trends of water stress.

Table 2. Water stress indicator proposed by Smakhtin, 2005.

WSI	Stress Level
WSI > 1	Overexploited
0.6 ≤ WSI < 1	Heavily Exploited
0.3 ≤ WSI < 0.6	Moderately Exploited
WSI < 0.3	Slightly Exploited

Approach

United States FI & WSI

Once all the relevant data was retrieved (see figure A.2, figure A.4, and figure A.5 in the appendix), the FI and WSI for each state was calculated and assigned to the relevant stress level grouping within an excel spreadsheet. In order to geographically display these values in ArcGIS, shapefiles for all 50 states were collected from the US Census Bureau.[9] These shapefiles had STUSPS values (two-character state descriptions, such as "TX" for Texas) which were then used to join the shapefiles with the data table containing the FI and WSI calculations. Once joined together, the FI and WSI results were displayed as defined by Table 1 and Table 2, respectively.

World Countries FI & WSI

Similar calculations were completed for the world's countries (see figure A.3, figure A.6, and figure A.7 in the appendix). Shapefiles were retrieved from the US Department of State, which were then joined to the relevant data tables using each country's 3-character code defined by the

International Organization of Standardization (ISO).[10] This data was displayed using the same color scheme as seen in the US figures.

Water Stress Normalization

While these maps are beneficial for visualizing where scarcity is present, their coarseness lacks the precision necessary to inform change. Therefore, in order to better understand where change was necessary and how much change was necessary, overall FI and WSI values were calculated for the sum of all regions: the sum of population and withdrawals in all countries was used to calculate the global FI and WSI, and the sums in the states were used for the US. These parameters were then used to equalize each region's data.

In the case of the US data, the population and withdrawals of all 50 states were summed together and compared to the summation of the MAR values seen in all 50 states. The resulting FI and WSI values were subtracted from the individual values calculated for each state, and this difference was used to calculate each state's required change in population and withdrawals necessary to equalize FI and WSI across the nation. Essentially, the optimal population and withdrawals for each state, based on the MAR seen by that state, were calculated such that each of the 50 states would have identical FI and WSI values.

A similar procedure was conducted in order to calculate the FI and WSI values for all countries. In the case of the global calculation, the state data was ignored (though the US was included as a single country) and values for total global MAR, population, and withdrawals were summed.

Results and Discussion

United States FI & WSI

Below are the resultant FI (figure 1) and WSI (figure 2) maps for the US. By quick observation it is quite clear that, though the population in the US may be reasonable in terms of water availability (MAR), the withdrawals most certainly are not. Further details can be gathered by comparing WSI values of EWR of 0% (figure A.8), 20% (figure 2), and 50% (figure A.9). Technically these WSI adjustments show the differences in water stress based on available MAR; but if MAR is assumed to be constant, these changes in WSI can be correlated to withdrawals, and the trend from 0% to 20% to 50% EWR can instead demonstrate the trend of water stress as withdrawals increase.

By comparing these different values of EWR it becomes apparent which states are closer to the group cutoffs (ie. which states are more likely to shift to the next categorization) of water stress based on increases in withdrawals. These trends are valuable in identifying which states are more or less delicate in terms of changes to withdrawals, which makes it apparent that the least sensitive areas are the Northeast and the Northwest due to their moderate changes when comparing the three figures. However, because a large number of states are "Overexploited" even in the 0% EWR case, the details of these states cannot be determined by observing solely this trend. A workaround to this issue will be mentioned later, when a finer gradient is defined to determine required changes to global withdrawals for WSI equalization.

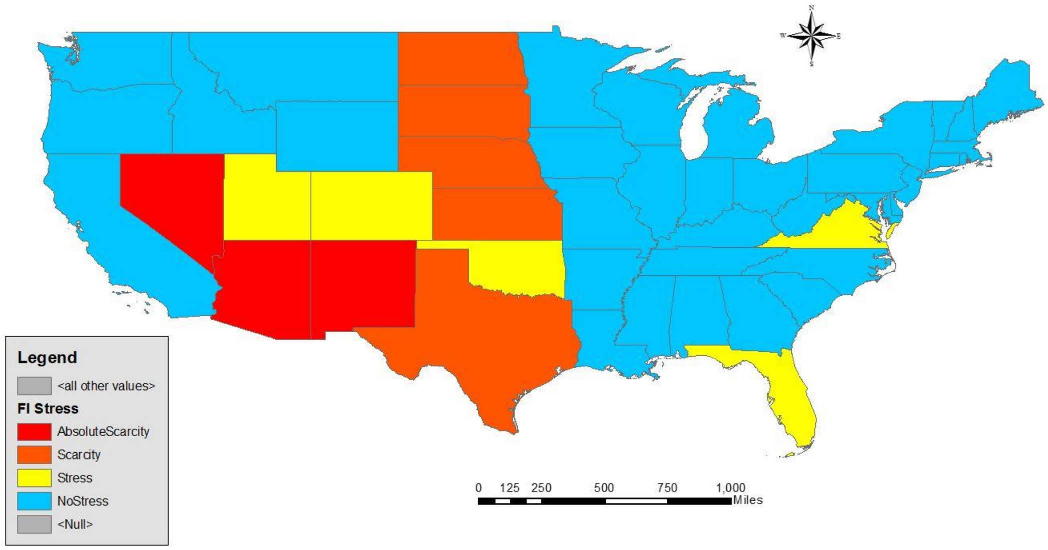

Figure 1 - United States Falkenmark Stress Index

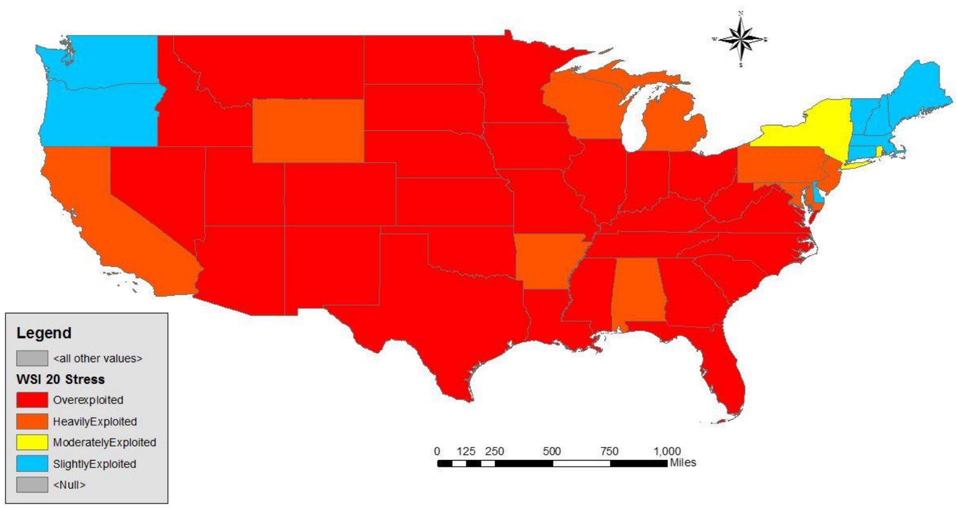

Figure 2 - United States Water Stress Indicator, 20% EWR

World Countries FI and WSI

Figure 3 and figure 4 display the FI and WSI on a global scale, with the US displayed as a single country. Here, again, the displayed WSI uses 20% EWR, whereas WSI maps for 0% and 50% EWR can be seen in the appendix (figures A.10 and A.11). It is important to note that the global models mapped the US as one country (as opposed to 50 states); it was this over-simplification that motivated the mapping of all 50 states for more detailed awareness of water stresses in the US as compared to the world's other countries.

Similarly to the US maps, comparisons can be made between the three WSI maps in order to identify regional sensitivity to water stress based on withdrawals. Some countries, such as France and the US, seem to increase in scarcity level fairly consistently, suggesting that these countries are in a very delicate balance in terms of withdrawals and MAR. Other countries, such as Canada, do not change at all and therefore suggest no susceptibility; while Argentina and

Australia change only once, suggesting that they are more susceptible to water stress than Canada but less susceptible than France. Similar assessments can be made for all countries.

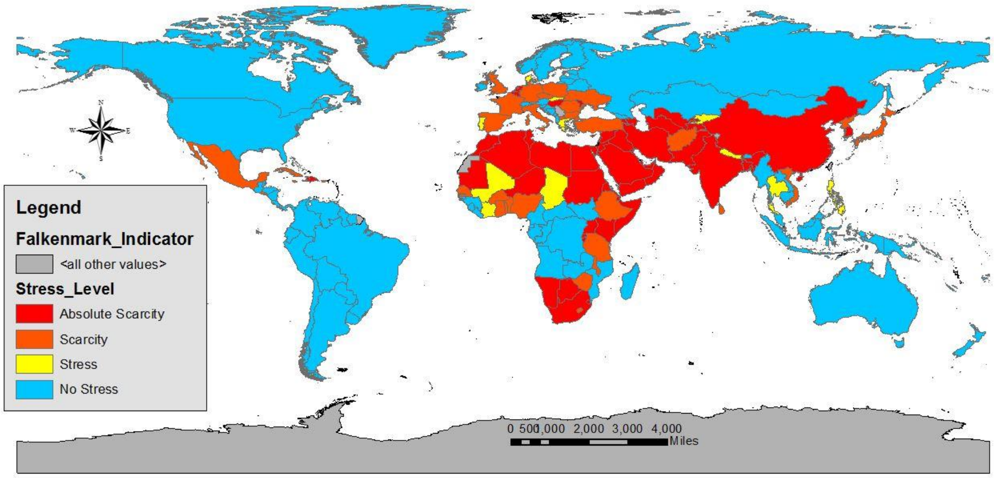

Figure 3 - Global Falkenmark Stress Index

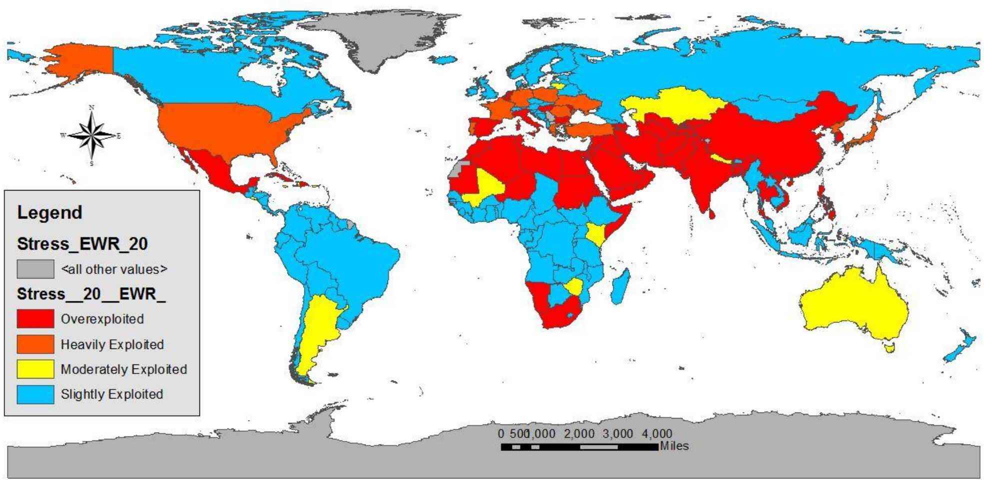

Figure 4 - Global Water Stress Indicator, 20% EWR

United States and World Countries FI & WSI Combined

The following figures combine the maps of US and global water stress in order to more easily view the different states' water stress levels as compared to the rest of the world. The FI map (figure 5) shows that the US is experiencing some water stress, despite the "no stress" classification assigned in figure 1. This alone justifies the need for more spatially resolved maps of water stress indices.

The WSI map (figure 6) demonstrates that the majority of the US is withdrawing water unsustainably (as expected, based on figure 4). Additionally, WSI trends based on figure A.12, figure 6, and figure A.13 show that the US is worsening more quickly than the remainder of the world in terms of withdrawal-induced water stresses.

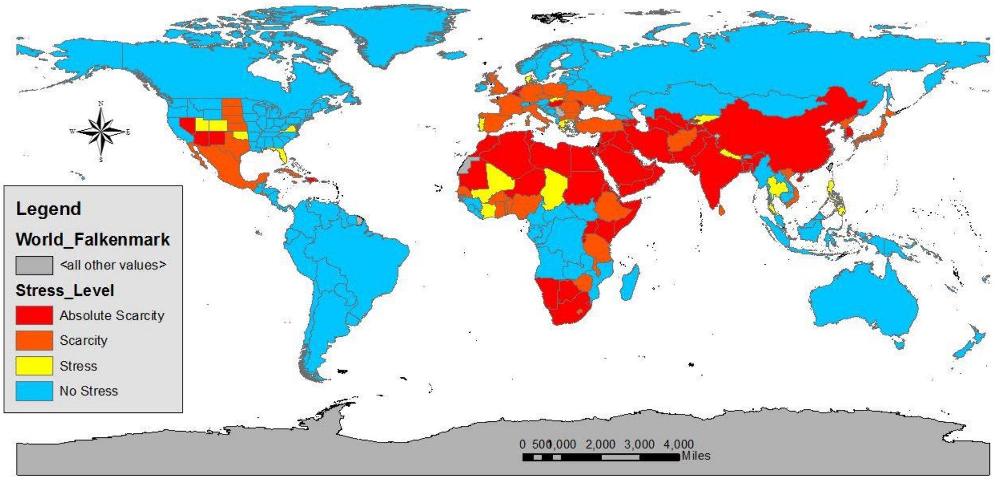

Figure 5 - Combined US and Global Falkenmark Stress Index

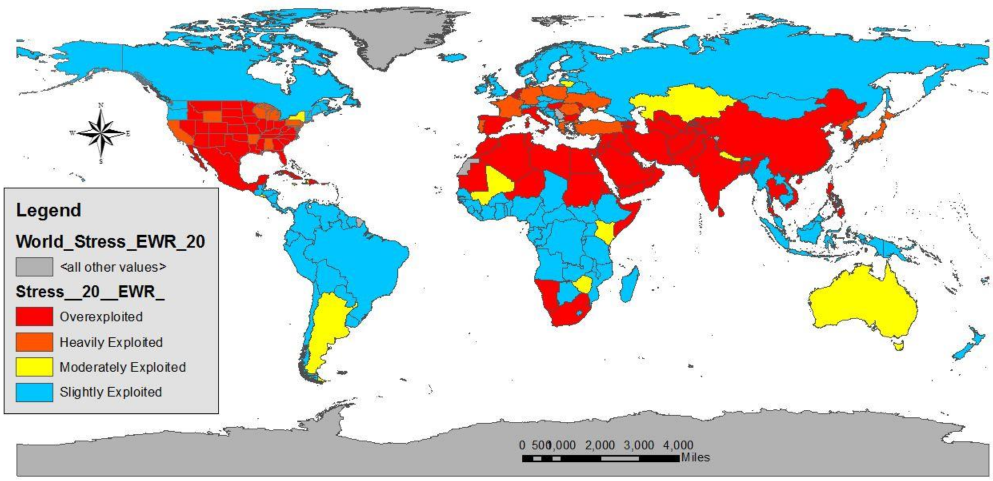

Figure 6 - Combined US and Global Water Stress Indicator, 20% EWR

Water Stress Normalization

The following figures show the gradient of required changes to population (figure 7) and withdrawals (figure 8) required to equalize FI and WSI values on a global scale. Green regions have room to increase their populations, while red regions should decrease their populations in order to globally equalize the FI. Regarding the WSI, green regions can increase their withdrawals and red regions should decrease their withdrawals for global equalization.

Though this classification may seem overly-idealistic, its merit is primarily in the visual gradient it creates, allowing for a better understanding of which regions are most severely stressed. Some regions, such as the state of Texas, were previously classified as experiencing "scarcity" by the FI; but in this model it appears that, when compared globally, Texas actually has room for more people (ie. is not water stressed). These observations are informative for truly understanding the spread of water stress: with this map, it is possible to see how severely stressed both China and India are, how unstressed Canada and Russia are, and where every other country falls between these extreme limits.

By extending this observation, these maps become a display of where change is most needed. Shifting populations in order to equalize the FI would be very difficult, and therefore the population map is only a display of which countries are overpopulated in terms of water availability. Withdrawal patterns rely on consumptive patterns and therefore are fairly difficult to change, though not impossible; these required changes to withdrawals can therefore be used to inform intelligent policy changes in the regions experiencing the most scarcity.

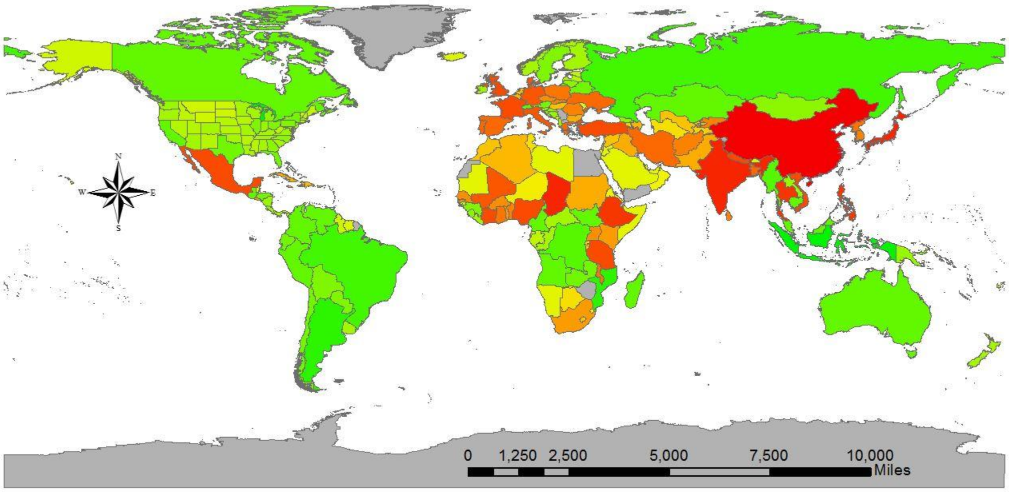

Figure 7 - Required Change in Population for Water Stress Equalization

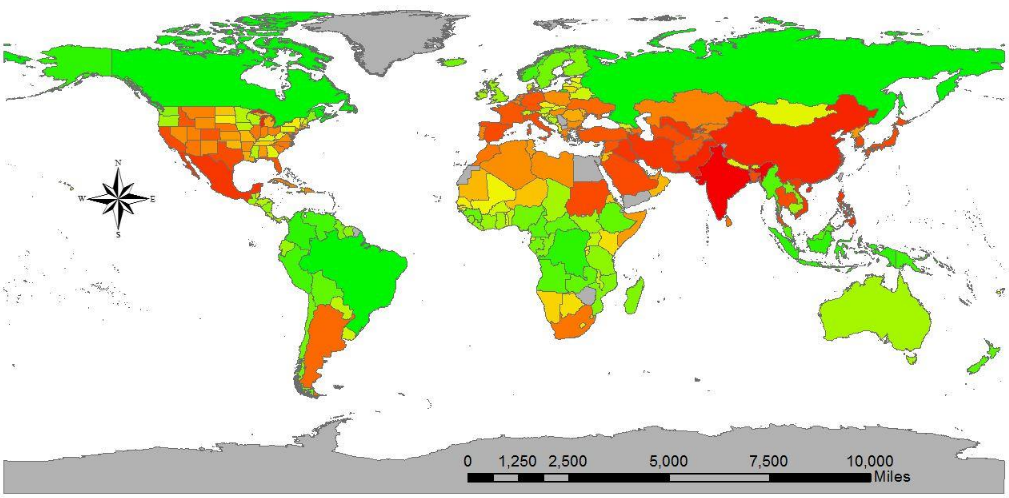

Figure 8 - Required Change in Withdrawals for Water Stress Equalization

Future Work

It was initially intended that this project would include temporal water stress estimates, assessing which year each country (and state) would reach each level of water stress according to both the FI and WSI indices. The first step would be to calculate the population and withdrawals necessary for each country to jump to the next water stress classification: in the case of the

Falkenmark Indicator, the MAR of each country would be used to calculate at what population these countries would reach “No Stress”, “Stress”, “Scarcity”, and “Absolute Scarcity” as defined in Table 1. Once these data were collected, predictions of future population and withdrawals for each country must be calculated.

In order to accurately predict future population and withdrawal values, data from previous years would be used to develop a curve which would then be extended to the desired years (for example, the curve might use available data from 1980 to 2015 and extend this data out to 2050). Correctional measures could be taken by finding available population and withdrawal predictions and seeing how closely these data matched the developed curve, though this would not be critical.

Once developed, the required population and withdrawals values required for each country to switch classifications would be correlated to the years on these country’s respective population and withdrawal curves. With the resultant data, “year-to-scarcity” (YtS) values could be calculated by subtracting the calculated years from the current year. Finally, these YtS values could be mapped in order to determine where water stresses would worsen most quickly (and therefore where corrective action was most imminent). Similar procedures could be conducted in reverse in order to determine how long each stressed country has been stressed by extending the population and withdrawal curves back in time.

Though these YtS maps would be useful in assessing future water stresses, the methodology here developed for creating the maps was deemed too laborious for this term project. Unless population and withdrawals predictions exist that include all future years (as opposed to only every 10 years, for example), then these curves must be developed and read for each country and state independently. If more time had been available, this would be the next course of action for this project.

Conclusions

Overall, this project has implications in determining which regions of the world have the most unsustainable population sizes and water withdrawals. By combining US data with global country data, each individual state can be compared to the rest of the world to better understand each state’s water stress on a global scale. These data can then be normalized to determine where change is most needed in terms of population size and withdrawal volumes, and this required change can then inform future policy decisions. Had more time been available, further maps would have been created determining the year-to-scarcity of each country and state, and these maps would also have implications on global policy decision-making.

References

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Appendix

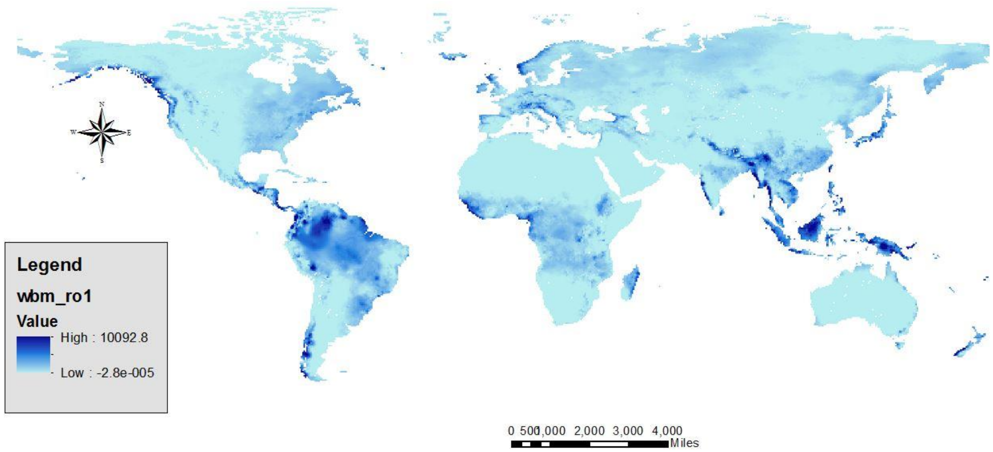

Figure A.1 - Global Composite Runoff Fields V 1.0

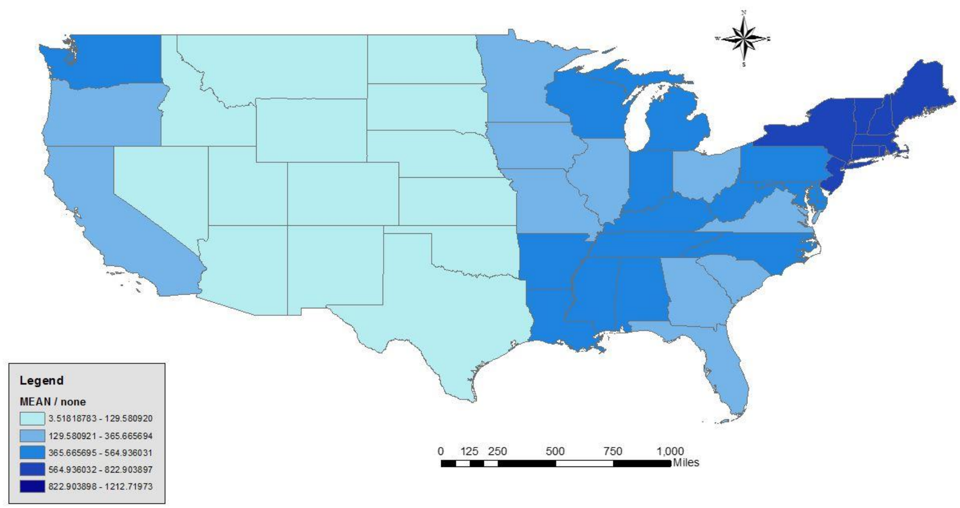

Figure A.2 - US Mean Annual Runoff by State

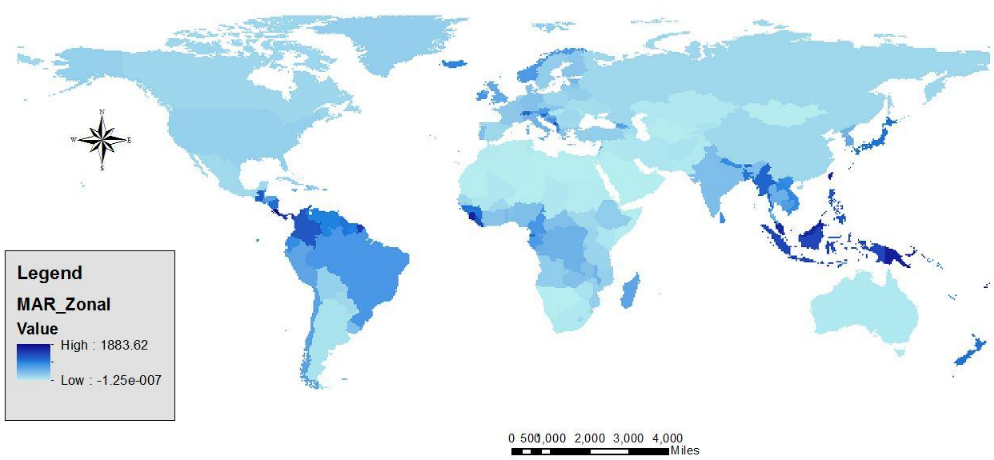

Figure A.3 - Global Mean Annual Runoff by Country

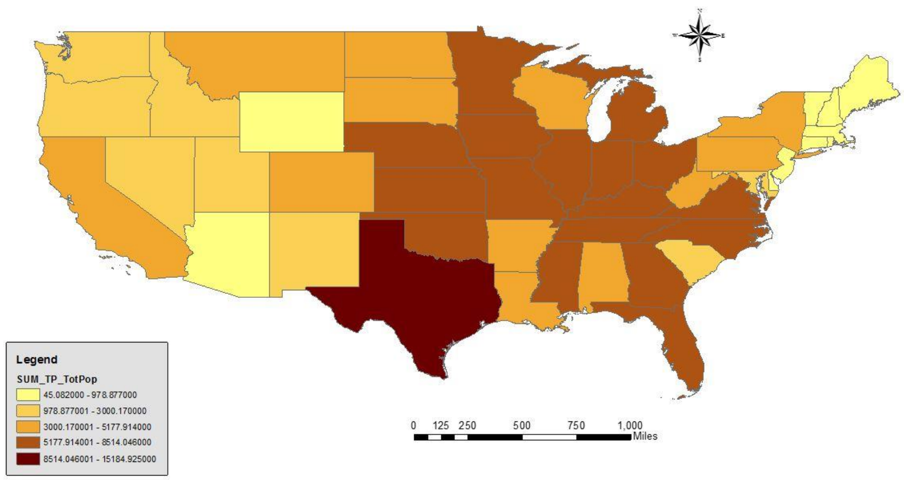

Figure A.4 - US Population (thousands)

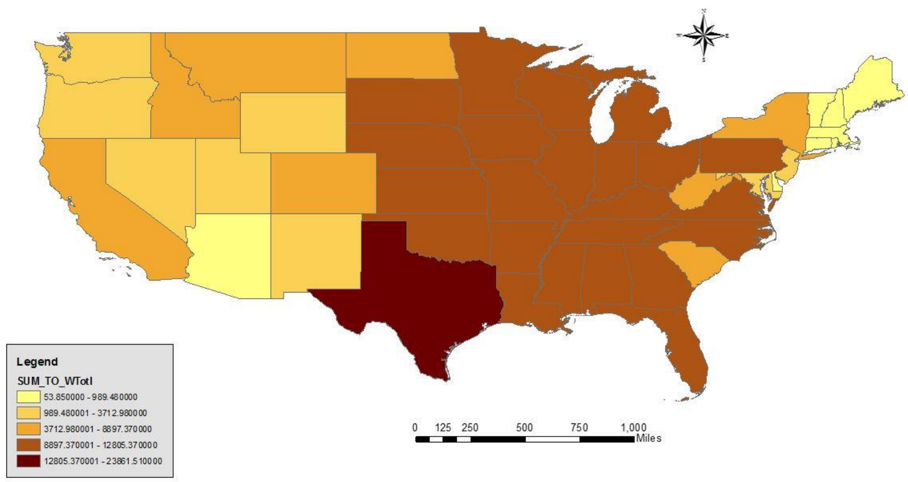

Figure A.5 - US Withdrawals (Mgal/day)

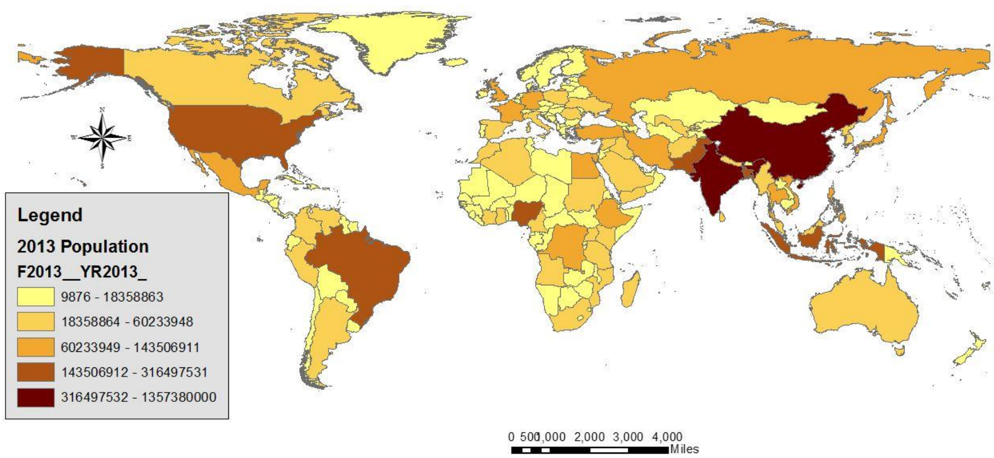

Figure A.6 - Global Population

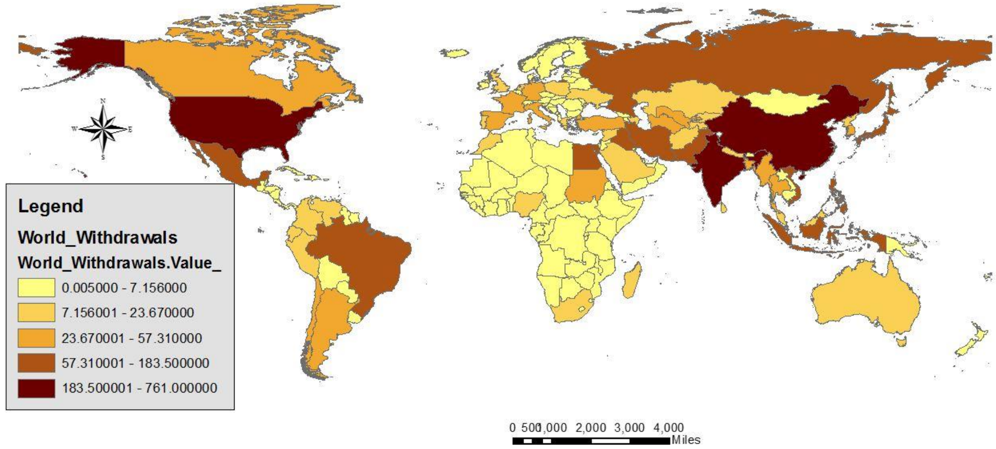

Figure A.7 - Global Withdrawals

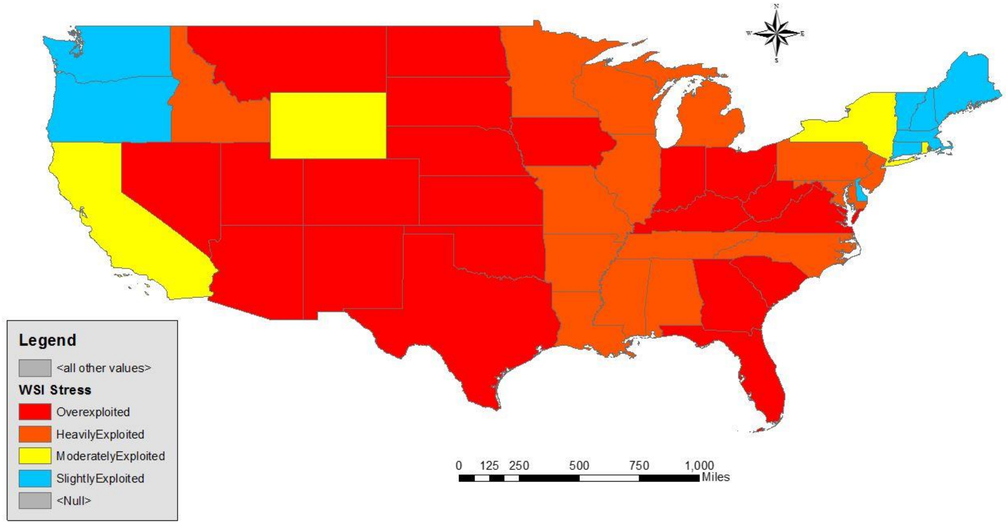

Figure A.8 – United States Water Stress Indicator, 0% EWR

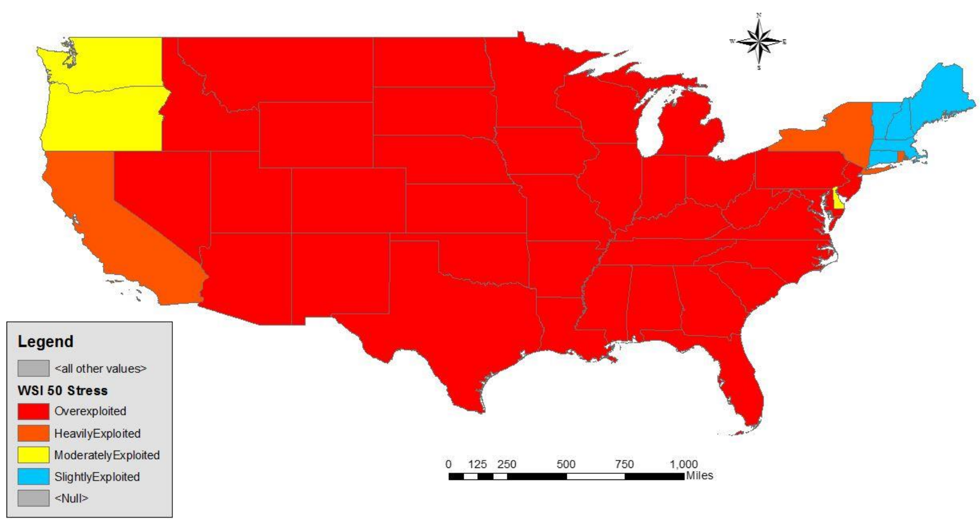

Figure A.9 – United States Water Stress Indicator, 50% EWR

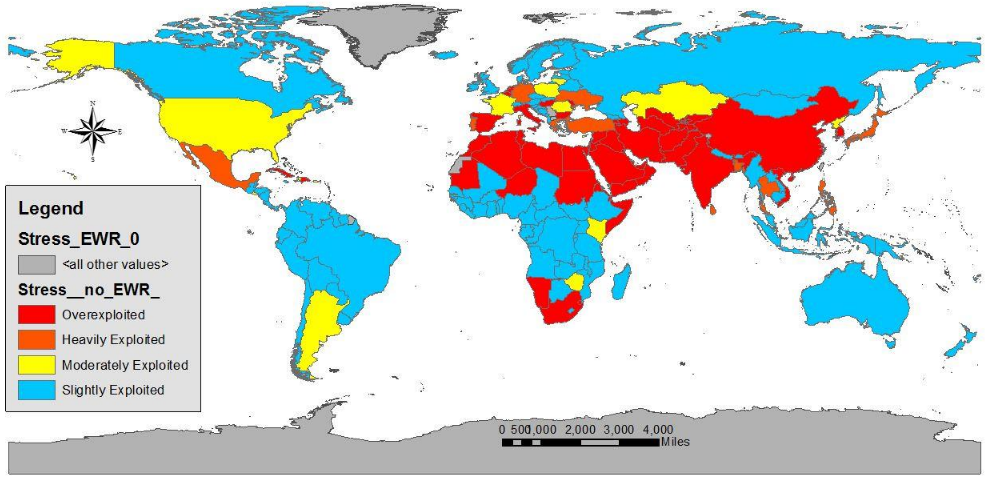

Figure A.10 - Global Water Stress Indicator, 0% EWR

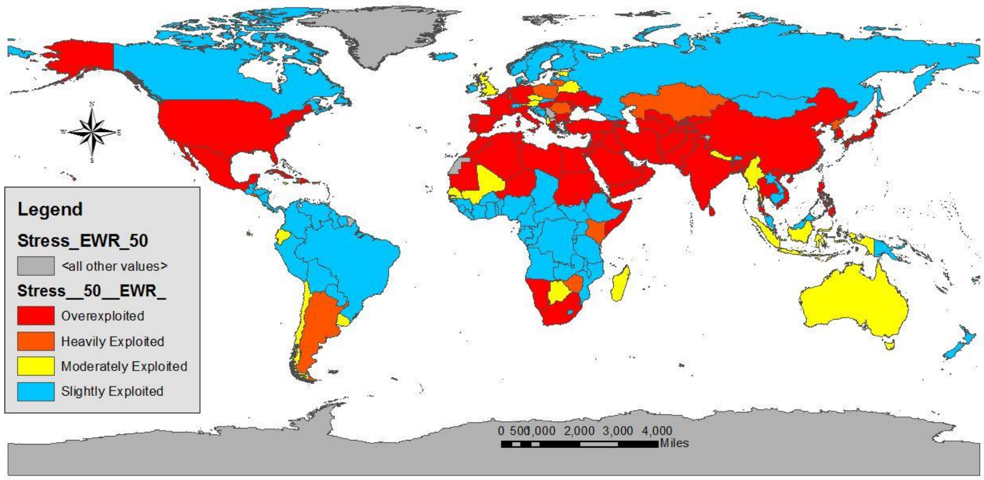

Figure A.11 - Global Water Stress Indicator, 50% EWR

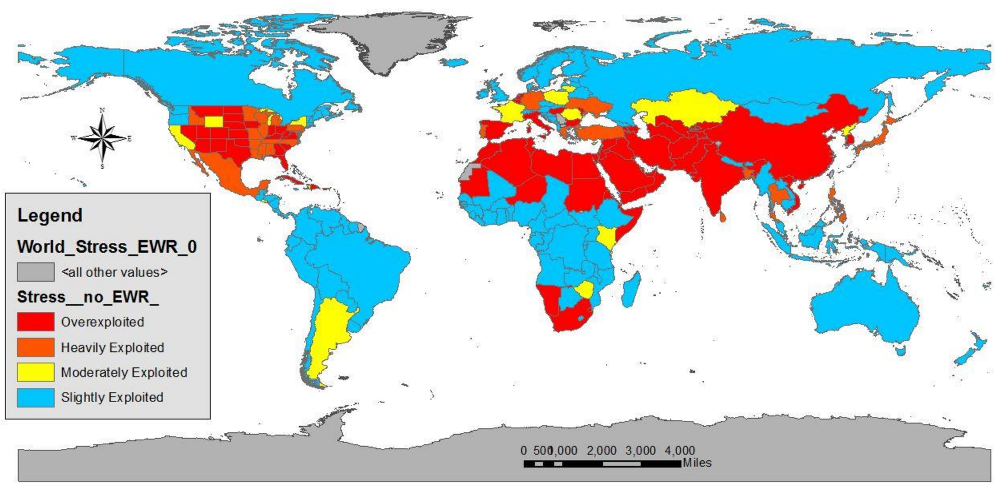

Figure A.12 – Combined US and Global Water Stress Indicator, 0% EWR

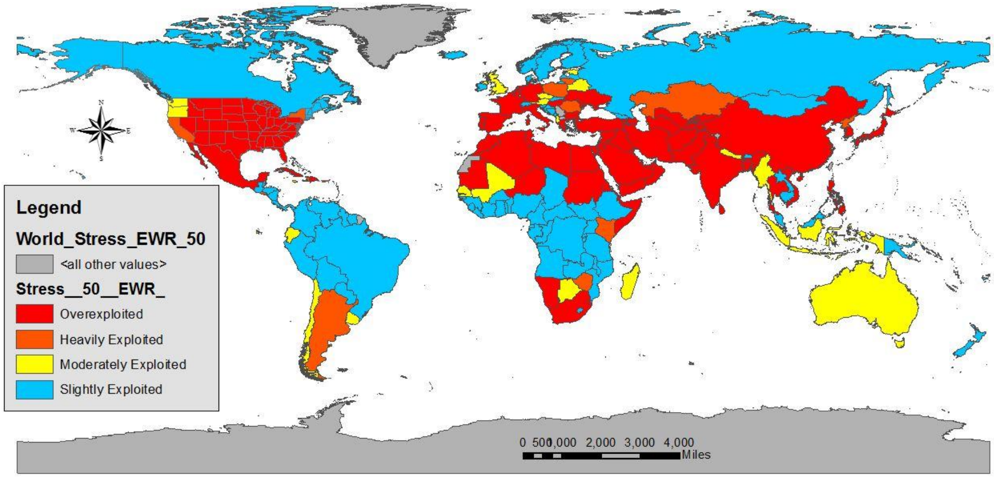

Figure A.13 – Combined US and Global Water Stress Indicator, 50% EWR