Direct Human Interventions Drive Non-Stationarity in Annual Peak Streamflow Patterns Across the United States

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Confronting Earth System Model Trends with Observations: The Good, the Bad, and the Ugly
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The hydrologic behavior of a watershed or a region can be learned from its streamflow response, which in turn can help to understand the relative role of natural and human factors affecting the watershed. The objective of this study is to investigate how the annual peak streamflow has changed at 3907 gauging stations across the Contiguous United States in the last 60 years and then assess how much of this change can be attributed to the changing climate and human intervention. The change in climate is captured by quantifying the change in annual average and maximum precipitation at each location, whereas human intervention is captured by quantifying the change in land cover and water storage from dams/reservoirs. An analysis employing multiple linear regression and different forms of the Mann-Kendall test using the United States Geological Survey streamflow gauging station data shows that human intervention plays a more significant role compared to climate change in controlling the annual peak streamflow. A further analysis using the reference and non-reference sites from the Geospatial Attributes of Gages for Evaluating Streamflow (GAGES)-II data and the total runoff (QRUNOFF) variable from the Community Earth System Model version 2 - Large Ensemble (CESM2-LE) shows that the effect of direct human interventions is inadequately captured by climate models. Considering that many water resources management decisions are being made using climate model outputs, the results from this study highlight the need to incorporate human activities at a finer scale to generate more realistic projections of water fluxes for the future.

Long-Term Trend Analysis

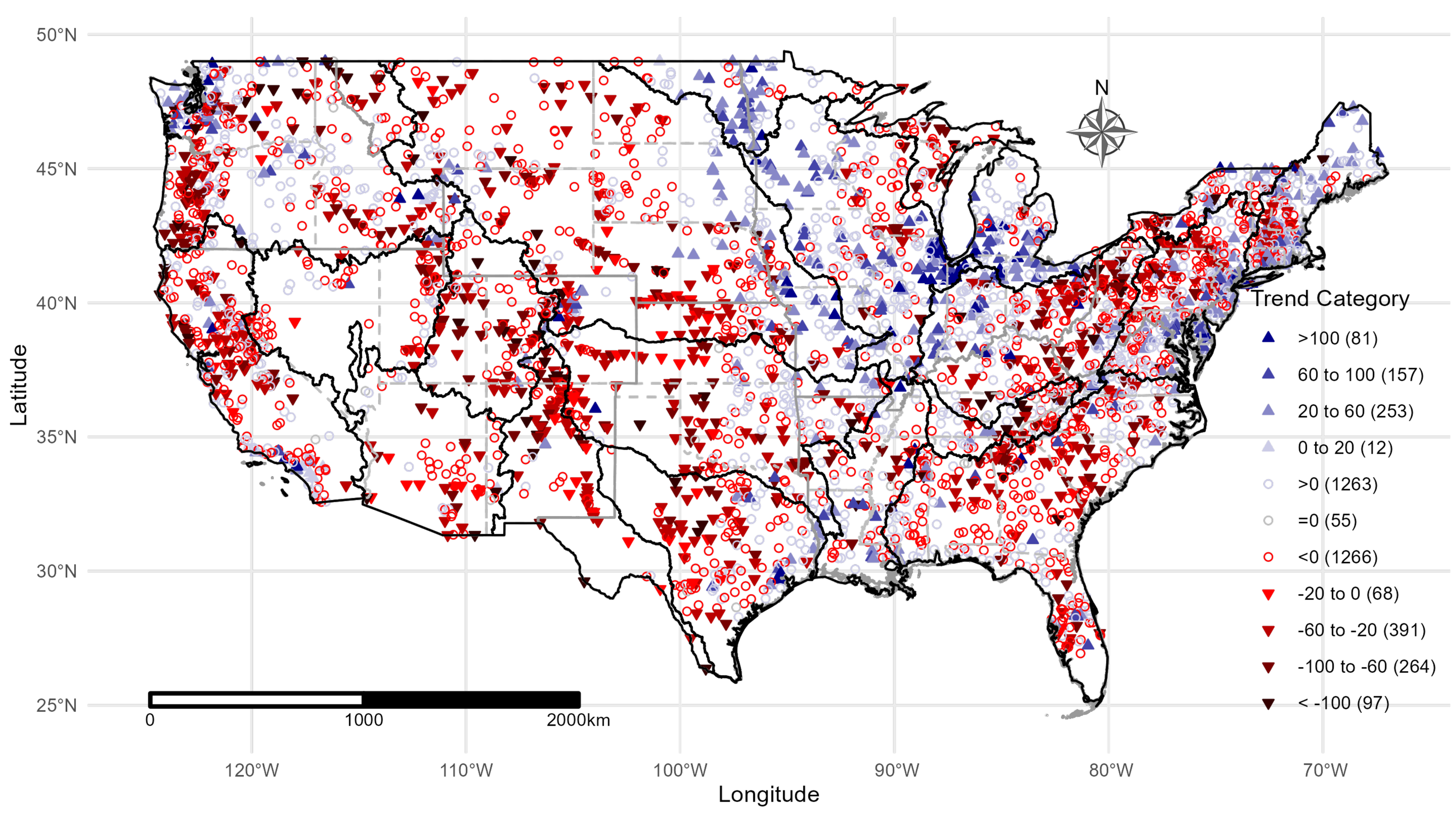
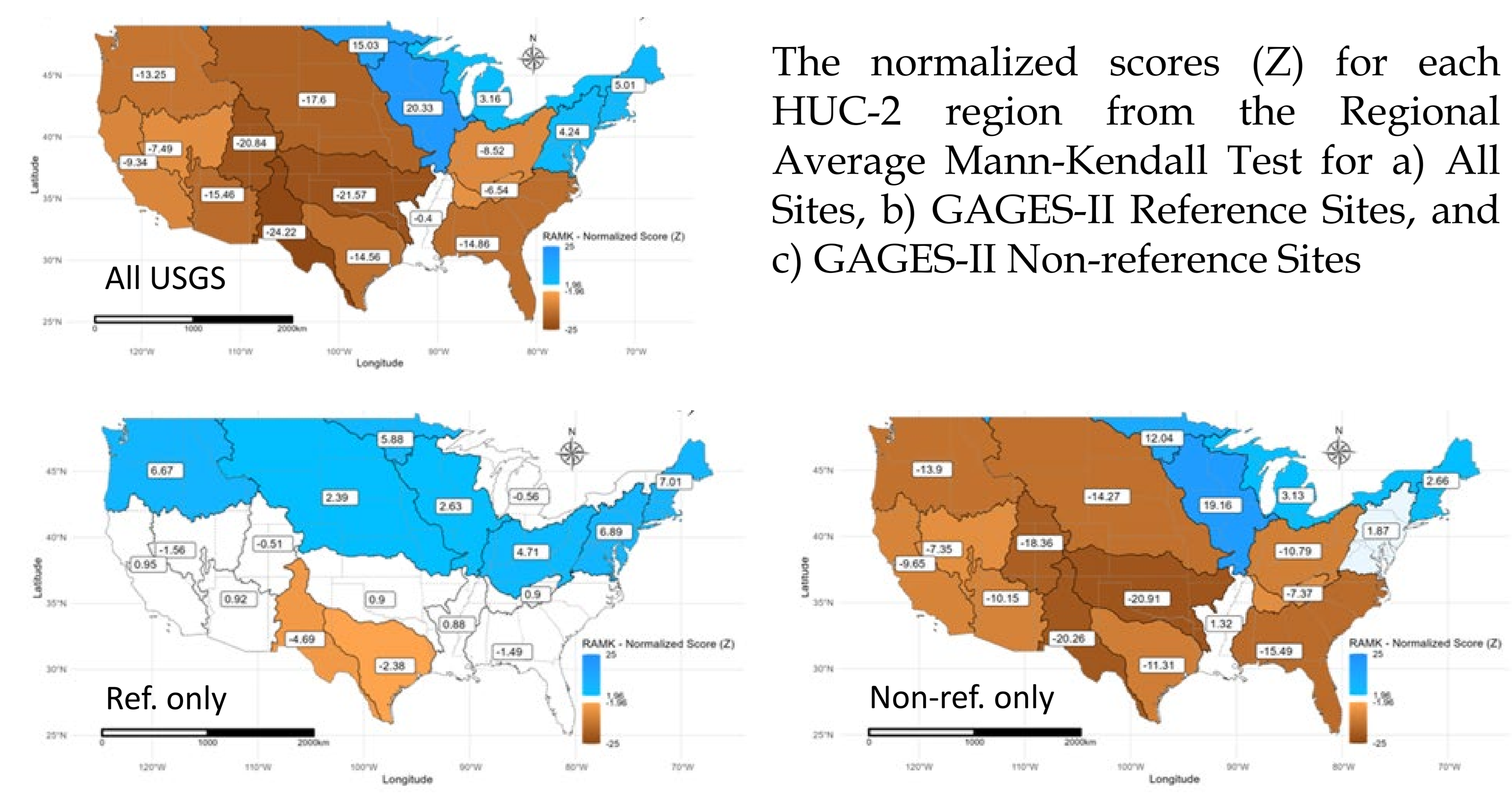


Figure 1: Human influence on the hydrological system - long-term (>60 years) trends in observed peakflow. Figure shows observed peakflow trends at all 3907 USGS stations. Open circles represent non-significant trends. Up and down arrows represent statistically significant (p-value < 0.05) trends using the non-parametric method, and unit as % of standard deviation in 60 years, i.e. 100% change represents 1 standard deviation change in 60 years.

Normalized Score (Regional Averaged MK Test)



The normalized scores (Z) for each HUC-2 region from the Regional Average Mann-Kendall Test for a) All Sites, b) GAGES-II Reference Sites, and c) GAGES-II Non-reference Sites

Figure 2: Regional peak flow trends (a) all USGS stations, (b) reference-only stations, and (d) non-reference stations. Panels show Regional Average Mann-Kendall Z values to indicate the statistical significance of trends considering all individual stations in the region (see Method). Z value < -1.96 and Z value > 1.96 represent statistically significant regional trends; the higher the magnitude of the Z value, the higher the confidence in the statistical significance.

Climate Model Assessment

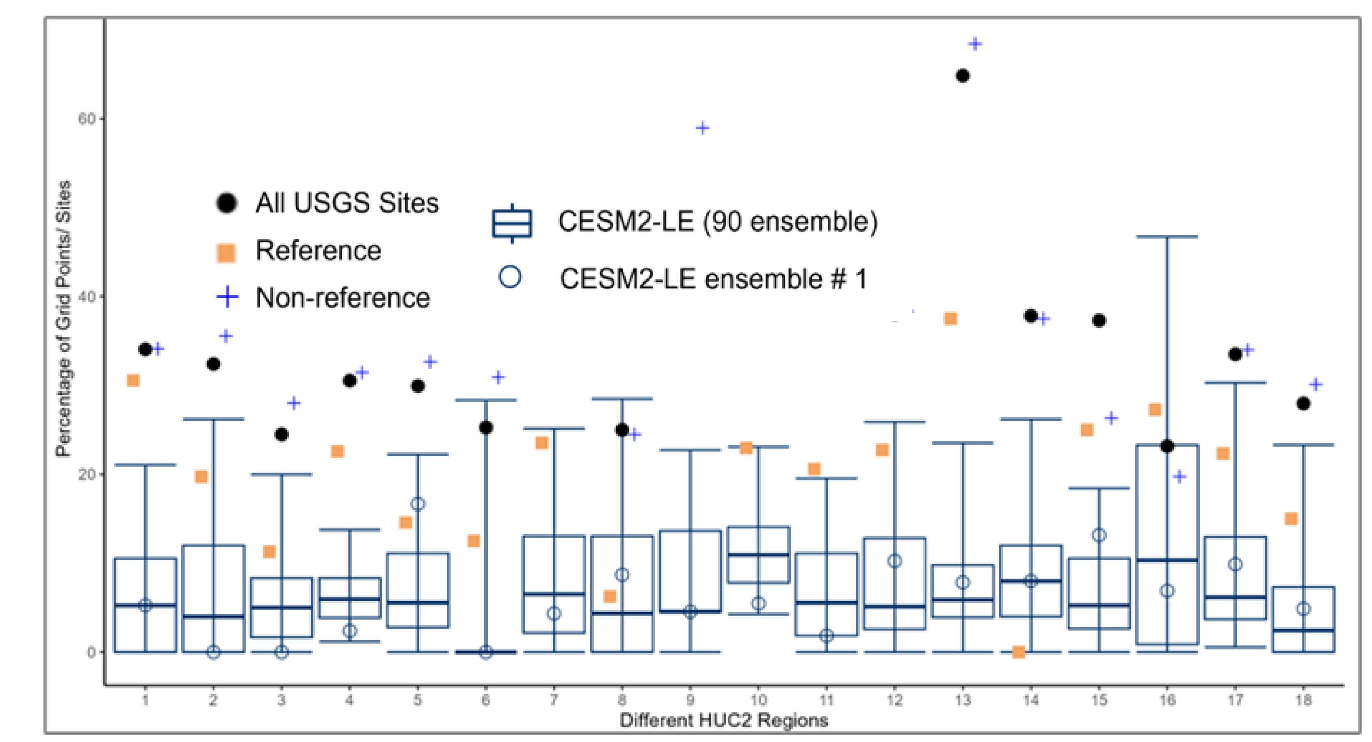


Figure 4: Climate model (CESM2-LE) evaluation for non-stationarity in peakflow. The climate model generally captures the observed trends and non-stationarity at reference stations in 12 HUC2 regions, whereas it fails to capture observations at non-reference stations in 15 HUC2 regions. Trends are evaluated using 90-member ensemble CESM2-LE data, and their spread, including 5th, 25th, 50th, 75th, and 95th percentiles, are represented using a box plot.

Statistical Test Insights

Non-stationarity metrics		All USGS stations [3907]	Climate Change (reference only)		Direct human interventions + Climate change (non-reference)	
			HCDN [439]	GAGESII-reference [620]	GAGES II non-reference [2830]	Other USGS [457]
Trend	Increasing	503 (12.9%)	65 (14.8%)	85 (13.7%)	363 (12.8%)	55 (12.0%)
	Decreasing	820 (21.0%)	27 (6.2%)	39 (6.3%)	638 (22.5%)	143 (31.3%)
Variance	Unequal Variance	674 (17.3%)	34 (7.7%)	46 (7.4%)	525 (18.6%)	103 (22.5%)
Stationarity	Non-stationary	1195 (30.6%)	65 (14.8%)	91 (14.7%)	917 (32.4%)	187 (40.9%)

Drivers of Peak Streamflow Trends

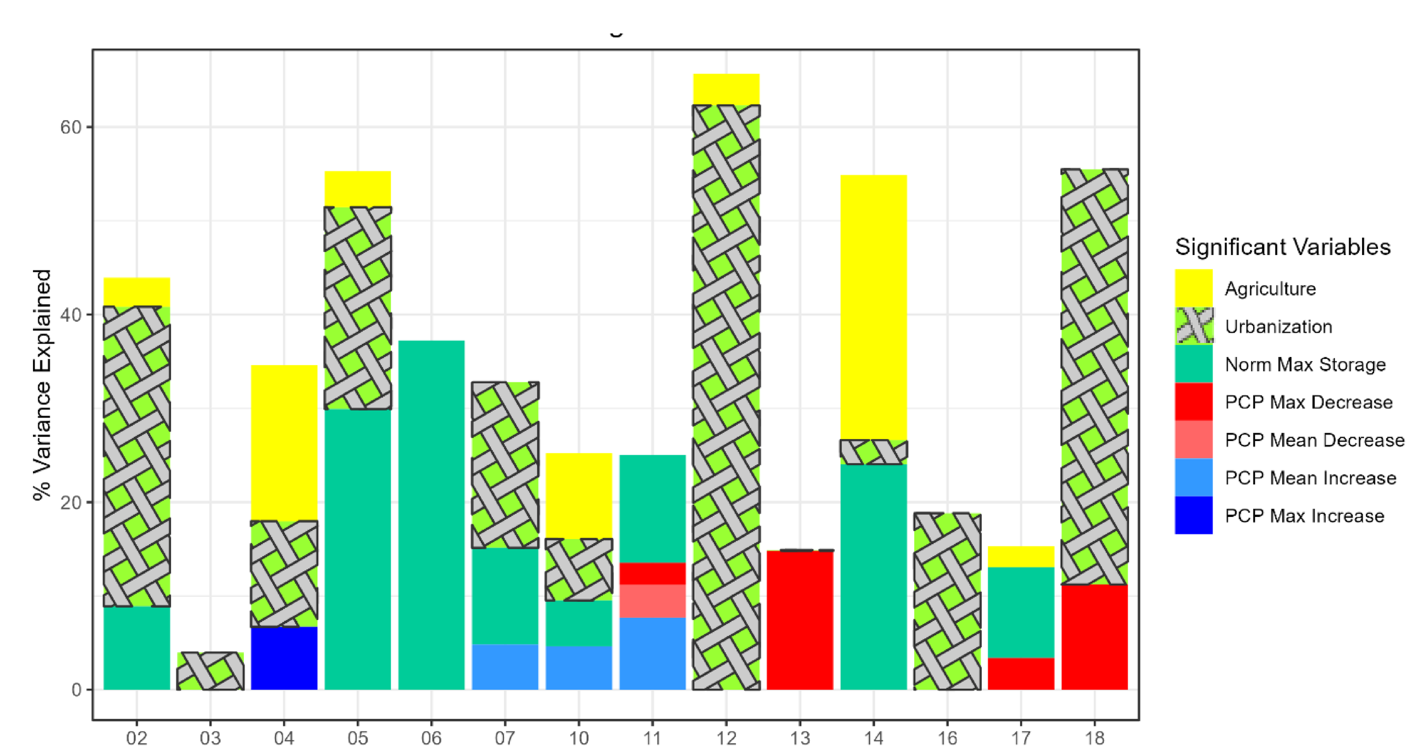


Figure 3: Drivers of peakflow trends in the United States. The figure depicts the statistically significant variances explained by climate, land use factors, and water management aspects (normalized maximum storage) in each HUC2 region shown on the x-axis. The y-axis represents the percentage of explained variances.

Summary and Conclusions

- ✓ We have detected significant trends in 34% of all USGS stations. Among these, two-thirds exhibit decreasing trends distributed across the United States, while the remaining one-third show increasing trends, predominantly in the Northeast and Great Lakes regions.
- ✓ Urbanization emerges as the principal driver, followed by water management, agriculture, and climate.
- ✓ Despite their extensive number of climate realizations (large ensemble), the latest generation of climate and earth system models inadequately captures these human-induced factors, limiting their predictive accuracy.
- ✓ By demonstrating the outsized influence of human interventions on peakflow trends and inadequacies in current climate models, our findings stress the imperative of integrating water management and urbanization effects into climate models for more accurate water predictions.

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Reference: Joseph J., Kumar, S., Merwade, V., and Johnson, D., Direct Human Interventions Drive Non-Stationarity in Annual Peak Streamflow Patterns Across the United States, Submitted to *Nature*.