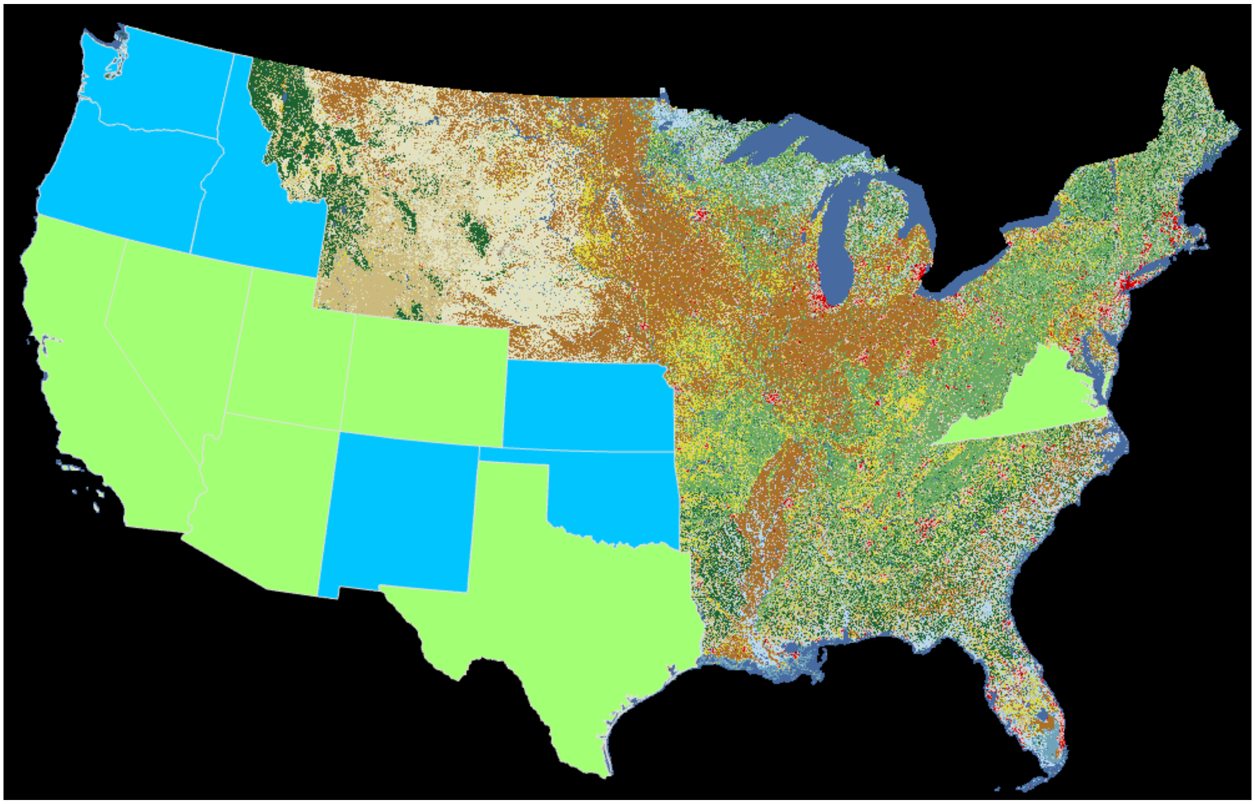
Predicting the Year that a State Will Reach Water Scarcity



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Abstract

The Falkenmark Indicator (FI) is an internationally utilized metric for determining the surface water available to a population. In this study, FI scores were calculated for 13 states in the U.S. for each year between 2011 and 2050 to determine the date at which each state reached the water scarcity threshold (1000m^3/year/capita). Mean annual runoff was treated as time and state dependent, and was decomposed into the state area, precipitation, and a runoff ratio calculated using the SCS Curve Number method. State-averaged curve numbers and precipitation were calculated and adjusted accounting for projected changes. State population was similarly extrapolated to the year 2050. The results of this study were that no state reached the water scarcity threshold before 2050.

Introduction

"Water will be to the 21st century what oil was to the 20th" is the slogan first coined by Shawn Tully of Fortune Magazine in 2000. Tully's article was certainly not the first to discuss to issue of clean water as a commodity, nor was it the last. Since then, many major magazines have run articles emphasizing the importance of, or deploring the lack of availability to, clean water to the global population (Scientific American, 2012; The Economist, 2008; Rolling Stone, 2011; The Globalist, 2014). Some have even gone as far as to claim that the cause of the next global conflict will feature water resources at the center of the strife (NPR, 2010).

While occasionally the issue is with too much water, like the flooding in South Carolina or Great Britain in recent years (The Globalist, 2014), all too often the more persistent and concerning issue is the *lack* of clean water to entire regions of the world. A critical author on this topic, perhaps ahead of her time, was Malin Falkenmark from the Stockholm International Water Institute. In her 1989 paper, Falkenmark remarked on the water catastrophe plaguing Africa and how it had gone unaddressed for too long. Since 1989, persistent droughts and epidemics have since brought significant attention to this issue, not just in Africa, but globally. An internationally recognized water stress index, the Falkenmark Indicator (FI), was established as a result of this publication. The Falkenmark Indicator is a ratio of the mean annual runoff (MEA) of a region to the population of that region, or, essentially, the population-normalized volume of surface water that flows in a region per year. Falkenmark posited that a threshold of 1000m^3/year/capita constituted a region with "water scarcity".

In the fall of 2015, Paul Ruess analyzed the whole world on the basis of two water stress indices: that which was proposed by Falkenmark, and another, the Smakhtin's Water Stress Indicator. What he found was that a frightening portion of the world, including many of the United States, already exploited their available water resources to an unsustainable degree. Ruess's analysis used low-resolution runoff data obtained from the University of New Hampshire and the Global Runoff Data Center, as well as census data from the World Bank. One obvious point from the host of media attention this issue has received, as well as more scientific analysis, like that conducted by Ruess, is that the global water condition is already poor, and that it is getting worse.

The intent of this term project was to expand on Ruess's analysis. A higher resolution method for determining MEA was used to compare results. Additionally, a time dimension was added to each of the factors in a decomposed FI so that water stress could be predicted on a yearly basis into the future. The ultimate objective was to determine the year in which each of the United States reaches water scarcity.

Methodology

FI Time-Dependence

The main purpose of this analysis was to determine the year in which each state's surface water resource will drop below 1000m^3/year/person. In order for this to be done, the FI must be able to be calculated for each year until the water scarcity threshold is reached. To reiterate, the FI is the ratio of mean annual runoff of a region to its population.

$$FI = \frac{MEA}{Population} \tag{1}$$

This means that both the MEA and the Population must be time dimensionalized in order for the FI to be a function of time.

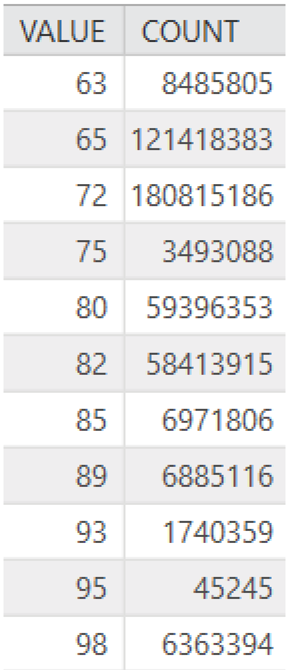
Time Dependence – Mean Annual Runoff

As discussed earlier, a high-resolution method was used for determining the MEA for each state. This method was the curve number (CN) method proposed by the U.S. Department of Agriculture's Soil Conservation Service. The curve number method works by assigning a dimensionless value to the land receiving precipitation, between 0 and 100, that is a measure of how much direct runoff there is off of a certain surface. Impermeable surfaces, like roads, typically have a CN of 98-100, while unadulterated forests might have a curve number as low as 35. Because of this trend, greater curve numbers typically indicate higher levels of urbanization. For the sake of this analysis, it is interesting to note that more urbanization leads to more runoff and a higher Falkenmark Indicator score, but this effect is often overcompensated by the direct increase in population that forced the urbanization to occur. Curve number values can also vary based on antecedent moisture conditions and soil types, but these corrections were ignored in this analysis.

For each state in the analysis, curve number values were calculated using the National Land Cover Data (NLCD) set. The NLCD contains 30meter land cover data that was trimmed to the boundaries of each state using the ArcGIS "extract by mask" tool. Then, using the "reclassify" tool, the "value" that is given in the NLCD raster (which corresponds to the index of the land type that exists in that pixel) was converted to the curve number that best reflects that land usage. The curve number values were obtained from Water Resources Engineering: Second Edition by Larry Mays.

Figure 1. NLCD 2001 “extracted by mask” to California polygon

Table 1. California NLCD 2001 Index Numbers “reclassified” to curve numbers



VALUE	COUNT
63	8485805
65	121418383
72	180815186
75	3493088
80	59396353
82	58413915
85	6971806
89	6885116
93	1740359
95	45245
98	6363394

Figure 1 and Table 1, taken from the 2001 NLCD trimmed to California, show that each curve number (under the reclassified “value” column) has a pixel count related to it. The average curve number for the state of California in 2001 could then be calculated using a weighted average. Precisely this method was then used using the 2006 and 2011 NLCD dataset to get a sense of how the curve number of each state was evolving over time.

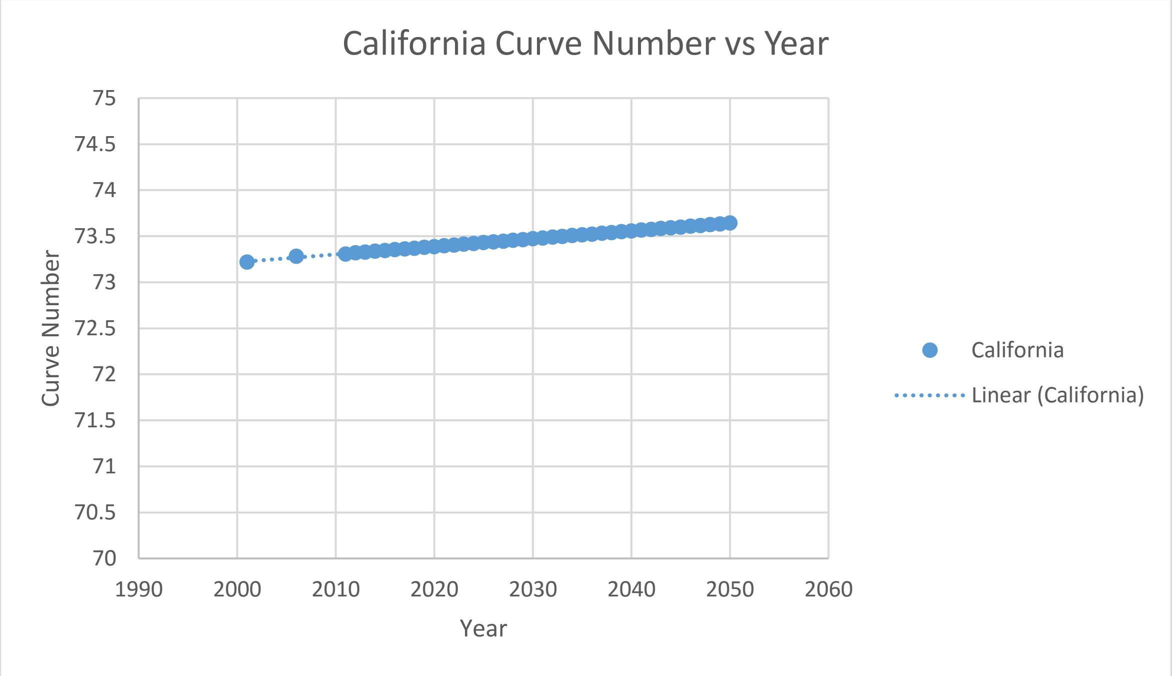


Figure 2. Curve number projections for California from 2001-2050

A best-fit linear regression was used to extrapolate and predict the average curve numbers of a state until the year 2050 assuming the growth rate of the state from 2001-2011 remained constant. It is worth noting here that the starting date being considered was 2011, as constrained by the NLCD sets available. The end date of 2050 was constrained by the population variable and will be discussed later.

These yearly curve numbers were then converted into a "potential maximum retention" factor (S) with units of length

$$S(t) = \frac{1000}{CN(t)} - 10 \tag{2}$$

which was, in turn, used to calculate the surface runoff (P_e) from a certain depth of precipitation (P).

$$P_e = \frac{(P-0.2*S(t))^2}{P+0.8*S(t)} \tag{3}$$

However, in order for the runoff to be calculated on a yearly basis, the potential changes in annual precipitation must also be considered. The United Nations-sanctioned International Panel on Climate Change (IPCC) submits reports based on the most current scientific research surrounding the immense field of climate change science. Their most recent submission, the Fifth Assessment Report (AR5), in 2013 included regionally specific changes to precipitation considering an incremental chance in the earth's climate. Just this summer, the Paris agreement was an international covenant to limit the earth's, now inevitable, warming to 2°C above pre-industrial averages.

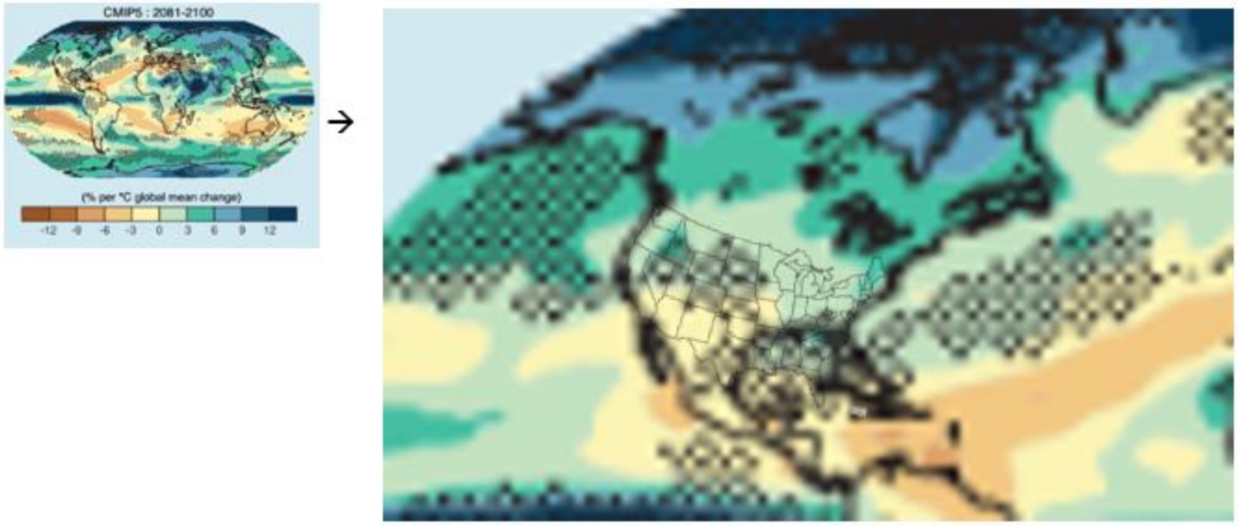


Figure 3. Image from IPCC's AR5 (2013) expanded to accent North America with U.S. map overlay

Figure 3 was taken from the IPCC's AR5 and blown up to more clearly show North America. A hollow image of the continental United States was overlain to show patterns of expected increased and decreased precipitation. It is worth noting here that, while much of the subtropical world will likely suffer less precipitation and prolonged drought, that is not the dominant trend predicted for the United States. Instead, the United States mainly falls within the mild precipitation increase zone characteristic of mid-latitude regions, although some drying of the Southwest and Central states may occur.

These rough percentage increases suggested by the AR5 were adopted as a temporal correction factor for data from the NOAA's National Climatic Data Center that consisted of statewide averages for the years 1971-2000. This yielded the projected annual precipitation for each state in 2100, allowing for the encompassed year's data to be interpolated. Of these anticipated precipitation data from 2000-2100, only the data that fell within 2011-2050 was used in this analysis.

The P variable in Eq. 3 could then be considered another time-dependent function, the annual average precipitation for the state. The resulting runoff computed each year using Eq.3 was multiplied by the area of the state to yield the annual runoff for that state.

$$MEA(t) = Area * P_e(t) = Area * \frac{(P(t) - 0.2 * S(t))^2}{P(t) + 0.8 * S(t)} \tag{4}$$

Time Dependence - Population

The denominator of the Falkenmark Indicator is the population of the region under scrutiny. Population is constantly changing and closely monitored in the U.S. Every ten years, the U.S. Census Bureau conducts a nation-wide census. The original purpose is described in the Constitution, to determine how congressional representatives should be allotted, but this spatially accurate population data is valuable for many other purposes as well.

For this analysis, the 2010 Census was consulted. One component of the 2010 Census report was a 5-year projection of population for each state. These predictions were trusted over the alternative of a regression built from decadal census data, and each states US Census Bureau's predicted population was extrapolated out to 2050. Three basic trends were represented in the US Census population predictions: some states' population growth tended to be logarithmic, some states' growth could be predicted more closely with a linear trendline, and some states' growth was exponential.

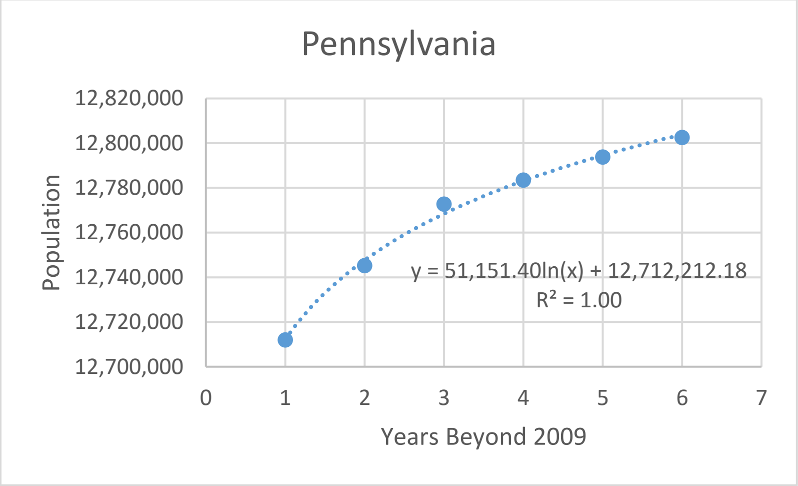


Figure 4. Logarithmic growth example: Pennsylvania.

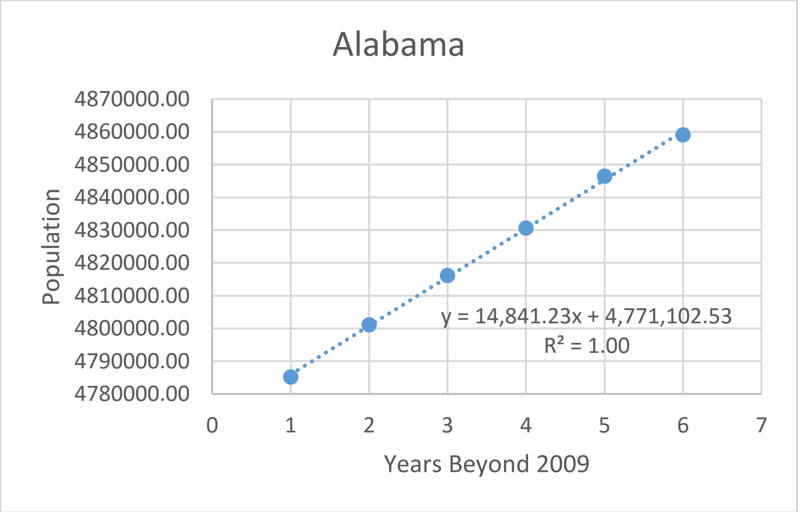


Figure 5. Linear growth example: Alabama.

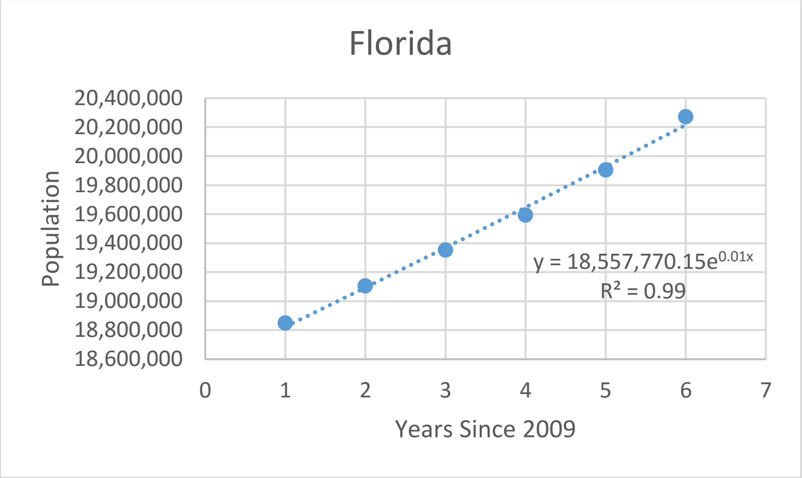


Figure 6. Exponential growth example: Florida.

Each of the 50 states fell into one of the three categories outlined by Figures 4-6. The best-fit regression defined the equation that was used to extrapolate the population of each state out to 2050. 2050 was chosen as the analysis stop date because it represented a far enough time in the future for meaningful results (~35 years), but cut off the extrapolations before some of the exponential population models approached infeasibility (for example, California's population reached 100 million before 2100 according to its best-fit regression).

Results

The three time-dependent functions of state-averaged curve number, annual precipitation, and population meant that the decomposed Falkenmark Indicator could be reconstructed as a water stress index dependent on the year and the state for which it was being computed.

$$FI(state, year) = \frac{MAR(state,year)}{Population(state,year)} = \frac{Area(state) * \frac{(P(state,year) - 0.2 * S(state,year))^2}{P(state,year) + 0.8 * S(state,year)}}{Population(state,year)} \quad (5)$$

FI was computed initially for 12 states in the western U.S. considered to be the likely candidates for water scarcity on the basis of annual precipitation: Washington, Oregon, Idaho, California, Nevada, Arizona, Utah, Colorado, New Mexico, Kansas, Oklahoma, and Texas. Virginia was also included in the analysis.

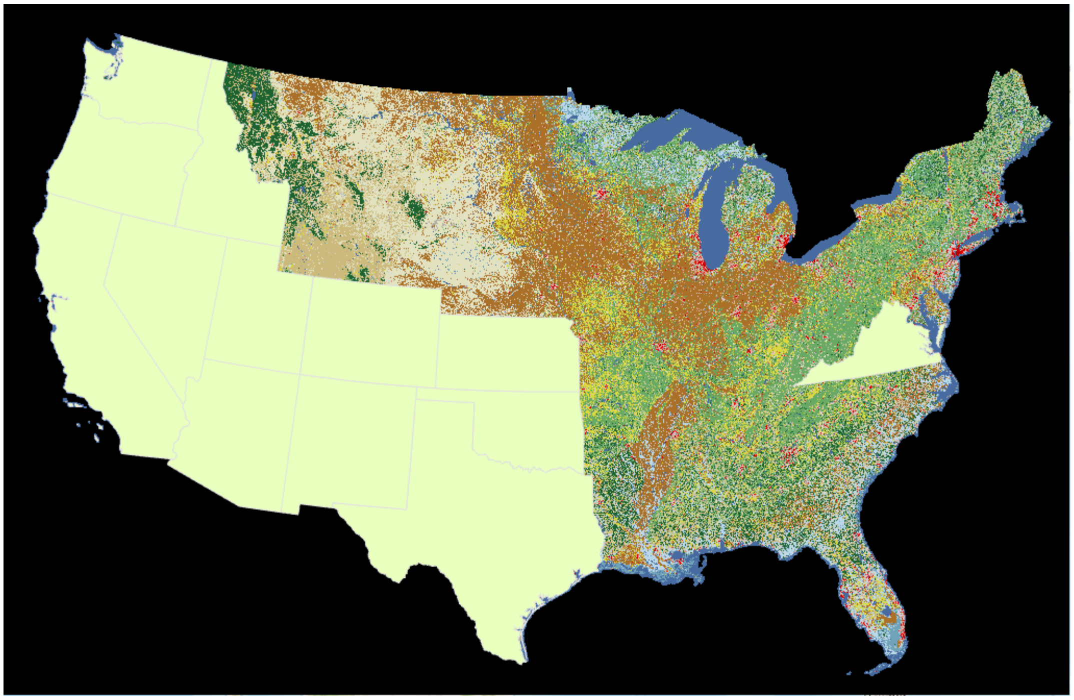


Figure 7. Map of states included in primary analysis atop 2011 NLCD raster.

The FI scores for each of these states for 2011-2050 were then plotted against the water scarcity threshold of 1000m^3/year/capita.

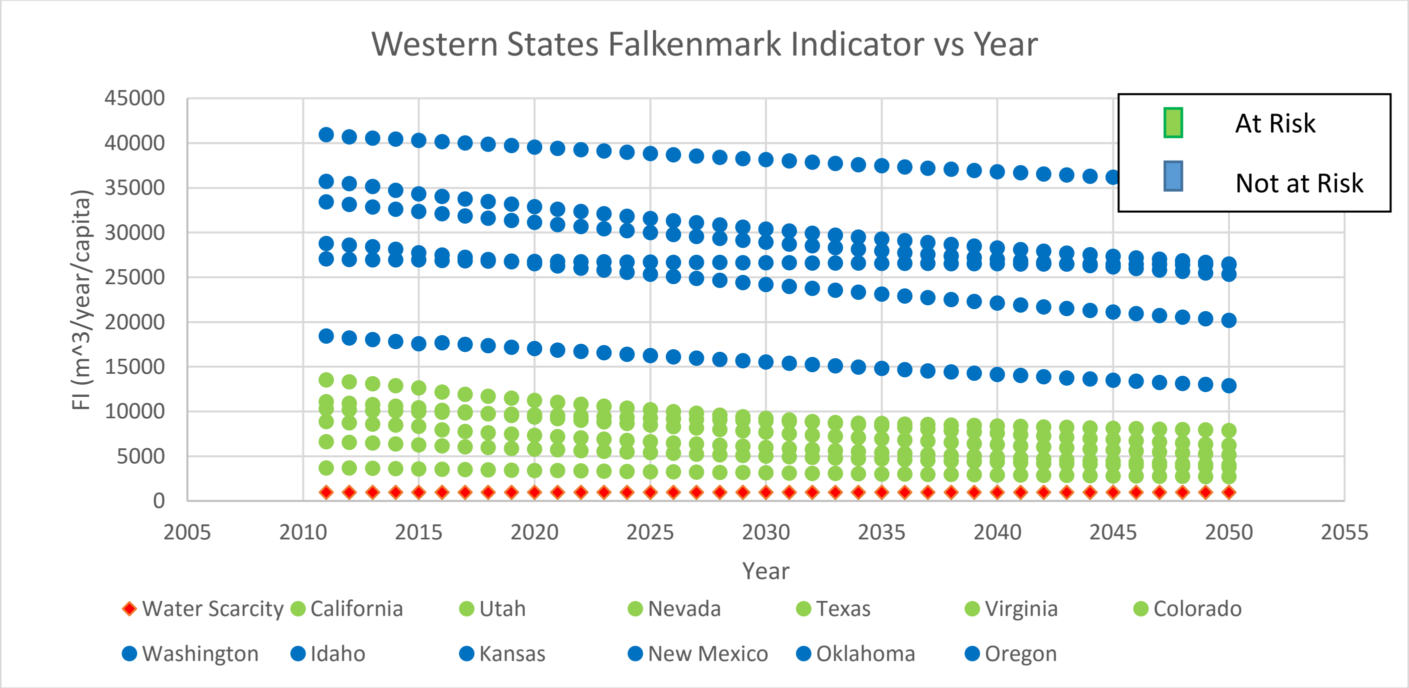


Figure 8. FI scores for 12 states analyzed from 2011-2050 [Arizona (at risk) was excluded from plot for formatting reasons]. Water scarcity threshold in red.

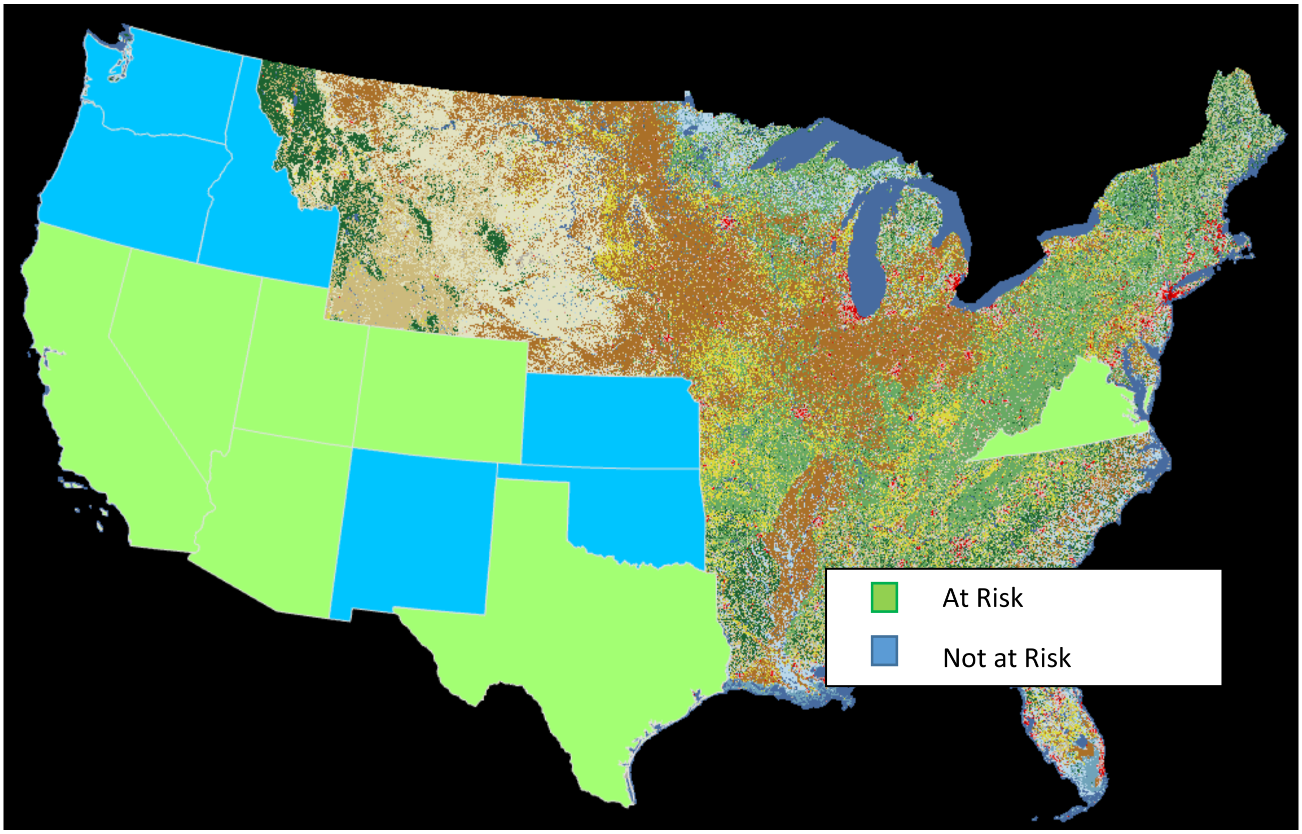


Figure 9. Map of 13 states analyzed colored in accordance with Figure 8 legend.

Discussion

The primary function of this discussion section will be to enumerate conclusions that can be drawn from Figures 8 and 9. The most interesting takeaway from Figures 8 and 9 is that none of the states considered most likely to obtain a water scarcity status by 2050 were actually predicted to do so. The state that came the closest was California, who's predicted FI score in 2050 was roughly 2700m^3/year/capita, or 2.7x the Falkenmark-diagnosed water scarcity threshold. The legend for Figures 8 and 9 was color-coded arbitrarily as none of that states could be labelled as attaining water scarcity status. States that were within an *order of magnitude* of the water scarcity threshold by 2050 were considered "at risk" and colored green. Those that were more than an order of magnitude above the threshold were considered "not at risk" and colored blue. The 12 western cities analyzed constituted the states with the lowest average annual precipitation, as well as the greatest likelihood of precipitation decrease (as opposed to the precipitation increase that might be seen elsewhere in the country). From this assumption and the results shown in Figures 8 and 9 it can be reasonably concluded that the water scarcity threshold is not crossed by any state in the country within this time frame. This is highly disparate from the conclusions drawn by Paul Ruess in his 2015 analysis of the United States' water scarcity.

Figure 1 - United States Falkenmark Stress Index

Figure 10. Taken from Ruess (2015). Shows current FI scores for states according to his analysis.

Figure 10, taken directly from the term paper submitted by Paul Ruess last year, shows that several states reached not only water scarcity, but absolute scarcity. Absolute scarcity was defined by Falkenmark was 500m^3/year/capita. It is clear that, in relative terms, Ruess's figure paints a more dire picture of America's water scarcity situation, while this analysis is more optimistic.

There are several potential reasons behind this discrepancy in conclusions between 2015 and 2016 analyses. Obvious among them is the different sources for mean annual runoff between the two studies. Ruess's methodology called directly for mean annual runoff data that was available in low-resolution form from the University of New Hampshire and the Global Runoff Data Center. This was appropriate for Ruess's purposes of computing the FI scores of entire nations. The analysis described in this paper required a temporally flexible data source, and so the SCS curve number method was used. While in theory the curve number offers a higher resolution option for computing runoff, mostly owing to its dependence on the high-resolution and precise NLCD, it certainly has its drawbacks. The curve number method does not handle precipitation in the form of snowfall very well, so states that receive a significant portion of their precipitation in the frozen form may have been misrepresented. Additionally, the curve numbers assigned to each land type can vary considerably depending on the antecedent moisture condition and the soil type underneath that land type. For example, the curve numbers corresponding to an open field (a fair portion of the western United States) can vary from 35 to 85 depending on if the soil is closer in consistency to sand or to clay. Because the potential maximum retention, "S", value used in the calculation of runoff is inversely proportional to curve number variations in the curve number affect the mean annual runoff such that underestimating the curve number affects the MAR more than overestimating the curve number. The purpose of admitting these limitations of the curve number method is to postulate that the difference between Ruess's conclusions and the conclusions of this analysis could potentially be accredited to inaccurate curve number assignment.

However, a larger issue related to the SCS curve number may have truly derailed this analysis. Equation 3, which described the amount of runoff that would occur given a certain precipitation and land cover, is only valid over a single runoff event. In this analysis, it was used to determine the runoff from a year's worth of rain, effectively reducing the annual precipitation to one massive rain event. The effect this had was dramatically overestimating the amount of runoff that would occur in a given year for a given state. This overestimation could have been identified if a checking exercise had been conducted. For example, in Exercise 2 the San Marcos basin was delineated using the NHDPlus flowlines, which contained data for the mean annual flow through the basin.

Table 2. Information from NHDPlus flowlines from Exercise 2

SiteName	DASqMile	MAFlow	MAVol	MADepth
Blanco Rv at Wimberley, Tx	355	142	4481179200	5.433471
Blanco Rv nr Kyle, Tx	412	165	5207004000	5.440065
Plum Ck at Lockhart, Tx	112	49	1546322400	5.942859
Plum Ck nr Luling, Tx	309	114	3597566400	5.011454
San Marcos Rv at Luling, Tx	838	408	1.2876E+10	6.613533
San Marcos Rv at San Marcos, Tx	48.9	176	5554137600	48.89013

Table 2 shows that the mean annual flow depth through this typical basin in Texas is on the order of 5-6 inches of the 35+ inches that fall in Texas per year. This suggests that the runoff calculated for Texas was 5-6 times higher than what the NHDPlus data indicates actually flows through a typical Texas basin. This overestimation could, and probably does, account for the majority of the discrepancy between Ruess's conclusions and the conclusions drawn by this analysis.

It is possible that the NHDPlus data could have been used to determine an acceptable value for mean annual runoff for each of the states analyzed, but simply using the NHDPlus would not have allowed for the time dependence that was a critical component of this analysis. It is also unclear whether coastal watersheds, or other National Hydrography Dataset delineated boundaries that have more than one exit point, would offer the same mean annual flow data that is available for landlocked, one exit point systems.

Future Work Recommendations

The question attempted to be answered by Ruess 2015 as well as this study remains a pertinent and important one. It is clear that it is critical to understand how the water resources of a region exist currently, as well as how they might evolve in the future. The dominating factors in this analysis were the population predictions and the curve number assignments. Population growth is highly political and subject to rapid swings, so there is not a clear method for modelling population more accurately decades into the future. The curve number method used in this analysis, however, stands for improvement.

A possibility for a future study would be to join the national land cover data with soil survey data that would potentially add a factor of 2 precision to the average curve number calculation. This soil survey data is available through another U.S. Department of Agriculture subsidiary, the National Resource Conservation Service (NRCS). A potential drawback of doing this correction would be the lengthy amount of computing time in ArcGIS for commands concerning the entire country. This computing time consideration is the primary reason that only 13 states were actually analyzed in this study.

Another potential area for revisiting this study would be in the low spatial resolution of the rainfall. ESRI offers a much higher resolution data set for precipitation than does NOAA. Using ESRI's data preloaded into ArcGIS, the local precipitation and runoff could be computed, with the state-average being determined at the runoff stage of the calculation, rather than the permeability stage as in this analysis.

One problem that must certainly be addressed in future work is the erroneous assumption that the annual precipitation can be reasonably modeled as one storm event. As is shown in the discussion section, this yields runoffs that are nearly an order of magnitude too high. The observed runoff and flow data from the University of New Hampshire and the National Hydrography Dataset, while accurate and potentially higher resolution than the curve number method, fails to meet the condition of being adjustable and predictable over time. Because of the significant disadvantages of each of the methods mentioned thus far to try to satisfy the objective of this study, a new method for modeling future mean annual runoff would have to be proposed.

The ambitious nature of this study, attempting to predict and evaluate a complex metric across a time scale of 40 years, left it open to simplifying and error-introducing assumptions. Nevertheless, it is important for these types of water availability questions to receive significant attention. Human lives and national security depend on it.

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