A graphical non-parametric hydrologic alteration test using flow duration curves

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Abstract

Hydrologic alteration results from a variety of natural and human forces including climate change and variability, water use and water infrastructure, and land cover alterations. The assessment of statistically significant hydrologic alteration is a critical challenge. One common tool to aid in this assessment is an annual flow duration curve (FDC), a plot of daily streamflow versus its probability of exceedance in a given year. Utilizing annual FDCs, the Modified Mood's Median Test (MMMT) was applied to percentiles of the median annual FDCs at 122 disturbed sites in the conterminous U.S. A simple graphical tool based on the MMMT was developed to illustrate the significance of hydrologic alteration over a wide range of streamflow conditions at each site. Hydrologic disturbance was mostly caused by dams, though other forms of alteration were explored. In addition, 308 minimally regulated HCDN sites were investigated to assess regional climatic drivers of hydrologic alteration. Results indicate that dams can have varying effects on the hydrologic regime, but generally impact low flows more often than high flows in the U.S. Urbanization and water transfers can also have large impacts on hydrologic regimes. At HDCN sites, we observe significant changes to hydrologic regimes in many regions, especially to low and median flows in the upper midwestern and eastern U.S. A graphical tool based on the MMMT was developed to show the significance of hydrologic alteration over a range of streamflow conditions; this tool is publicly available for other applications.

Key Words: Hydrologic alteration, flow duration curve, streamflow data, non-parametric hypothesis tests, median.

1.0 Introduction

Hydrologic systems evolve in response to a variety of natural and human forces such as climate change and variability and change, water use and water infrastructure, and land cover alterations. Such changes in hydrologic systems impact socioeconomic, ecological, and climate systems at multiple scales, leading to a coevolution of these interlinked systems (Vogel et al., 2015). Hydrologic disturbance can result from either intended or unintended activities. Rivers and streams system can be disturbed through flow regulation to either mitigate the outcome of extreme events (e.g., floods, droughts) or to better make use of these resources (e.g., water supply, irrigation, hydropower) (Malmqvist and Rundle, 2002; Richter et al., 1996). While river flow regulation often results from the construction and operation of dams (Nilsson et al., 2005; Poff et al., 2007), including off-stream reservoirs (Hecht et al., 2014), streams can also be disturbed due to climate and land use changes, interbasin water transfers, and inputs to streams such as via wastewater treatment plant discharges (Bradford et al., 2018). The resulting hydrologic alteration can cause loss of floodplains and wetlands, habitat fragmentation and ecological degradation, reduction in water quality, and the loss of ecosystem services (Bunn and Arthington, 2002; Magilligan and Nislow, 2005; Postel et al., 1996; Rosenberg et al., 2000; Sabater et al., 2018; Yusa et al., 2015). Although predicting the impact of hydrologic alteration on ecosystem services may be challenging, a recent review article by Jumani et al. (2020) concludes that improved assessment of the significance of hydrologic alteration is needed to better inform both water and ecological management decisions.

To assess hydrologic alterations, various metrics and indices have been developed (Dudley et al., 2020; Gao et al., 2009; Poff et al., 2010; Richter et al., 1996; Yang et al., 2017, 2008). Richter et al. (1996) proposed the Indicators of Hydrologic Alteration (IHA), which consists of 33 streamflow statistics that characterize a wide range of hydrologic conditions. Poff et al. (2010) developed the Ecological Limits of Hydrologic Alteration (ELOHA) framework providing empirical relationships between flow alteration and ecological responses. When using such metrics, assessing the significance of alteration can be challenging. Individual statistics which comprise these metrics often capture only one portion of the hydrologic cycle or only one aspect of the hydrologic phenomenon which impacts the system (e.g., flows in a specific month). For instance, Dudley et al. (2020) utilized the annual 7-day low streamflow to detect trends within human-impacted basins in the U.S. Unfortunately, many of the advocated metrics and indices are plagued by both redundancy and correlation (Olden and Poff, 2003), which has led to the development of reduced sets of indices. Gao et al. (2009) used principal component analysis to produce a smaller set of independent and characteristic hydrologic indicators which could more fully represent a wider range of streamflow conditions impacted by hydrologic alteration. Yang et al. (2008) used a data mining approach to identify the most ecologically relevant hydrologic indicators (ERHIs) from the IHA. Yang et al. (2017) developed a Criteria of Importance Through Intercriteria Correlation (CRITIC) algorithm to produce more representative indicators of hydrologic alteration. Vogel et al. (2007) introduced integrated indicators of hydrologic alteration referred to as seasonal ecodeficit/ecosurplus for evaluating the impact of reservoir regulation on ecological flow regimes. While these proposed approaches address some of the issues of redundancy and correlation among metrics, it is still unclear how many or which indices are needed to fully reflect hydrologic alteration. There is a need for a convenient tool that could help to evaluate the significance of hydrologic alteration resulting from a wide range of types and causes of streamflow alteration.

One common tool used to assess hydrologic alteration is a flow duration curve (FDC). A FDC is a plot of streamflow versus its probability of exceedance (Vogel and Fennessey, 1994). The FDC captures the entire range of streamflow magnitudes, and thus integrates the complete streamflow regime into a single tool. FDCs have been utilized for a wide range of applications, including but not limited to hydropower design, habitat assessment, flood abatement, water quality evaluation, wasteload allocations, inundation mapping and for comparative hydrologic assessments (Castellarin et al., 2013; Vogel and Fennessey, 1995). In one of the most widely cited articles on the application of FDC's, Brown et al. (2005) document the value of FDC's in paired catchment studies for "gaining a greater understanding of the impact of vegetation on the distribution of daily flows." In a recent review of applications of FDCs over the period 2000-2020, Leong and Yokoo (2021) highlighted an "enormous volume of literature available on FDC studies within this time frame" and they highlighted the need for future research to improve our ability to incorporate anthropogenic influences on the behavior of FDCs. Many hydrologists, scientists and water managers would not make water resource decisions without reference to a FDC. Even statisticians consider graphical displays as the single most effective and robust statistical tool (Wainer, 1990). Importantly, FDCs are an effective graphical instrument for conveying information regarding a wide range of water resource problems; hence, they provide an effective medium for communication between water resource engineers, lawyers, managers, planners, politicians, and others. It is for these reasons that our goal is to develop a graphical hypothesis test based on a FDC. A FDC is also a convenient tool for the detection and attribution of hydrologic change. For instance, if a dam and associated reservoir is introduced, one might expect a flattening of the FDC downstream of the dam; water withdrawals or reductions in precipitation would generally result in a lowering of the entire FDC (Atieh et al., 2017; Moyle and Mount, 2007; Vogel et al., 2007). FDCs are part of a river's *streamflow signature* that can represent both the natural state of rivers and their responses to hydrologic alteration.

It is often challenging to determine whether alterations to the hydrologic system are significant or are instead simply the consequences of the natural variability of streamflow under stationary conditions (Allan, 2004). Kroll et al. (2015) used shifts in annual FDCs to develop four hypothesis tests of hydrologic alteration based on different methods of bootstrap resampling. Using dam sites in the U.S. which were assumed to have undergone hydrologic alteration, they found a confidence interval test (which is more accurately termed a "tolerance interval test") of the average annual FDC to have the highest power, among the four tests considered. Unfortunately, that test only examined the most extreme shifts in the mean annual FDC and did not consider hydrologic alteration across a range of streamflow conditions, a goal of this study. In addition, the test proposed by Kroll et al. (2015) was generally based on the condition when the post-alteration streamflow record was much shorter than the pre-alteration streamflow record, allowing for bootstrap resampling of the pre-alteration streamflow to develop the critical value of the hypothesis test. Hecht et al. (2020) assessed hydropower-ecosystem tradeoffs by examining the decrease of the 5th percentile and the increase of the 95th percentile of annual FDCs, determining the type-1 and type-2 errors of a Mann-Whitney-Wilcoxon test (MWW). While the hypothesis tests introduced by Kroll et al. (2015) and Hecht et al. (2020) do provide an evaluation of the significance of hydrologic alteration, the resulting tests are generally complicated to understand, implement and explain to water managers. A more general hypothesis test of hydrologic alteration that is easy to interpret and communicate and could be applied to a wider set of streamflow conditions is needed. We exploit the widely understood and attractive graphical features of FDCs to enable the development of such a hypothesis test as well its ease of implementation and acceptance in practice. One approach to the development of hypothesis tests for annual FDC's would be to exploit confidence (or more correctly, tolerance) intervals for annual FDC's introduced by Vogel and Fennessey (1994), reviewed by Castellarin et al. (2007) and extended more generally by Serinaldi (2011). Serinaldi (2011) introduced an attractive and general analytical approach to develop confidence intervals for annual flow duration curves, which could be adapted to construct hypothesis tests of hydrologic alteration. However, since his approach is based on index FDC's and requires assumptions concerning the distribution of streamflow, we did not adapt this approach here for our purposes.

Due to inherent problems in parametric hypothesis tests when distributional assumptions are violated (Ernst and Albers, 2017; Williams et al., 2013), nonparametric approaches are often preferred (Helsel et al., 2019), especially when dealing with daily streamflow series which exhibit extremely complex tail behavior (Blum et al., 2017). A non-parametric modification of Mood's median hypothesis test proposed by Fligner and Rust (1982) is explored here. The median (as opposed to the mean) better captures the central tendency of skewed data (Ames, 2006; Helsel et al., 2019), and FDCs based on daily streamflows are known to exhibit extraordinary levels of skewness (Ye et al., 2021). Vogel and Fennessey (1994) introduced the median annual FDC which represents the FDC in a "typical" or median year. Our hypothesis testing approach evaluates whether or not flow variations within a typical or median year differ before and after a potential hydrologic disturbance. A case study is performed using 122 gaged U.S. streamflow records that are impacted by different types of disturbance. Although most of the sites included in this study are streams with dams, we also explore other types of disturbance including urbanization, wastewater treatment plant (WWTP) effluent discharge, and interbasin water transfer. We also explore our hypothesis test using 308 minimally disturbed U.S. gaged sites to assess impacts of potential regional climatic changes. Our hypothesis test is also illustrated using a simple graphical tool to enable visualization of hydrologic alteration across the entire range of streamflow conditions. This graphical tool, which was created in R, produces a graphical representation of hydrologic alteration that is easy to implement, understand and communicate, should aid water planners and managers when addressing potential hydrologic alterations, and is posted on Github (https://github.com/cnkroll/MMMT.git) for others to use. Our overall goal is to introduce a nonparametric graphical hypothesis test which should be useful in most applications of annual FDC's, a considerable challenge given the now widespread application of annual FDC's in hydrology.

2.0 Study Area and Methodology

2.1. Study area

Case studies at USGS streamflow gages are implemented to evaluate the proposed hypothesis test. We employ 3 sets of gages: (1) 117 USGS streamflow gages with dams previously used by Kroll et al. (2015), (2) 5 USGS streamflow gages which represent other forms of potential hydrologic disturbance, and (3) 308 minimally regulated sites from the USGS Hydro-Climatic Data Network (HCDN). All sites have at least 15 water years of daily observations both before and after the "disturbance" year. Note that a disturbance could be an anthropogenic intervention such as a dam, urbanization, or interbasin water transfer, or it could be a potential climatic change point. Figure 1 shows the locations of the 122 potentially disturbed sites, while Figure 6 shows the location of the 308 minimally regulated HCDN sites considered. Mowafy (2021,

Appendix 1) summarizes the 122 disturbed sites, providing their drainage area, hydrologic disturbance index (HDI), type and year of disturbance and the start and end year of the streamflow record. The HDI is a composite index of hydrologic disturbance which ranges from 0 (no disturbance) to approximately 40 (heavily disturbed) (Falcone et al., 2010). The HDI is composed of seven disturbance metrics: major dam density, change in dam storage, percent canals and artificial paths, distance to National Pollutant Discharge Elimination Sites, freshwater withdrawals, road density, and landscape fragmentation.

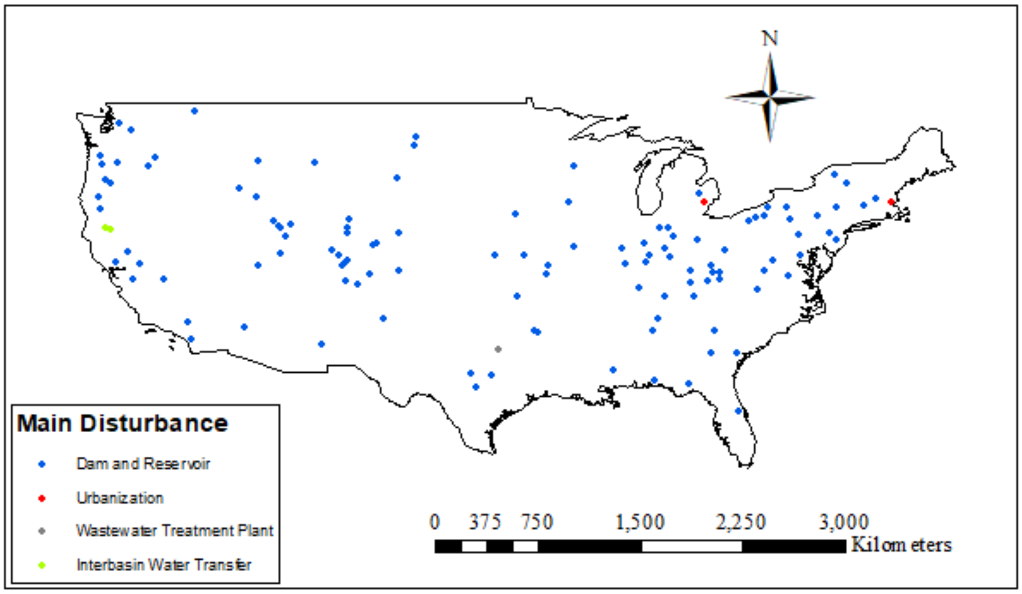

Figure 1: Locations of the 122 USGS stream gages with potential disturbance employed in this analysis (minimally regulated HCDN sites' locations depicted in Figure 6).

2.2. Modified Mood's Median Test Methodology (MMMT)

At each site a continuous daily streamflow record was separated into water years (October 1st to September 30th) and divided into pre- and post-alteration samples. For the sites with dams, the 5 years before and after the disturbance were omitted from the record to minimize the impact of dam construction and reservoir filling. The median annual FDC was constructed for 199 percentiles (p = 0.005, 0.01, 0.015, …, 0.995) employing the nonparametric quantile estimator introduced by Harrell and Davis (1982) in which each percentile of the FDC is computed from a linear combination of all the ordered observations. Vogel and Fennessey (1994) evaluated four different estimators for FDC quantiles and found that among those estimators, the estimator proposed by Harrell and Davis (1982) and given in equation 5a of Vogel and Fennessey (1994) provided smoother estimators for small samples than alternative estimators based on only a few of the ordered observations. Below we describe a hypothesis test of medians for each percentile of pre- and post-disturbance annual FDCs.

Let $X_1, \ldots, X_m$ and $Y_1, \ldots, Y_n$ denote independent random samples (from a pre-disturbance and post-disturbance annual FDC percentile), with sample sizes m and n, respectively. In addition, let $Z_1, \ldots, Z_N$ denote the combined sample where $N = m+n$. The true (population) medians for both populations are assumed to be M_1 and M_2, so that the cumulative density functions (CDFs) are $F_1(M_1) = F_2(M_2) = 0.5$. Of concern is testing:

$$\text{Ho: } M_1 - M_2 = 0$$

$$\text{versus Ha: } M_1 - M_2 \neq 0$$

Friedman (1937) proposed an analysis of ranked data instead of an analysis of variance to perform the above hypothesis test to avoid the assumption of normality. Friedman's ranked-based test statistic approaches a Chi-square distribution as the sample size increases (Friedman, 1937). Based on this approach, the Mood's median test was developed by ranking the combined set of observations and utilizing the sum of squared deviations of rank totals from their corresponding expected values as a test statistic (Brown and Mood, 1951). Mood's test statistic, T, is the number of observations from one of the samples (here assumed to be Y_i) that are less than or equal to the combined sample median, $\widehat{M}$. An attractive feature of this test is that under the null hypothesis, when the medians of both distributions are equal, the test statistic only depends on the ranks of the observations and is thus a distribution free or nonparametric test.

In the derivation of their test, Brown and Mood (1951) assumed that both populations have the same distributional shape, a poor assumption for this study. Instead, we utilize a modification to the Mood's test that was proposed by Fligner and Rust (1982) to avoid the assumption of similarly shaped distributions. Under the null hypothesis (equal medians), $(n^*(T-1))^{1/2}$ will have a limiting normal distribution with a mean of 0 and a variance of σ^2:

$$\sigma^2 = \frac{1}{4}\ \rho\,(1+\rho R^2)\,/\,(1+\rho R)^2 \qquad (1)$$

where $\rho = \lim(m/n)$ as $m \rightarrow \infty$ and $n \rightarrow \infty$ and $R = f_1(M)/f_2(M)$, where $f_1(M)$ and $f_2(M)$ are the probability density functions of the medians of the pre- and post-disturbance populations, respectively. Under the Mood's original median test assumption that both records exhibit the same distributional shape, R would equal 1 and the variance in (1) simplifies to:

$$\sigma^2 = \frac{1}{4}\ \rho/(1+\rho) \qquad (2)$$

When the samples do not have the same distributional shape, a new estimator of σ^2 based on a range of order statistics centered on the sample median was proposed by Fligner and Rust (1982). The lower and upper bounds of this range are $L = Z_{N-b_N}$ and $U = Z_{b_N}$, respectively, where b_N assigns the rank location of these bounds using:

$$b_N = [\,\frac{1}{2}(N+1) + N^{\frac{1}{2}}\,] \qquad (3)$$

where the square brackets represent the greatest integer function and Z_i denotes the i^th ordered value of Z from the combined sample of length N=m+n. R is then estimated by:

$$\hat{R} = (F_1(U) - F_1(L))/(F_2(U) - F_2(L)) \qquad (4)$$

where F_1 and F_2 are estimated by linearly interpolating across the pre- and post-disturbance cdfs using a Weibull plotting position. If either L or U falls out of the pre- or post-disturbance sample range for a given percentile, it is assigned to be either the smallest or the largest streamflow value of the corresponding sample, and that value is also employed to calculate $F_i(U)$ or $F_i(L)$ for both samples. Fligner and Rust (1982) proposed the MMMT test statistic:

$$\hat{T} = n^{\frac{1}{2}} \left(T - \frac{1}{2}\right) / \hat{\sigma} \qquad (5)$$

where:

$$\hat{\sigma}^2 = \frac{1}{4}\, p\,(1+p\,\hat{R}^2) / (1+p\,\hat{R})^2 \qquad \text{if } F_1(U) - F_1(L) > 0 \text{ and } F_2(U) - F_2(L) > 0 \qquad (6)$$

$$\hat{\sigma}^2 = \frac{1}{4}\, p \qquad \text{if either } F_1(U) - F_1(L) = 0 \text{ or } F_2(U) - F_2(L) = 0$$

Where $p = m/n$. Note that for the case in equation 6 where either $F_1(U) - F_1(L) = 0$ or $F_2(U) - F_2(L) = 0$ we have modified an apparent typographic error ($\hat{\sigma}^2 = \frac{1}{4}$) in Fligner and Rust (1982 p. 223). The null hypothesis is rejected when $|\hat{T}| \geq t_{N,\frac{\alpha}{2}}$ where $t_{N,\frac{\alpha}{2}}$ is the $(1-\frac{\alpha}{2})$*100% percentile of a Student T distribution with N=(m+n) degrees of freedom. The p-value for a two-tailed test can be determined by:

$$\text{p-value} = 2P(T_N \geq |\hat{T}|) \qquad (7)$$

In some situations when nearly all of the values of F_1 are greater than F_2 (or vice versa), L may become greater than U when either L or U falls out of the pre- or post-disturbance sample range for a given percentile (from equation 6). For this case, $\hat{T}$ is set to -3 and p-value is set to 0.005 as defaults.

3.0 Graphical Hypothesis Test Results

In Section 3.1, the MMMT is performed at the 117 sites with dams. In Section 3.2, a graphical tool is developed to visually assess hydrologic alteration at percentiles of median annual FDCs, and selected dam sites from our dataset are examined to better understanding the impacts of dam and reservoir systems on resulting hydrologic disturbance. In Section 3.3, sites with other forms of disturbance are examined. Finally, in Section 3.4, the test is performed at HCDN sites using 1970 as a climatic “break-point”.

3.1. Performance of MMMT at Selected U.S. Dam Sites

If $\hat{R}$ from equation (4) is equal to 1, then MMMT defaults to the Mood’s Median Test. Using the 117 sites with dams, $\hat{R}$ was calculated for each percentile, and Figure 2 presents a box plot of $\hat{R}$ across all sites at all percentiles. Across these sites and percentiles, there is a wide range of $\hat{R}$, and a t-test assessing Ho: $R = 1$ versus Ha: $R \neq 1$ indicates that R is significantly different than 1 across all sites (p-value $< < 0.01$).

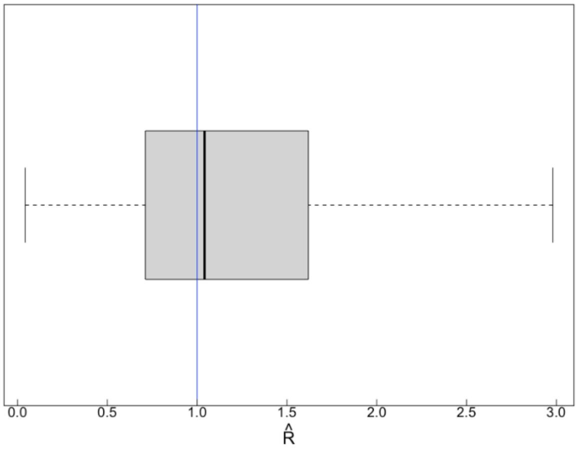

Figure 2: Box plot of $\hat{R}$ values across 117 U. S. dam sites at all percentiles.

To evaluate the outcome of applying the MMMT across all the dam sites, Figure 3 shows the percentage of dam sites with a significant alteration for a given percentile at three different hypothesis test significance levels (1%, 5% and 10%) based on the pre- and post-alteration annual FDCs. In general, there was a general increase in the percentage of sites with significant changes in the median annual FDC percentile as the exceedance probability increases. At significance levels of 10%/5%/1%, approximately 20%/25%/35% of the sites experienced a significant alteration at extreme high flows (0.5th to 5th percentiles) and approximately 55%/65%/75% of the sites had significant alteration at extreme low flows (95th to 99th percentiles), respectively, indicating that dams more often significantly alter low flows than high flows in the U.S. This makes sense given that streamflow alterations would generally have a larger impact on the lowest streamflows. In addition, at the lowest exceedance probabilities (highest flows), we see a slight increase in the percentage of sites with significant alteration. Dams are often installed for flood control, reducing the impact of the largest streamflows. Note that a comparison (not shown here) was made between the MMMT and a similar test based on the ratio of medians using the method developed by Bonett and Price (2020). Results indicated that the 2 methods had a similar percentage of alteration across the dam sites shown in Figure 1 (Mowafy, 2021). Since the Bonett and Price method requires a logarithmic transformation, it cannot easily handle flows recorded as 0 (unlike MMMT), and thus is not recommended for assessing alteration in the median annual FDC.

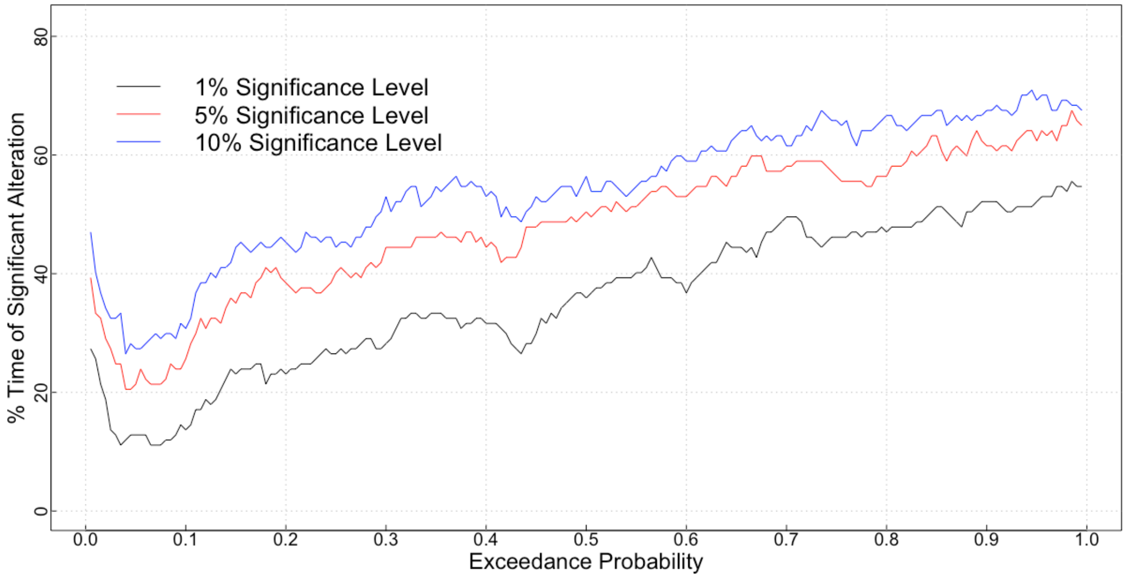

Figure 3: Percentage of time that 117 U. S. dam sites had significant alteration to median annual FDC at different FDC percentiles.

3.2 Graphical Illustration of Hydrologic Disturbance at Dam Sites

To better understand the impacts of dam and reservoir disturbances on the hydrologic flow regime, 4 of the 117 dam sites were selected to further examine hydrologic alteration and to identify and attribute drivers of the disturbance. Each of the selected sites was paired with a less regulated site (a nearby site with a lower HDI). The selection criteria for these paired less regulated sites were: (1) having a concurrent record with the disturbed site, (2) being located in the same 2-digit US Hydrologic Unit Code (HUC), and (3) having a drainage area within 70% to 130% of the dam site's drainage area. The purpose of this comparison is to assess whether the hydrologic disturbance results from anthropogenic activities or due to other drivers (e.g., regional climate), in which case an alteration should be evident at both sites. A summary of the dam and reservoir characteristics at each site can be found in Table 1 (data from USACE, 2000). The four sites with dams were selected based on different patterns of alteration as shown in the column labeled "Purpose" in Table 1. Watershed and hydrologic information for both the dam sites and paired sites can be found in Table 2 (data from Falcone, 2011).

One of the primary contributions of this study is to provide a graphical display of the results of our hypothesis tests which is very easy to understand and communicate. This contribution is illustrated in Figures 4a-d which document the pre- and post-disturbance annual and median annual FDCs at both the disturbed and undisturbed sites. The annual FDCs for the pre- and post-disturbance records are the lighter lines on the plots, while the darker symbols are the median annual FDCs for the pre- and post-disturbance records. When the p-values of the MMMT are less than 1%, between 1% and 5%, and between 5% and 10%, the points on the median annual FDCs are colored red, orange and yellow, respectively, and when the p-value is greater than 10%

the points are blue. The resulting figures provided a comprehensive graphical tool to assess the magnitude of hydrologic alteration across the range of exceedance probabilities.

Table 1: National Inventory of Dams (NID) information for 4 selected dam/reservoir sites.

Stream	**NID ID**	**H**	**S**	**S_{Max}**	**Q_{Max}**	**L**	**Purpose**	**Dam Name**	**Dam Operator**
Tualatin River near Dilley, OR	OR03317	22	27.5	27.5	111	300	IP	Tualatin Park	Not provided
Fine Creek at Fine Creek Mills, VA	VA145025	11	19	69	267	415	IR	Telmans Dam	USDA NRCS
Encampment River near Encampment, WY	CO00991	31	38	94	1160	140	FPR	Ginger Quill Reservoir	Ginger Quill Ranch Corp
Priest River near Coolin, ID	ID00318	12	76100	Not provided	4400	194	FR	Priest Lake Outlet Dam	IDWR

Variables: **H**: Dam Height (ft), **S**: Normal Storage (acre-ft), **S_{Max}**: Maximum Storage (acre-ft), **Q_{Max}**: Maximum Discharge (cfs), **L**: Dam Length (ft)

Purpose: **H**: Hydropower, **R**: Recreation, **C**: Flood Control, **I**: Irrigation, **F**: Fish and Wildlife Pond, **P**: Fire Protection, Stock, or Small Fish Pond.

Table 2: Streamflow and watershed information for paired dam and unregulated watersheds.

Stream	**USGS ID**	**Drainage Area (km^2)**	**HDI***	**Mean Annual Precipitation (cm)**	**Dam Storage on Stream (Ml/km^2)**
Tualatin River near Dilley, OR	14203500	325	25	115	228
Chehalis River near Doty, WA	12020000	293	8	143	0
Fine Creek at Fine Creek Mills, VA	02036500	58	12	110	14.2
Piscataway Creek near Tappahannock, VA	01669000	72.3	6	113	0
Encampment River near Encampment, WY	06625000	678	17	28	41.6
Gardner River near Mammoth, MT	06191000	513	5	35	0
Priest River near Coolin, ID	12394000	1570	11	77	112.29
Goose Creek near Oakley, ID	13082500	1633	7	32.14	0.04

*HDI: Hydrologic Disturbance Index

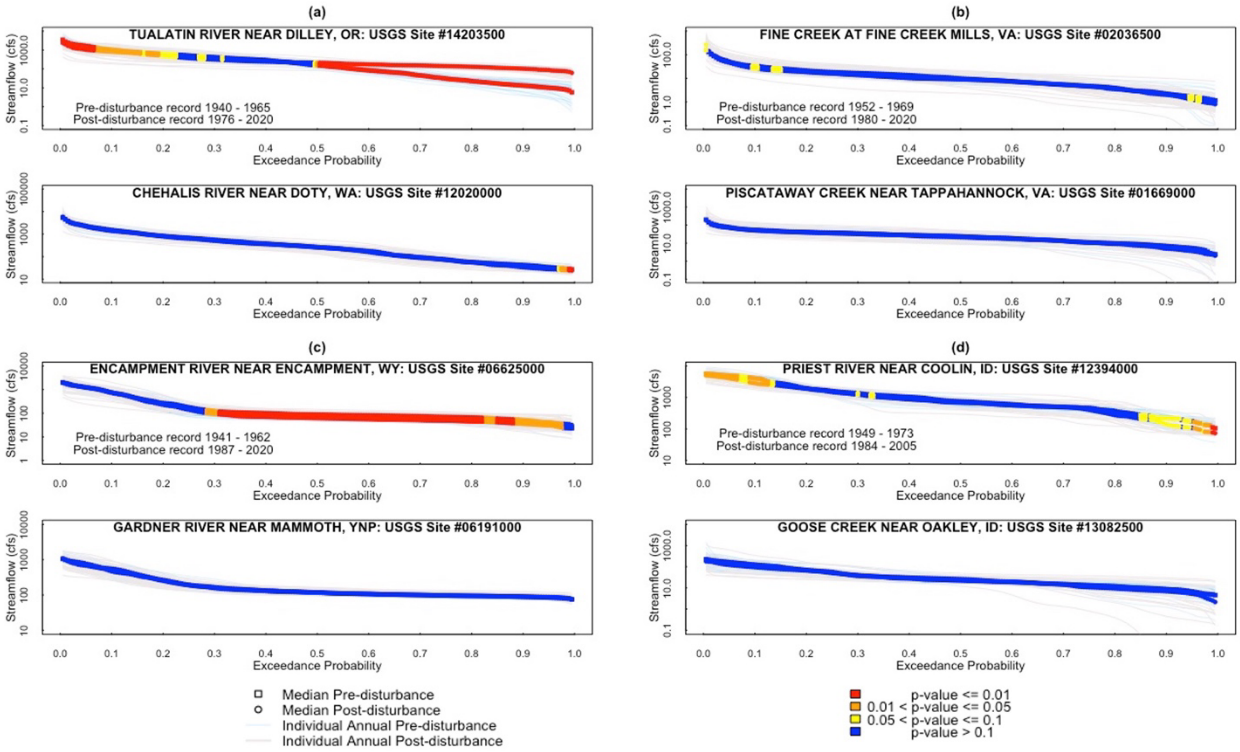

Figure 4: Graphical Hypothesis Test Results of MMMT at paired dam/no dam sites: a) Tualatin River/Chehalis River, b) Fine Creek/Piscataway Creek, c) Encampment River/Gardner River, and d) Priest River/Goose Creek. See Tables 1 and 2 for details on selected sites.

Figure 4a shows the pre-and post-disturbance median annual FDCs for the Tualatin River near Dilley, OR (USGS#14203500), where a reservoir was placed on the stream in 1970 and the HDI is 25. This site was paired with a site subject to minor regulation, the Chehalis River near Doty, WA (USGS#12020000) with an HDI of 8. The dam on the Tualatin River provides flood protection which significantly lowers high flows and provides drought augmentation which significantly increases low streamflows. Alteration in median annual FDC percentiles below an exceedance probably of about 5% (extreme high flows) and above an exceedance probability of 50% (generally low streamflows) were significant at a 1% level. On the Chehalis River, significant alterations were only observed for the highest exceedance percentiles (extreme low flows). The Tualatin River has a multipurpose dam operated for flood control, irrigation water supply, fishing, and fire protection (USACE, 2000).

Figure 4b contains the pre- and post-alteration median annual FDCs of Fine Creek at Fine Creek Mills in Virginia (USGS#02036500), where a reservoir has been in operation since 1974 and has an HDI of 12. This site was paired with Piscataway Creek near Tappahannock, VA (USGS#01669000) with an HDI of 6. At Fine Creek only minimal significant alteration (5% < p-value < 10%) was observed at a few percentiles while Piscataway Creek showed no signs of significant alteration during the same time interval (water years 1944-2020). The minimal significant alteration at Fine Creek may be due to the relatively small reservoir on this river with a primary purpose of irrigation water supply and recreational activities (USACE, 2000).

Figure 4c shows the pre- and post-alteration median annual FDCs for the Encampment River near Encampment, WY (USGS#06625000), where a reservoir has been in operation since 1967 and the HDI is 17. This site was paired with a site with minor alteration, the Gardner River near Mammoth, MT (USGS#06191000) with an HDI of 5. More than two thirds of the median annual FDC of the Encampment River (intermediate and low flows) had a significant alteration at a 1% level. In contrast, the FDC of the Gardner River indicates no significant alteration through the same time period (water years 1940-2020). This could suggest that the alteration in the FDC of the Encampment River was driven by a reservoir created primarily for a fish and wildlife pond, fire protection and recreation (USACE, 2000). Unlike the Tualatin River (Figure 4a), no significant alteration to the high flows on the Encampment River was observed. Unlike the Encampment River, the Tualatin River reservoir had an additional operating goal to provide downstream flood protection.

Figure 4d illustrates the median annual FDCs for the Priest River near Coolin, ID (USGS#12394000), where a reservoir was placed on the stream in 1978 with an HDI of 11. This site was paired with a site with minor regulation, Goose Creek near Oakley, ID (USGS#13082500) with an HDI of 7. Both low flows and extreme high flows have been significantly altered on the Priest River. Median annual FDC percentiles below an exceedance probably of about 5% (extreme high flows) and median annual FDC percentiles above an exceedance probability of 95% were significant at a 5% level. On Goose Creek, there was no significant alteration to the median annual FDC during the same time period (water years 1949-2005). The significant alteration to low flows on the Priest River was a decrease and not an increase in low flows, which is commonly expected when a dam is used to augment streamflow during drought periods. Priest Lake maintains high water levels during the summer months for recreational purposes, and then drops the water level in the fall to accommodate the spawning of Kokanee salmon (BCLC, 2021). Such regulation appears to have caused a drop in low streamflows after the dam was installed. In 2018 the Idaho Water Resources Board started the "Priest Lake Water Management Project" to upgrade the Priest Lake outlet dam to improve low flow management (IDWR, 2021).

3.3. Graphical Illustration of Other Forms of Hydrologic Disturbance

To examine the impacts of different forms of hydrologic disturbance on median annual FDCs, five sites were identified: two sites that have undergone urbanization activities, one site potentially disturbed by wastewater treatment plant (WWTP) effluent discharge, and two sites that have undergone an interbasin water transfer (source and receiving end). The first site examined was the Aberjona River at Winchester, MA (USGS#01102500) with an HDI of 17.

This site was paired with a site with minor regulation, the Mount Hope River near Warrenville, CT (USGS#01121000) with an HDI of 12. The Aberjona River has undergone an increasing trend in urbanization over time; for this analysis we chose an approximate midpoint of the historical record as the year of alteration (1990). As shown in Figure 5a, the entire FDC of the Aberjona River witnessed an alteration with more than 90% of the quantiles showing significant alteration at a 1% significance level and the remaining percentiles showing significant alteration at a 5% significance level. The Mount Hope River only exhibited alteration for the smallest FDC exceedance percentiles (largest flows) over the concurrent record (water years from 1940-2020). The alteration on the Aberjona River is clearly linked to urbanization activities, with the area experiencing a gradual change in land use, from primarily farms to residential and urban areas (Solo-Gabriele and Perkins, 1997). This result is also consistent with the findings of Allaire et al. (2015) who provide additional information on the impact of urbanization and water withdrawals on FDCs of the Aberjona River.

The second urbanization site is the Upper River Rouge at Farmington, MI (USGS#04166300) with an HDI of 15 (Figure 5b). This site was paired with a site with a slightly lower HDI, Stony Creek at Romeo, MI (USGS#04161580) with an HDI of 12. Nearly all of the FDC percentiles of the Upper River Rouge shows a significant alteration with flows with greater than a 50% exceedance probability (low flows) significant at a 1% level. The absence of alteration at the reference site led us to link alteration on the Upper River Rouge to the documented increase in housing density in the watershed (Falcone, 2017).

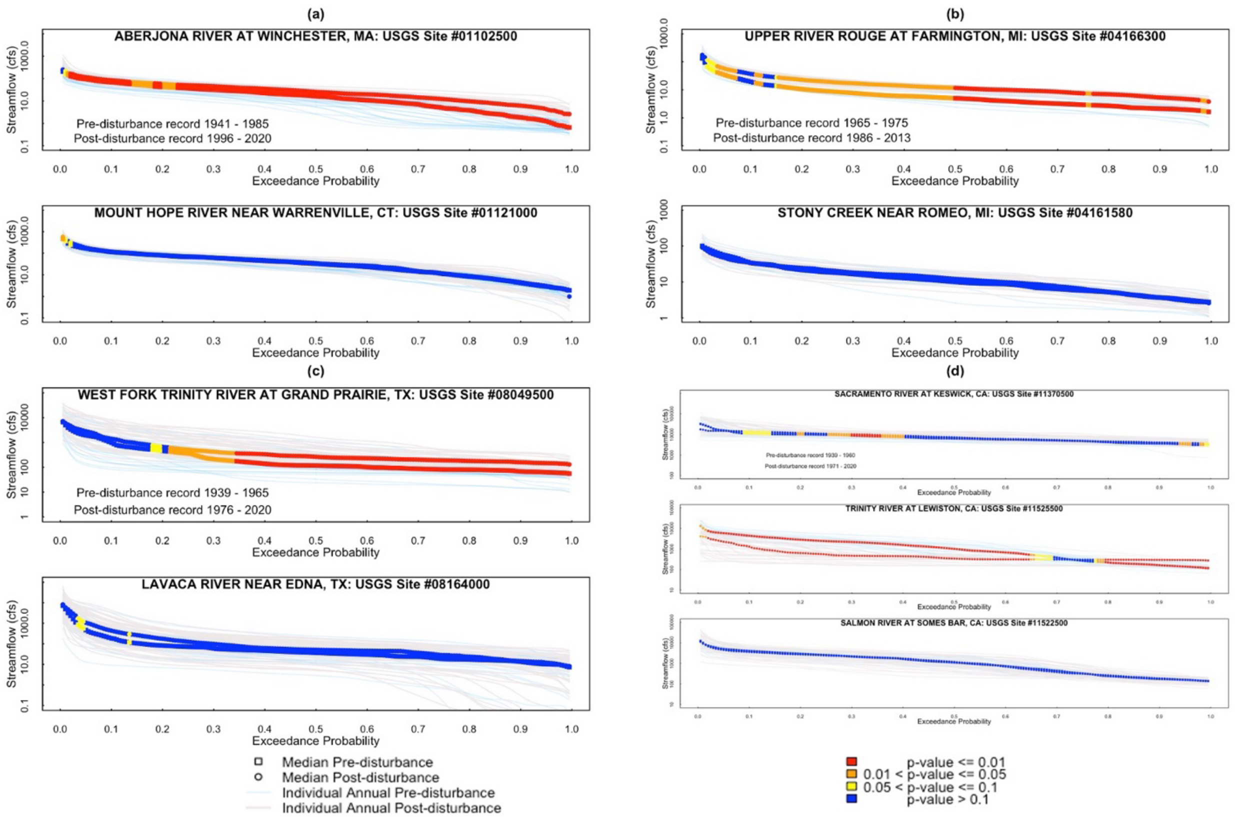

Figure 5: Results of MMMT at paired disturbed/not disturbed sites: a) Aberjona River (urbanization)/Mount Hope River, Upper River Rouge (urbanization)/Stony Creek, (b) West Fork (WF) Trinity River (wastewater effluent)/Lavaca River, and (d) Sacramento, Trinity River (interbasin transfer)/Salman River.

Figure 5c contains the pre- and post-alteration FDCs on the West 1 Trinity River at Grand Prairie, TX (USGS#08049500) with an HDI of 23. Upstream from this site, the Village Creek Water Reclamation Facility discharges wastewater effluent into the stream. This site was paired with the Lavaca River near Edna, TX (USGS#08164000) with an HDI of 13. On the West Fork Trinity River, almost two thirds of the FDC percentiles (intermediate and low flows) show significant alteration at a 1% level, while at the Lavaca River for the same concurrent record (water years from 1939-2020) a significant alteration at a 10% significance level occurred at only a few (high flow) percentiles near an exceedance probability of 1%. This example documents the significant impact wastewater effluent can have on streamflow, especially for moderate to low flows. One would expect such impacts to be related to the magnitude of both the wastewater discharge and streamflow.

Figure 5d contains pre- and post-alteration annual FDCs for three rivers. The first two are the Sacramento River at Keswick, CA (USGS#11370500; HDI 16) and the Trinity River at Lewiston, CA (USGS#11525500; HDI 17), with the Sacramento River receiving water transferred from the Trinity River. These two sites were paired with a site with very minor regulation, the Salmon River at Somes Bar, CA (USGS#11522500) with an HDI of 6. The Central Valley Project utilizes the surplus water (704,000 acre-feet/year) in the Trinity River Basin for the benefit of the San Joaquin River Valley. While this water transfer only has minimal significant impact on the Sacramento River with some significant changes between the exceedance probabilities of 10% and 40% and above 95%, on the Trinity River a much more significant impact can be observed, with median annual FDC percentiles significant at a 1% level across nearly the entire FDC. In contrast, the FDC of the minimally regulated Salmon River, showed no signs of significant alteration. Interbasin transfers are not the only form of alteration on the Sacramento and Trinity Rivers, as both sites have upstream lakes/reservoirs (Lake Shasta and Trinity Lake, respectively). The hydrologic alteration exhibited by these two rivers could be related to the combined impact of the interbasin water transfer as well as upstream reservoir operations.

3.4 HCDN Sites

McCabe and Wolock (2002) found a significant increase in average annual minimum and median daily streamflow at a subset of HCDN sites in the CONUS starting in 1970, with the most prominent increases in the eastern U.S. They attributed these increases to step changes in precipitation around 1970, a result corroborated by Small et al. (2006), Karkauer and Fung (2008) and Wang and Hejazi (2012). Of interest here is applying the MMMT to minimally regulated streamflow sites in the CONUS using the 1970 breakpoint to assess potential climatic changes on streamflows across the U.S. Here we employ a subset of the USGS's HCDN-2009 watersheds, which are generally considered minimally regulated, to assess significant changes in the median annual FDC at exceedance probabilities of 1% (Q01, high flows), 50% (Q50, median flows), and 99% (Q99, low flows) using the 1970 break point. Only HCDN-2009 sites with at least 15 years before 1970 and 15 years after 1970 were employed. To maximize the concurrent record our pre-disturbance record was 1952 – 1970 and our post-disturbance record was 1971 – 2020, resulting in 308 HCDN sites. We employ concurrent records across all sites so that our results are less impacted by varying record lengths and the regional climate is also expected to be more consistent across sites.

Figure 6 illustrates the results for Q01 (high flows), where the HCDN site locations are colored red if the p-value is less than 0.01, yellow if between 0.01 and 0.05, and orange if between 0.05 and 0.1 and blue otherwise. Since most of the points in Figure 5 are blue, we conclude that there are only minimum significant changes in the median annual Q01 before and after 1970. Table 3 contains the number of sites in each super region with significant changes in the median annual Q01. The percentage of sites with significant changes in the median annual Q01 (p-value < 0.1) ranged from 0% to 31% across super regions, with the upper midwestern U.S. and the southeastern U.S. having the largest percentages of significant differences.

Figure 7 illustrates the results for Q99 (low flows). Unlike for Q01, we see many significant changes in the median annual Q99. The percentage of sites with significant changes in the median annual Q99 (p-value < 0.1) ranged from 18% to 81% across super regions, with the upper midwestern U.S. having the most sites with significant changes and the midwestern and eastern U.S. having more than 40% of the sites with significant changes in the average Q99. These results are similar to those found by Douglas et al. (2000) who examined regional significance of trends in high and low flows, finding the upper midwestern U.S. to have the most significant trends in low flows. They are also similar to results found by McCabe and Wolock (2002) who identified significant changes in low streamflows in the northeastern U.S. using a 1970 break point.

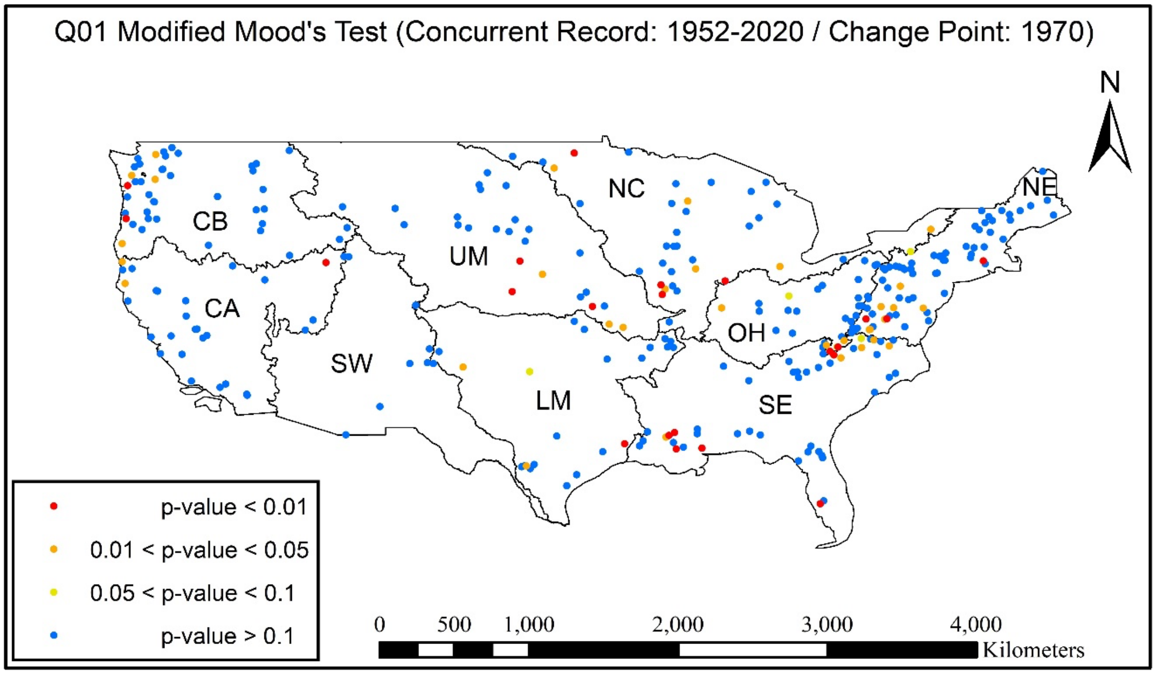

Figure 6: Results of MMMT for high flows (Q01) at 308 HCDN sites.

Table 3: Percentage of sites with significant changes in the median annual Q01, Q99 and Q50.

		High Flows (Q01)				**Median Flows (Q50)**				**Low Flows (Q99)**			
Region	**Number of Sites**	**p < 0.01**	**0.01 < p < 0.05**	**0.05 < p < 0.1**	**p > 0. 1**	**p < 0.01**	**0.01 < p < 0.05**	**0.05 < p < 0.1**	**p > 0.1**	**p < 0.01**	**0.01 < p < 0.05**	**0.05 < p < 0.1**	**p > 0.1**
NE	70	4.3%	10%	0.0%	85.7%	40.0%	30.0%	0.0%	30.0%	24.3%	20.0%	0.0%	55.7%
OH	26	7.7%	7.7%	7.7%	76.9%	61.5%	23.1%	3.8%	11.5%	34.6%	26.9%	0.0%	38.5%
SE	50	12.0%	12.0%	2.0%	74.0%	20.0%	18.0%	2.0%	60.0%	14.0%	4.0%	0.0%	82.0%
NC	36	11.1%	16.7%	2.8%	69.4%	41.7%	30.6%	2.8%	25.0%	55.6%	22.2%	2.8%	19.4%
UM	25	12.0%	12.0%	0.0%	76.0%	32.0%	12.0%	0.0%	56.0%	36.0%	16.0%	0.0%	48.0%
LM	23	4.3%	8.8%	4.3%	82.6%	17.4%	21.8%	4.3%	56.5%	21.8%	17.4%	4.3%	56.5%
SW	8	0.0%	0.0%	0.0%	100%	0.0%	25.0%	0.0%	75.0%	25.0%	0.0%	0.0%	75.0%
CB	42	4.8%	9.5%	0.0%	85.7%	2.4%	4.8%	0.0%	92.9%	19.0%	19.0%	2.4%	59.5%
CA	28	3.6%	7.1%	0.0%	89.3%	10.7%	3.6%	0.0%	85.7%	25.0%	14.3%	3.6%	57.1%
Total	**308**												

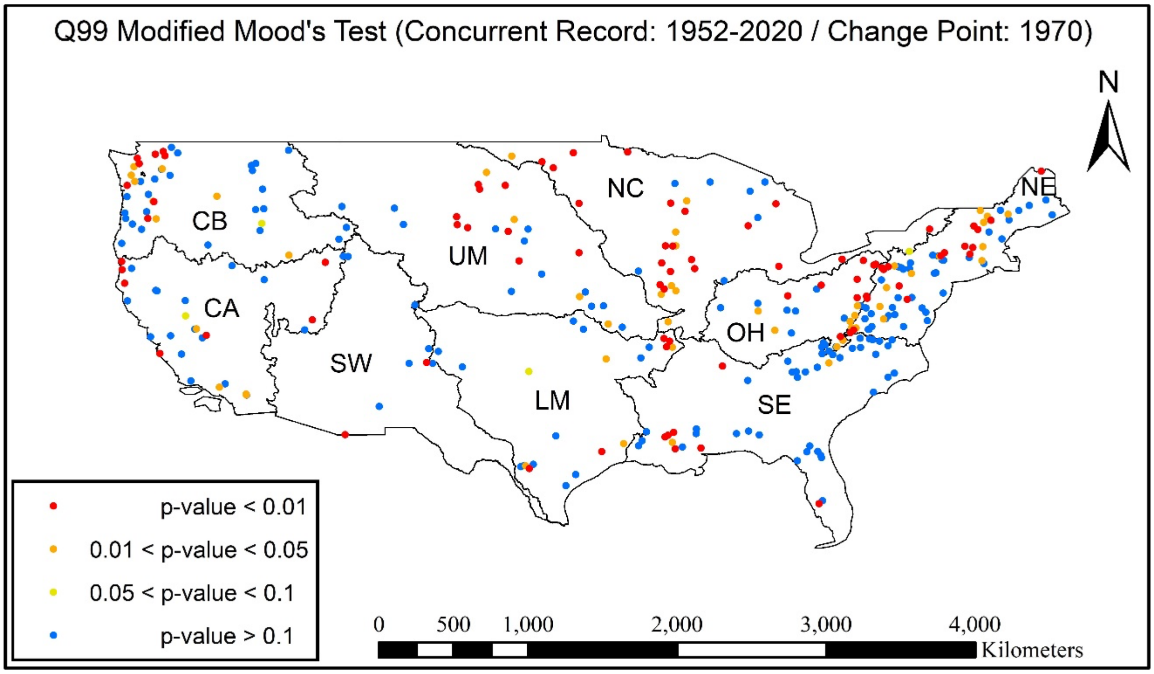

Figure 7: Results of MMMT for low flows (Q99) at 308 HCDN sites.

Figure 8 illustrates results for median annual Q50 (median flows), which indicate significant changes in the median annual Q50 at many HCDN sites across the U.S. The percentage of sites with significant changes in the median annual Q50 (p-value < 0.1) ranged from 7% to 88% across super regions, with the upper midwestern U.S., Ohio River Region and eastern U.S.

having the highest percentage of sites with significant changes in the median annual Q50. These results are similar to those found by McCabe and Wolock (2002), who also identified significant changes in the eastern U.S.

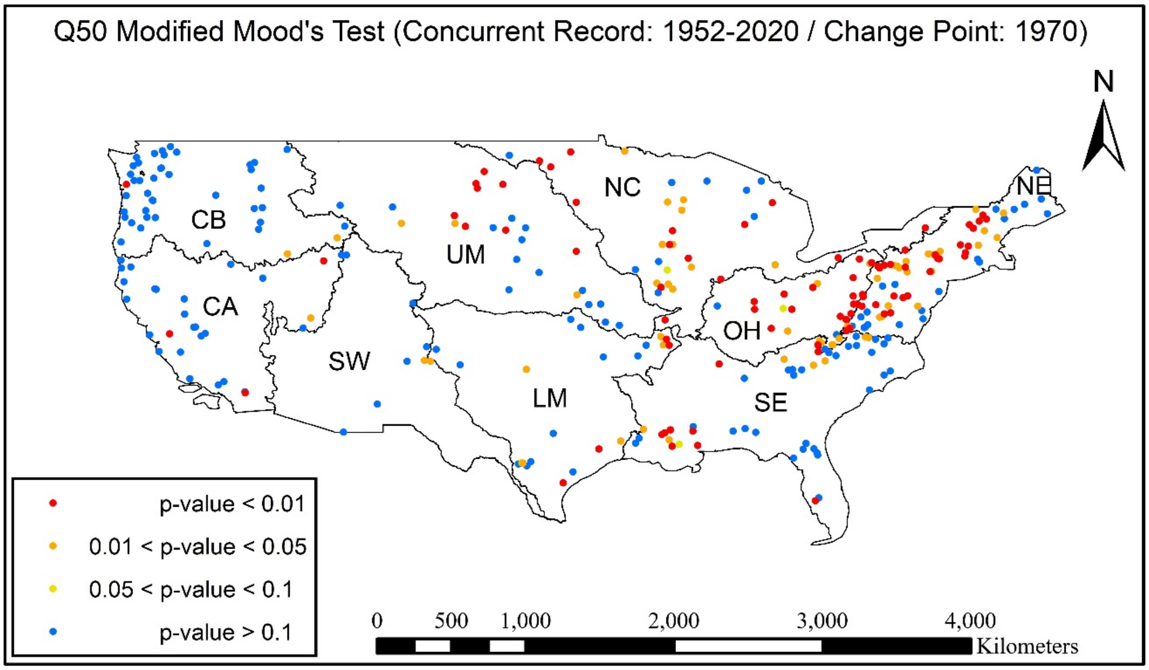

Figure 8: Results of MMMT for median flows (Q50) at 308 HCDN sites.

4.0 Discussion

Our graphical FDC-based hypothesis test based on MMMT has enabled us to demonstrate and illustrate that the alteration of flow regimes varies with the form and magnitude of disturbances. One would expect that alterations caused by a dam and reservoir operations would be different from alterations resulting from other forms of disturbance such as urbanization, climate change and/or wastewater treatment plant effluent discharge. Even for sites with a dam and reservoir, there was large variability in the alteration patterns. At a 5% significance level, around 41% of the sites with dams had significant alteration only at low flows, 10% of the dam sites showed significant alteration for only the high flows, and approximately 28% of the dam sites saw significant alterations for both low and high flows. While examining the reservoir operations policy is not part of this study, one might expect that the level of hydrologic alteration could be related to operating rules, characteristics of the reservoir and the primary purpose(s) of the reservoir system. Of course, there is also the possibility of several different disturbances acting together at a site. While the Tualatin River downstream from a multipurpose dam showed the expected behavior of significant alteration to high flows (decreasing) and low flows (increasing), the other three selected dam sites showed varied patterns of alteration. These patterns appear to be linked to the characteristics of the reservoirs and their management policies and purposes, though other additional forms of disturbance may also be involved at these sites.

Sites with other forms of hydrologic disturbance were also examined. Urbanization caused significant alterations (increases) to the entire FDC, a result consistent with the study by Allaire et al. (2015). At the West Fork Trinity River, where discharge from a wastewater treatment plant occurs above the gauge, two thirds of the FDC percentiles (intermediate and low flows) showed a significant alteration. This significant alteration for low and intermediate flows was not a surprise, given that the river may be composed of up to 90% wastewater during dry months (VCWRF, 2021). The impact of interbasin water transfers depends on the magnitude of both the transfer and the streamflows at both the donor and receiving watersheds. Additional sites with various forms of potential hydrologic disturbance should be examined to draw broader conclusions regarding patterns of alteration and other tools useful for evaluating the impact of multiple disturbances on streamflow regimes could also prove useful such as the multivariate elasticity approach introduced by Allaire et al. (2015) as well as the water regimes approach introduce by Weiskel et al. (2007).

Application of our methodology at minimally regulated HCDN sites spatially distributed across the CONUS indicated significant alteration to median and low streamflows in many regions of the U.S. when a 1970 break point was employed. The upper midwestern U.S. and eastern U.S. had the greatest densities of HCDN sites with significant alteration to median annual FDC percentiles with exceedance probabilities of 50% (median flows) and 99% (low flows). These results are consistent with those found be McCabe and Wolock (2002), who identified step changes in precipitation patterns in the eastern U.S. which drove changes in low flows before and after 1970. Douglas et al. (2000) also identified regionally significant trends in low flows in the upper midwestern U.S., which is consistent with our results. We recommend the application of the MMMT considering other break points, to further explore and illustrate the impacts of drivers of changes in hydrologic patterns across the U.S.

5.0 Conclusions and Recommendations

There is a need for a convenient, simple to understand graphical tool that illustrates and evaluates the statistical significance of impacts of hydrologic alteration across the entire range of streamflow. This study explored the use of Modified Mood's Median Test (MMMT), a non-parametric hypothesis tests that relies on no distributional or shape assumptions, for evaluating the significance and degree of hydrologic alteration based on the median annual flow duration curve (FDC). Importantly, this rigorous hypothesis test developed by others (Brown and Mood, 1951; Fligner and Rust, 1982) is introduced, evaluated, and converted into a graphical hydrologic tool to easily assess and illustrate hydrologic alteration across a wide variety of daily streamflow conditions. Prior to a potential hydrologic disturbance, it is assumed that there is an existing unaltered period of record with which the post-disturbance altered streamflow record can be compared. The graphical hypothesis test introduced was evaluated at 117 gaged sites spatially distributed across the U.S. (Figure 1) where a dam and reservoir has been placed on the stream, and 5 additional sites with other forms of hydrologic disturbance (urbanization, wastewater treatment plant discharge, and interbasin water transfer). Different types of disturbance generally alter the streamflow regime in different ways. In addition, using minimally regulated HCDN sites, we also evaluate this test to assess the hydrologic impacts of regional climate variations.

The results of these experiments indicated that:

- At sites with dams, significant hydrologic alteration was generally found to be much more likely for low flows than for flood flows. Across 117 sites with dams, Figure 3 documents that the percentage of sites with significant alteration consistently increased as the exceedance probability increased (flow magnitudes decreased). In contrast, at the lowest exceedance probabilities (flood flows) the percentage of sites with significant alteration consistently decreased as their flow exceedance decreased (flow increased).
- The four dam sites selected for more detailed analysis showed different patterns of alteration over different portions of the FDCs. These different patterns were generally linked to the location, characteristics (e.g., storage volume) and the primary purpose of the dam and reservoir.
- The two sites disturbed by urbanization showed significant alterations at nearly all FDC percentiles, indicating urbanization activities generally increase all magnitudes of streamflow.
- Sites disturbed by effluent discharge from a wastewater treatment plant generally resulted in significant alteration at intermediate and low flows.

- At sites with interbasin water transfers, the significance of the alteration appears to be a function of the magnitude of both the streamflows at the sites and the characteristics of the water transfers.
- At HCDN sites, when using the year 1970 as a breakpoint, there are significant changes to low and median flows, particularly in midwestern and northeastern U.S., yet our results indicate only minimal significant change in high flows.

We have developed a convenient, general, and simple to understand graphical tool to assess hydrologic alteration. The tool requires the presence of a pre- and post-alteration hydrologic series and assesses whether hydrologic flows in a "typical" (median) year have significantly changed across a wide variety of hydrologic conditions. The MMMT is a non-parametric test that requires no assumption regarding the distribution of the pre- and post-alteration series. Importantly, the graphical hypothesis testing tool introduced here is very general, and although we have only applied it to daily streamflow series in this analysis, it could be employed with any temporal series to assess system changes. Furthermore, the test is suited to any application of FDC's, one of the most widely used graphical instruments employed in the field of hydrology. For example, FDC's can accommodate seasonal variations by developing FDC's by month or season. Similarly, Vogel and Fennessey (1995) document how FDC's can be applied to any "water resource index derived from streamflow such as hydropower plant power output, instream pollutant concentrations and/or loads, and ecological habitat suitability indices." It is our hope that this graphical hypothesis test can serve as a graphical user interface in a wide range of water resource software applications where FDC's provide an overall summary metric of watershed system behavior. This tool, MMMT, is available on Github at https://github.com/cnkroll/MMMT.git.

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