CLIMATE DRIVEN HYDROLOGIC NONSTATIONARITY PATTERNS ACROSS THE CONTIGUOUS UNITED STATES

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ABSTRACT

We calculated metrics of climate change, land use-land cover change, and hydrologic nonstationarity in 671 catchments across the Contiguous United States (CONUS) that are known not to have relatively little urbanization and anthropogenic land cover. Climate change is correlated with hydrologic nonstationarity in these basins. Land use-land cover change has no correlation with hydrologic nonstationarity in these basins. We present kriging maps over CONUS showing climate change, land use-land cover change, and hydrologic nonstationarity.

Introduction

Hydrologic nonstationarity has a few distinct, but not necessarily contradicting, meanings. In general, nonstationarity refers to a condition in which the statistical representation of a system is not constant. As an example, although the flow of a river fluctuates with the seasons and individual precipitation events, average annual flows are often used as a representative hydrologic characteristic. If the average annual flow has some trend (not just year to year fluctuations about a constant value), then it could be described as non stationary. Anthropogenic land use/land cover changes can also cause non stationary conditions. For example, if a watershed has increasing urbanization that increases the impervious surfaces, this can cause higher and quicker peak flows. Changing flow responses to similar precipitation events could be described as hydrologic non stationarity.

Hydrologic nonstationarity has been identified as a serious limitation of hydrologic modeling, specifically for the purposes of water resources management (Milly et al. 2008). Nonstationarity refers to the assumption that watershed properties that control water flow are considered to be time invariant (Sadegh et al. 2014, Lui et al. 2020). Climatological conditions have been identified as drivers of nonstationarity (Deb et al. 2019a). Surface water - groundwater interactions have also been linked as highly influential to non-stationary hydrologic responses (Deb et al. 2019b).

A study of the Mann-Kendall statistic on flow only across CONUS was done by Tamaddun et al. 2016. We expand on this study by including precipitation, annual land surface conditions and land cover.

We attempted to distinguish between climatological and land use/land cover (LULC) drivers of hydrologic nonstationarity in CONUS. We first revised the assumption that hydrologic nonstationarity exists across CONUS, and compared our analysis to Tamaddun et al. 2016. We then compared the relationship between changes in a hydrologic rainfall - runoff characteristic with changes in yearly climatological indexes and changing land cover.

We address the following research question: Can we distinguish between climate driven and land use / land cover driven hydrologic nonstationarity?

H0: Hydrologic nonstationarity is identifiable by geographic location

H1: Hydrologic nonstationarity is correlated with a changing climate

H2: Hydrologic nonstationarity is correlated with a changing land surface

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Methods and data

We analyze hydrologic nonstationarity at the CAMELS basins. Nonstationarity is calculated using a Mann-Kendall statistic (Mann 1945, Kendall 1975) for monotonic change during the years from 1980 to 2014. The Mann-Kendall statistic is a common test for hydrologic nonstationarity (Lui et al. 2019). The test was done for the ratio of annual volumetric runoff and annual volumetric precipitation across the basins. These data came from the USGS stream gauge network, and precipitation was from the NLDAS reanalysis from 1980 - 2014.

We analyze the monotonic change of yearly averaged climatological surface variables from the ERA5-Land monthly averaged - ECMWF climate reanalysis. We summarize changes in the land cover from forest (Sexton et al. 2016) and impervious surface (NLCD 3026).

Data product	Source	Spatial resolution	Temporal resolution	Temporal range
ERA5-Land monthly averaged - ECMWF climate reanalysis	ECMWF	0.1 degrees	Monthly	1981 - present
Global Forest Cover Change (GFCC) Tree Cover Multi-Year	GFCC	30 m	Semi annual	2000 - 2015
NLCD: USGS National Land Cover Database	NLCD	30 m	Semi-annual	1992 - 2015

Table 1: Data sources and their characteristics

We aggregated and extracted data for each of the 671 CAMELS basins (shown in Figure **?**) using Google Earth Engine (GEE). A feature collection containing polygons of the CAMELS basins was imported into Google Earth Engine. A function was developed to aggregate, reduce and clip raster data from image collections for any given polygon, then export those data to CSV files. That function was then mapped over the full CAMELS basin feature collection.

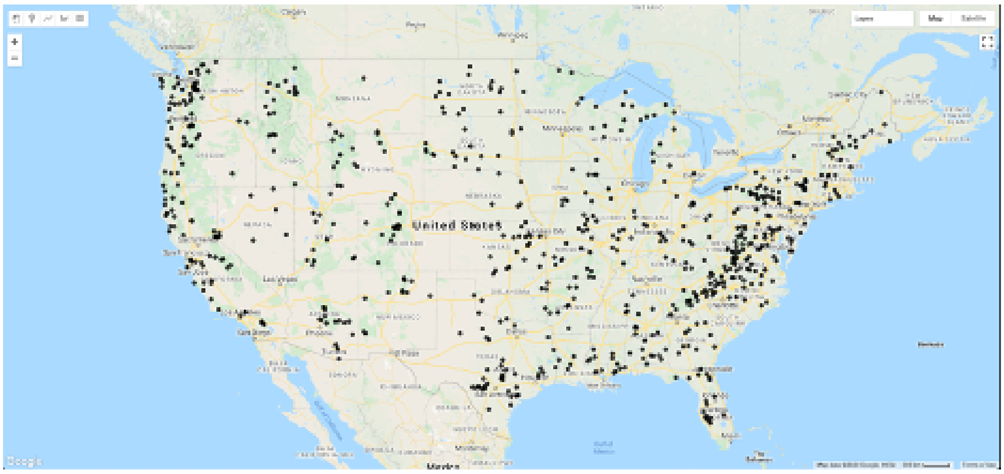

Figure 1: Locations of USGS stream gauges on the 671 basins used in this study.

Process workflow:

1. Google Earth Engine steps
    (a) Upload camels basins as feature collection to GEE.
    (b) Load in GEE image collection for target variable.
    (c) Clip image collection to basin shape.
    (d) Filter image collection by years.
    (e) Reduce images down to one image.
    (f) Reduce image down to representative statistic.
    (g) Export data.

2. Load data into python.
3. Calculate metrics for change.
   (a) Climate based on Mann Kendall.
   (b) Land cover based on basin area normalized mean annual change.
4. Set up regression model.
5. Let it rip.
6. Load basin change values back into GEE.
7. Interpolate across CONUS and plot.

To test our hypotheses we used random forest regression to correlate geographic location, changes in climate and land cover to changes in hydrologic conditions. We reject/fail to reject our hypotheses by subjectively looking at a scatter plot of these regressions.

H0: Hydrologic nonstationarity is a function of latitude and longitude
H1: Hydrologic nonstationarity is a function of Climate
H2: Hydrologic nonstationarity is a function of impervious land cover change

Results

This section presents the key findings of our study, illustrated through a series of figures. Each figure provides visual evidence supporting our analysis of hydrologic nonstationarity across the Continental United States.

Figure 2 depicts the spatial distribution of hydrologic nonstationarity across the Continental United States, based on the annual runoff ratio. This map uses Kriging to interpolate between the catchments. There i a clear negative change in the Pacific Northwest, Northern Plains, Northeast and Southern Florida. There is a noticible decrease in runoff ratio in the Great Lakes area and throughout the South West and Southeast.

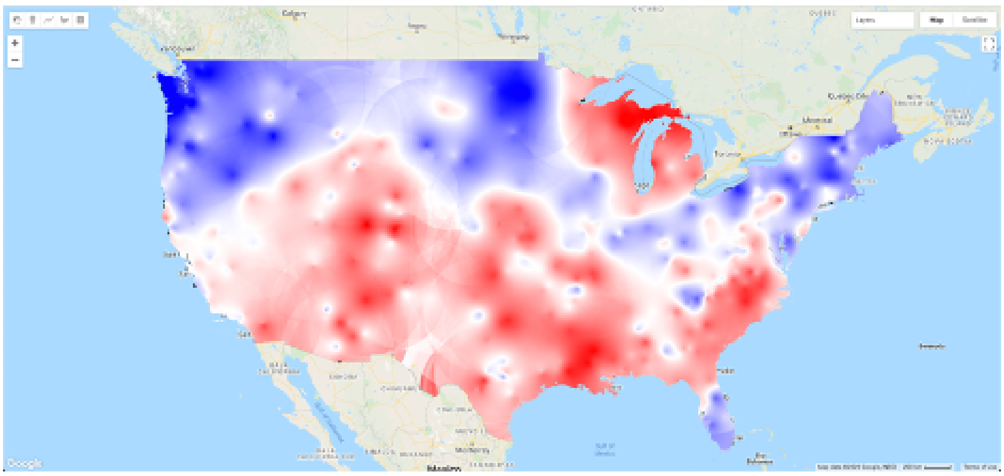

Figure 2: Hydrologic nonstationarity in terms of annual runoff ratio (Q / P).

0.1 Climate and land use changes across CONUS

Figure 3 illustrates changes in skin temperature across the United States from 1992 to 2015. I did not include figures for Soil Temperature, Transportation and Evaporation for the sake of brevity. The maps look somewhat similar anyways.

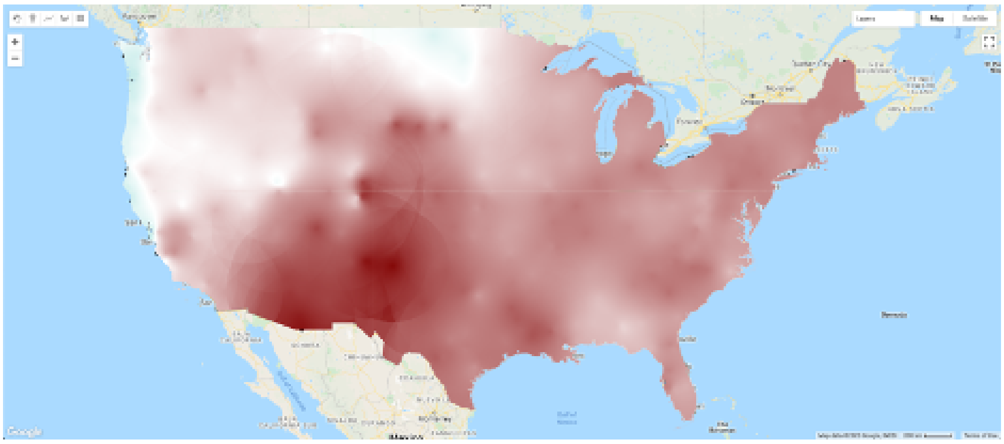

Figure 3: Change in skin temperature.

Figure 4 illustrates changes in impervious surfaces across the Continental United States from 1992 to 2015. The map highlights areas with significant changes, excluding urban regions as the basins studied are predominantly undeveloped. The map shows, however, that even outside of urban areas, there still is a noticeable increase in impervious surface cover near major metropolitan areas.

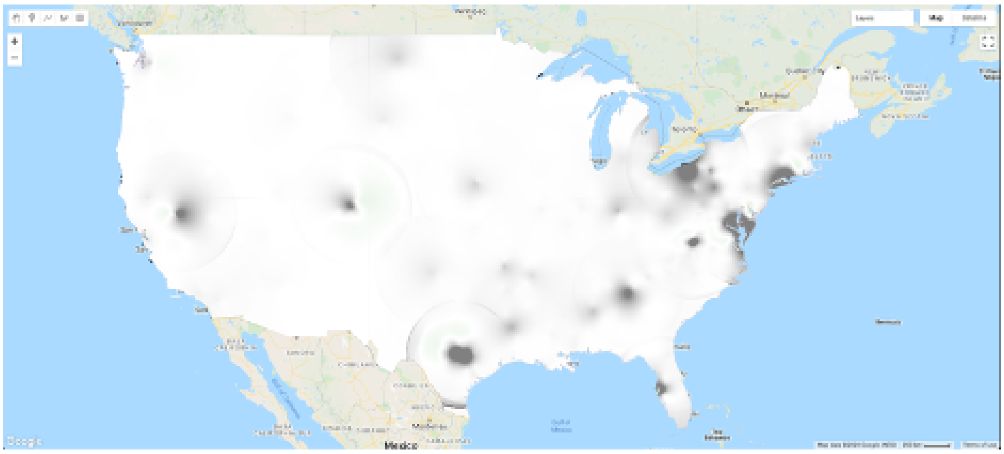

Figure 4: Change in impervious surfaces from 1992 to 2015. More grey indicating more change in impervious surface.

Figure 5 shows the changes in forest cover across the Continental United States. The map provides a unique perspective on forest cover dynamics. This map is actually kind of silly, because instead of interpolating at the samples, I could have just done the calculations on each pixel in the image. It would have been relatively easy to do, but it wouldn't have been useful for my correlations with average basin hydrologic characteristics.

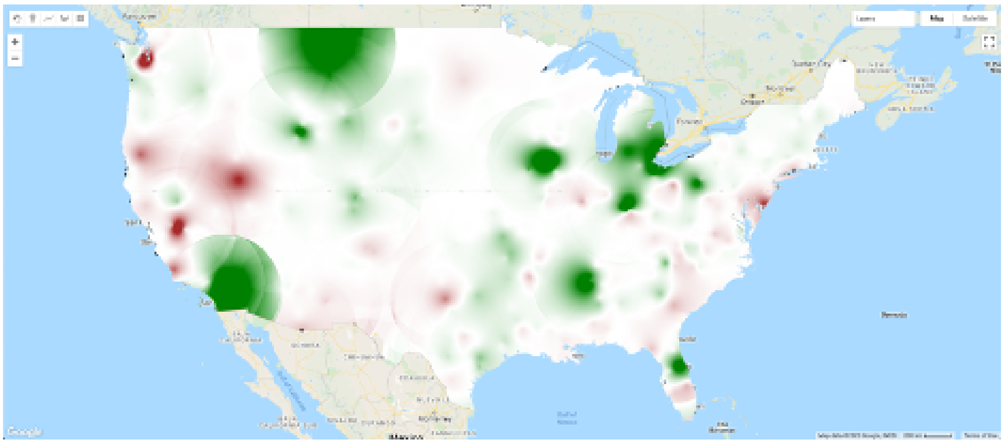

Figure 5: Forest cover changes interpolated across CONUS.

0.2 Correlations between changing land cover/climate and runoff ratio

Figure 6 presents the correlation between geographic location and hydrologic nonstationarity. The analysis indicates that geographic factors are not significant predictors of hydrologic nonstationarity, as evidenced by the Gini importance factors.

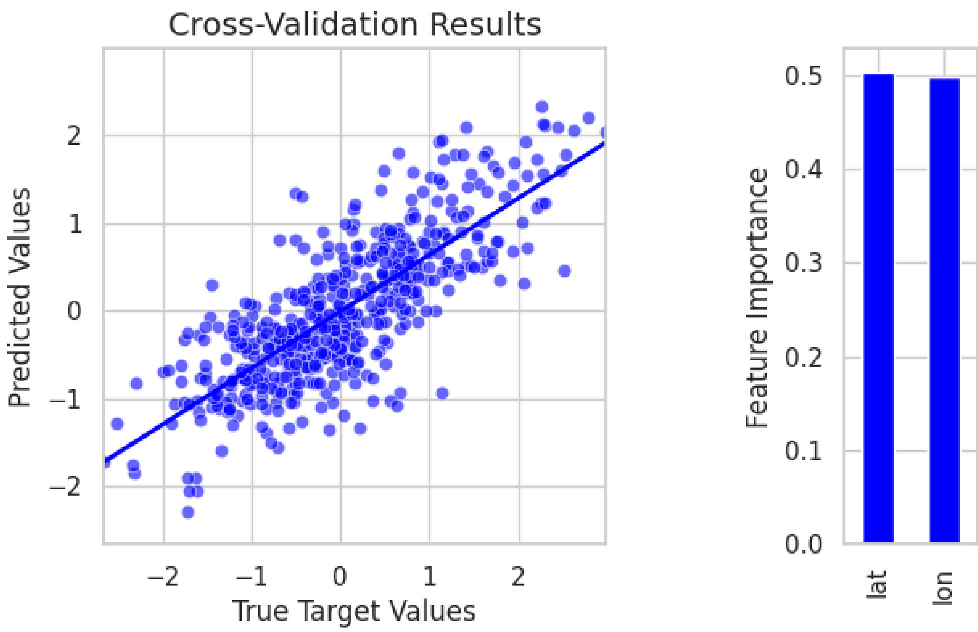

Figure 6: Correlation between geographic location and hydrologic nonstationarity. We fail to reject hypothesis 0. Also shown is the Gini importance factor showing that latitude and longitude are equally weighted when predicting hydrologic nonstationarity.

Figure 7 explores the relationship between annual climate variables and hydrologic nonstationarity. The findings suggest a strong correlation between these variables, with evaporation being the most influential factor.

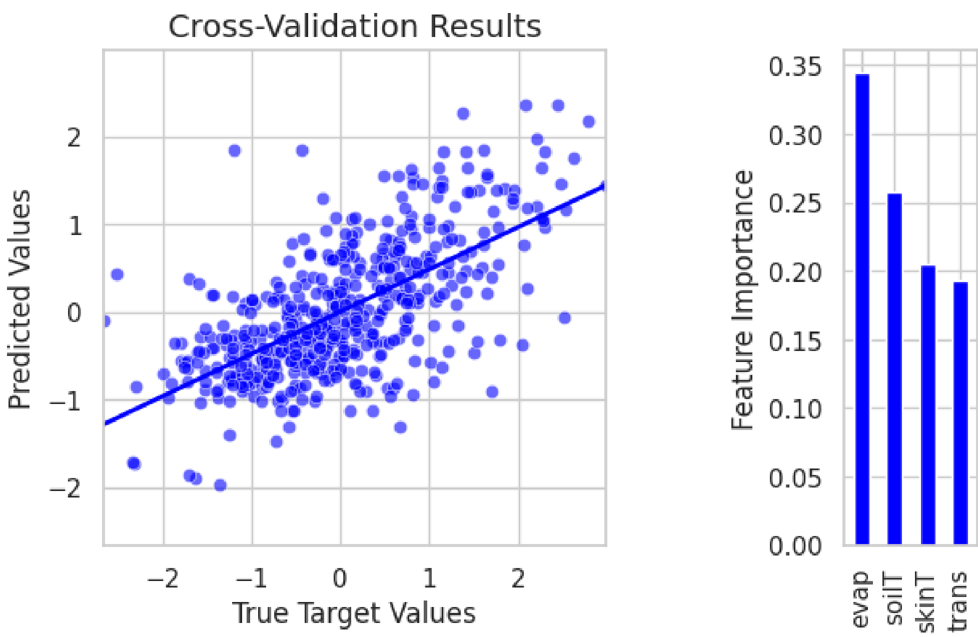

Figure 7: Correlation between annual climate variables and hydrologic nonstationarity. Also shown is the Gini importance factor showing that evaporation is the most weighted and transpiration is least weighted.

Figure 8 addresses the correlation between land cover changes and hydrologic nonstationarity. The skatter plot and nearly zero slope of the best fit line contradict the hypothesis that land cover change significantly influences hydrologic nonstationarity.

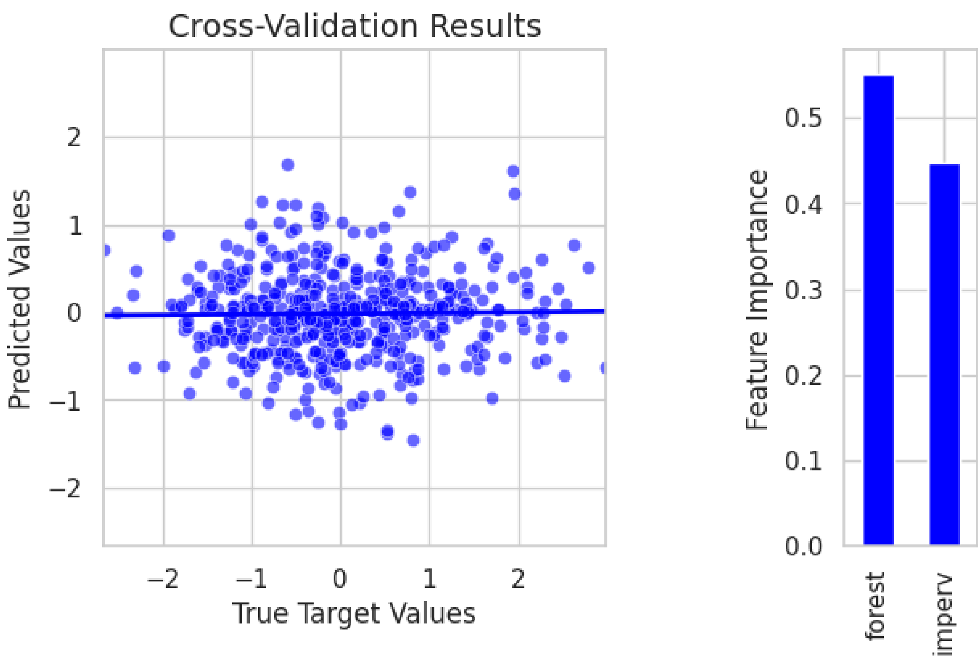

Figure 8: Lack of correlation between hydrologic nonstationarity and changes in land cover (impervious and forest). The weights on the right are meaningless, since there is no correlation.

Conclusions

Hydrologic nonstationarity at these 671 basins across CONUS is driven by climate, not land cover change. We conclude that Figure 2 shows the impact of climate change on general hydrologic conditions. Surface water runoff is increasing in the Northwest, Northern Plains, Northeast and Southern Florida. Surface water runoff is decreasing in most of the Southern United States, Michigan and Wisconsin.

1. We fail to reject the Hypothesis 0: Hydrologic nonstationarity is identifiable by geographic location.
2. We fail to reject Hypothesis 1: Hydrologic nonstationarity is correlated with a changing climate.
3. We reject Hypothesis 2: Hydrologic nonstationarity is correlated with a changing land surface. This is based on the demonstrated changes in impervious area, shown in Figures 4 and 5, but the lack of correlation with nonstationarity shown in Figure 8

Even though land use / land cover change has not been shown to be correlated with hydrologic nonstationarity, and thus not a driver, we still see some interesting results when interpolating the changes within 'natural' basin boundaries. Many hotspots appear to be undergoing significant increases in permeability land cover. Some of these include the Northeast, Houston TX and what looks like Reno NV. Interestingly the Pacific Northwest is not increasing in impermeability, and they are also seeing an increase in runoff. There also happens to be a hotspot of deforestation around the Seattle metropolitan area.

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Data availability

`https://github.com/jmframe/HydrologicStationarity`