Quantifying hydrologic alteration in an area lacking current reference conditions—The Mississippi alluvial plain of the south-central United States

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Abstract
Quantifying hydrologic alteration in the Mississippi Alluvial Plain (MAP) of the south-central United States is particularly difficult because of the lack of current reference, or even relatively undisturbed, streams and associated streamflow data. Impacts, such as water withdrawals for agriculture, weirs, dams, channelization, and other forms of regulation, within the MAP increased substantially beginning around 1960 suggesting that streamflow has since been altered. Using historical streamflow and climate data and explanatory variables, the U.S. Geological Survey developed random forest regression models to estimate expected reference monthly streamflows (pre-1960) at 76 sites in the MAP and two adjacent Level III Ecoregions. To compensate for the lack of current reference stream sites in the study area, the pre-1960 streamflow data were used as a surrogate to estimate current streamflow conditions without anthropogenic influence (inferring current reference conditions). Overall, nearly every site within the study area had less zero-flow days than what historically has been observed and there were more low-pulse spells. However, the frequency of floods remained relatively consistent.

KEYWORDS
environmental flows, hydrologic alteration, Mississippi Alluvial Plain, reference conditions

1 INTRODUCTION

Assessing the degree of hydrologic alteration in a stream is becoming increasingly important to water resource managers for understanding human effects on streamflow and for the establishment of ecological flow recommendations for the sustainability of a stream's biological health (Bunn & Arthington, 2002; Lytte & Poff, 2004; Poff et al., 1997; Poff & Zimmerman, 2010; and Richter, Baumgartner, Wigington, & Braun, 1997). To quantify the degree of hydrologic alteration in a given stream, reference streamflow conditions must first be established (Arthington, Bunn, Poff, & Naiman, 2006). A reference streamflow condition, in this context, is defined as streamflow considered relatively undisturbed by human activities such as irrigation withdrawals, impoundment, and channelization. At both a regional and national scale, streamflow records from reference (nondisturbed) U.S. Geological Survey (USGS) streamflow-gaging stations have been compared with streamflow records at altered locations to determine hydrologic alteration (Carlisle, Falcone, et al., 2010; Carlisle, Wolock, & Meador, 2010).
There are some geographic areas, however, where there is little to no streamflow data or where human disturbances are so pervasive that reference conditions can only be found in the historical streamflow record. Minihane (2012) used index-gage methods, a hydrologic model, and in-situ observations to estimate a 10-year historic baseline of mean monthly streamflows in the Rovuma River, an undeveloped stream with few streamflow observations, in southern Africa. In developed or altered streams, a variety of methods have been used to establish reference streamflow conditions using historical (pre-alteration) streamflow records (Henriksen, Heasley, Kennen, & Niewsand, 2006; Richter et al., 1997) so that the degree of alteration can be identified. The most common approach is to compare streamflow regimes between unimpacted and impacted time periods (Gao, Vogel, Kroll, Poff, & Olden, 2009). Candela, Tamoh, Olivares, and Gómez (2016) conducted a study in the Mediterranean basin and defined the baseline, historical period as 1984–2008 to compare streamflows with future climate and land-use change scenarios.

The Mississippi Alluvial Plain (MAP) of Arkansas, Louisiana, Mississippi, Missouri, and Tennessee (Figure 1) has been substantially modified by humans to facilitate agricultural production in the fertile floodplain of the Mississippi River. Land levelling, channelization, and irrigation withdrawals from surface-water and groundwater resources have changed the streamflow regime. For example, irrigation withdrawals from groundwater, and to a lesser extent surface water, in the MAP began prior to the 1920s. Compared with current (2014) conditions, groundwater withdrawals (Figure 2) were relatively low from the 1920s to about 1960 (Clark et al., 2011). Since 1960, withdrawals have increased and there have been subsequent observed decreases in streamflow and local areas of streamflow depletion within the MAP.

To identify the degree of hydrologic alteration of streams in the MAP, we used random forest (RF) regression methods (Breiman, 2001) to model the relation between six selected streamflow characteristics and explanatory variables (such as drainage area,......
precipitation, soils, and other watershed characteristics). RF models were chosen for this study because they have been proven to be more robust and accurate than traditional linear regression models (Carlisle, Falcone, et al., 2010; Lawler, White, Neilson, & Blaustein, 2006; Prasad, Iverson, & Liaw, 2006; Cutler et al., 2007). Expected monthly mean streamflow was estimated for a reference period (pre-1960) using daily streamflow data, climate data, and explanatory variables at 76 sites within the MAP and two adjacent Level III Ecoregions (study area). The reference period RF model was then used to estimate streamflow characteristics (flood frequency, high-flow duration, number of zero-flow days, frequency of low-pulse spells, and high-flow discharge index) and expected monthly streamflow for the 76 sites where post-1960 data were available. We discuss our results by comparing observed values with the expected values estimated by the RF models to identify stream sites that are altered within the study area. These analyses and considerations are crucial to better understand the effects of hydrologic alteration that impact human and biological water resource needs.

2 METHODS

2.1 Site selection

Streamflow-gaging stations with at least 5 years of continuous data prior to 1960 were considered candidate reference stations for this study (Figure 1). Cursory selection of stations with at least 5 years of data prior to 1960 within the MAP Level III Ecoregion (Omernik, 2004) yielded 52 stations (excluding the Mississippi River). Upon further investigation, stations with “chute” or “ditch” in their respective USGS station identifier names were removed; other stations were subsequently removed based upon review of historical literature, aerial photography, and topographic maps for the presence of anthropogenic influences, such as reservoirs, dams, weirs, and major channelization that occurred before 1960. Additionally, some stations were removed because much of their watershed was outside the boundary of the MAP. These reviews ultimately removed 37 stations leaving only 15 stations within the MAP, which was deemed insufficient for purposes of analysis for this study. To improve accuracy and minimize error of the regression models used to estimate expected streamflow, additional stations were needed. Thus, we extended the study area to adjacent Level III Ecoregions (the Mississippi Valley Loess Plains and the South Central Plains) to include additional stations having similar topographies and correlations of precipitation and evapotranspiration as those of the MAP (Wolock, 2003). After following the same review process used for selecting the original 15 stations within the MAP, 61 additional stations were included from adjacent ecoregions for a total of 76 potential stations (Figure 1; Table 1).

2.2 Estimation of expected values of streamflow and streamflow characteristics using RFs

RF regression methods (Kuhn & Johnson, 2016) were used to model relations between explanatory variables (such as climate, topography, soils, geology, and other watershed characteristics) and selected streamflow characteristics to produce a model that calculated expected monthly mean streamflow from daily mean streamflow for the reference period (preregulation or pre-1960) and the current (post-1960) period. For a detailed description of RF, see Cutler et al. (2007) and Liaw and Wiener (2002). For this study, R statistical software (R Development Core Team, 2014) was used to complete RF regressions using a package for R called “Random Forest” (Liaw & Wiener, 2002).

Observed mean monthly streamflow was calculated for every site for every month (for example, 10-1-1938 is the average flow for the
| Site number | USGS station number | USGS station name                              | Latitude (decimal degrees) | Longitude (decimal degrees) | Monthly mean flow average $O_{PR}$/E$_{PR}$ pre-1960 | Monthly mean flow average $O_{PR}$/E$_{PR}$ post-1960 | $O_{PR}$/E$_{PR}$ fh11 | $O_{PR}$/E$_{PR}$ dh20 | $O_{PR}$/E$_{PR}$ dl18 | $O_{PR}$/E$_{PR}$ fl3 | $O_{PR}$/E$_{PR}$ mh16 | Weighted $R^2$ for monthly mean flow |
|-------------|---------------------|------------------------------------------------|---------------------------|-----------------------------|--------------------------------------------------|--------------------------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|----------------------------------|
| 1           | 07024000            | Bayou De Chien near Clinton, Kentucky          | 36.628671                 | -88.963951                  | 0.82                                     | 0.94                               | 1.12                   | 0.62                   | 0.00                   | 0.00                   | 0.87                   | 0.91                             |
| 2           | 07025500            | North Fork Obion River near Union City, Tennessee | 36.399786                 | -88.995342                  | 0.94                                     | 0.89                               | 0.95                   | 0.72                   | 0.00                   | 0.00                   | 0.96                   | 0.93                             |
| 3           | 07026000            | Obion River at Obion, Tennessee                | 36.251179                 | -89.192569                  | 0.95                                     | 1.13                               | 0.94                   | 0.39                   | 0.00                   | 0.00                   | 0.96                   | 0.95                             |
| 4           | 07026040            | Obion River at Highway 51 near Obion, Tennessee | 36.240829                 | -89.217644                  | 0.95                                     | 1.06                               | 0.40                   | 0.00                   | 0.00                   | 0.00                   | 0.93                   | 0.95                             |
| 5           | 07026500            | Reelfoot Creek near Samburg, Tennessee         | 36.442286                 | -89.296459                  | 0.95                                     | 0.67                               | 1.00                   | 0.70                   | 0.20                   | 1.95                   | 1.03                   | 0.84                             |
| 6           | 07028000            | South Fork Forked Deer River at Chestnut Bluff, Tennessee | 35.862019                 | -89.347849                  | 0.95                                     | 1.02                               | 0.00                   | 0.00                   | 0.87                   | 0.96                   | 0.92                   |                                  |
| 7           | 07029000            | Middle Fork Forked Deer River near Alamo, Tennessee | 35.850627                 | -89.066732                  | 0.95                                     | 0.80                               | 0.63                   | 0.00                   | 0.00                   | 0.88                   | 0.96                   |                                  |
| 8           | 07030000            | Hatchie River near Stanton, Tennessee          | 35.522858                 | -89.349238                  | 0.95                                     | 0.93                               | 0.93                   | 0.40                   | 0.00                   | 0.00                   | 0.93                   |                                  |
| 9           | 07030500            | Wolf River at Rossville, Tennessee             | 35.054257                 | -89.54119                   | 0.95                                     | 1.08                               | 0.78                   | 0.00                   | 0.00                   | 0.70                   | 0.96                   |                                  |
| 10          | 07043000            | Castor River at Aquilla, Missouri              | 36.952733                 | -90.07034                   | 0.95                                     | 0.87                               | 1.21                   | 0.82                   | 0.36                   | 1.39                   | 1.09                   | 0.95                             |
| 11          | 07047600            | Tyronea River near Tyronea, Arkansas           | 35.505082                 | -90.380101                  | 0.91                                     | 0.93                               | 1.07                   | 0.58                   | 0.03                   | 0.01                   | 0.72                   | 0.91                             |
| 12          | 07047950            | LAnguille River at Palestine, Arkansas         | 34.972778                 | -90.885556                  | 0.85                                     | 1.00                               | 1.06                   | 1.01                   | 0.46                   | 0.67                   | 0.81                   | 0.91                             |
| 13          | 07077750            | Cache River at Patterson, Arkansas             | 35.269722                 | -91.236389                  | 0.93                                     | 1.22                               | 0.92                   | 1.36                   | 0.12                   | 0.70                   | 0.89                   | 0.96                             |
| 14          | 07078000            | Lagrange Bayou near Stuttgart, Arkansas        | 34.532042                 | -91.35568                   | 0.81                                     | 0.83                               | 0.00                   | 0.00                   | 0.88                   | 0.96                   | 0.92                   |                                  |
| 15          | 07264000            | Bayou Meto near Lonoke, Arkansas               | 34.736667                 | -91.915833                  | 0.64                                     | 0.69                               | 0.93                   | 0.98                   | 0.36                   | 0.93                   | 0.98                   | 0.9                             |
| 16          | 07264500            | Bayou Meto near Stuttgart, Arkansas            | 34.454263                 | -91.61624                   | 0.74                                     | 0.93                               | 0.93                   | 0.00                   | 0.00                   | 0.94                   | 0.94                   |                                  |
| 17          | 07265000            | Crooked Creek near Humphrey, Arkansas          | 34.426486                 | -91.667908                  | 0.65                                     | 0.94                               | 0.82                   | 0.00                   | 0.00                   | 0.85                   | 0.92                   |                                  |
| 18          | 07276000            | Coldwater River near Lewisburg, Mississippi    | 34.84093                  | -89.825643                  | 0.94                                     | 0.91                               | 0.91                   | 0.00                   | 0.00                   | 0.92                   | 0.92                   |                                  |
| 19          | 07277700            | Pigeonroost Creek near Lewisburg, Mississippi  | 34.83032                  | -89.822421                  | 0.92                                     | 1.35                               | 0.92                   | 0.00                   | 0.00                   | 0.95                   | 0.95                   |                                  |
| 20          | 07277500            | Coldwater River near Coldwater, Mississippi    | 34.720657                 | -89.988979                  | 0.90                                     | 0.82                               | 0.82                   | 0.00                   | 0.00                   | 0.92                   | 0.92                   |                                  |
| 21          | 07279500            | Coldwater River at Savage, Mississippi         | 34.633436                 | -90.23065                   | 0.95                                     | 0.71                               | 0.71                   | 0.00                   | 0.00                   | 0.84                   | 0.84                   |                                  |
| 22          | 07288500            | Big Sunflower River at Sunflower, Mississippi  | 33.54734                  | -90.543144                  | 0.96                                     | 1.00                               | 1.04                   | 0.76                   | 0.00                   | 0.78                   | 0.56                   | 0.91                             |
| 23          | 07290000            | Big Black River near Bovina, Mississippi       | 32.347778                 | -90.696944                  | 0.91                                     | 1.00                               | 1.01                   | 1.07                   | 0.00                   | 0.63                   | 0.58                   | 0.84                             |
| 24          | 07294500            | Homochitto River near Doloroso, Mississippi    | 31.331559                 | -91.360391                  | 0.94                                     | 0.65                               | 0.65                   | 0.00                   | 0.00                   | 0.91                   | 0.91                   |                                  |
| 25          | 07348700            | Bayou Dorcheat near Springhill, Louisiana      | 32.994581                 | -93.39656                   | 0.70                                     | 0.52                               | 0.66                   | 1.10                   | 0.01                   | 2.04                   | 0.85                   | 0.86                             |
| Site number | USGS station number | USGS station name                              | Latitude (decimal degrees) | Longitude (decimal degrees) | Monthly mean flow average |
|-------------|---------------------|------------------------------------------------|---------------------------|----------------------------|--------------------------|
| 26          | 07348800            | Flat Lick Bayou near Leaton, Louisiana          | 32.76959                  | -93.246835                 | 0.61                     |
| 27          | 07349430            | Bodcau Creek at Stamps, Arkansas                | 33.366791                 | -93.522399                 | 0.59                     |
| 28          | 07351900            | Bayou Dupont near Robeline, Louisiana           | 31.704334                 | -93.327394                 | 0.23                     |
| 29          | 07352000            | Saline Bayou near Lucky, Louisiana              | 32.250157                 | -92.976548                 | 0.90                     |
| 30          | 07352500            | Black Lake Bayou near Castor, Louisiana         | 32.261269                 | -93.214057                 | 0.88                     |
| 31          | 07352800            | Grand Bayou near Coushatta, Louisiana           | 32.048333                 | -93.302222                 | 0.69                     |
| 32          | 07353500            | Nantachie Creek near Montgomery, Louisiana      | 31.687667                 | -92.877934                 | 0.62                     |
| 33          | 07354000            | Little Sandy Creek at Kisatchie, Louisiana      | 31.40851                  | -93.170999                 | 0.66                     |
| 34          | 07354500            | Horsepen Creek near Provenal, Arkansas          | 31.601559                 | -93.201556                 | 0.02                     |
| 35          | 07355000            | Hemphill Creek near Hot Wells, Louisiana        | 31.297402                 | -92.736259                 | 0.61                     |
| 36          | 07362500            | Moro Creek near Fordyce, Arkansas               | 33.792222                 | -92.333333                 | 0.50                     |
| 37          | 07365000            | Saline River near Rye, Arkansas                 | 33.700833                 | -92.025833                 | 0.81                     |
| 38          | 07364150            | Bayou Bartholomew near McGhee, Arkansas         | 33.627778                 | -91.458333                 | 0.86                     |
| 39          | 07364300            | Chemin-A-Haut Bayou near Beekman, Louisiana     | 32.982072                 | -91.805682                 | 0.76                     |
| 40          | 07364500            | (COE) Bayou Bartholomew near Beekman, Louisiana | 32.872353                 | -91.867905                 | 0.87                     |
| 41          | 07364700            | Bayou De Loutre near Laran, Louisiana           | 32.955414                 | -92.49987                  | 0.94                     |
| 42          | 07365000            | Bayou D’Arbonne near Dubach, Louisiana          | 32.680702                 | -92.652928                 | 0.79                     |
| 43          | 07365500            | Middle Fork Bayou D’Arbonne near Bernice, Louisiana | 32.764034               | -92.658484                 | 0.73                     |
| 44          | 07365800            | Comie Bayou near Three Creeks, Arkansas         | 33.038056                 | -92.940556                 | 0.77                     |
| 45          | 07365900            | Three Creeks near Three Creeks, Arkansas        | 33.067082                 | -92.88405                  | 0.60                     |
| 46          | 07366200            | Little Comie Bayou near Lillie, Louisiana       | 32.929306                 | -92.62931                  | 0.86                     |
| 47          | 07368000            | Boed River near Girard, Louisiana               | 32.481253                 | -91.797904                 | 0.87                     |
| 48          | 07369500            | Tensas River at Tendal, Louisiana               | 32.432087                 | -91.366781                 | 0.84                     |
| 49          | 07369700            | Bayou Macon near Kilbourne, Louisiana           | 32.99318                  | -91.262162                 | 0.94                     |
| 50          | 07370500            | Castor Creek near Grayson, Louisiana            | 32.082103                 | -92.207083                 | 0.78                     |
| 51          | 07371500            | Dugdemona River near Jonesboro, Louisiana       | 32.207102                 | -92.901543                 | 0.82                     |
| 52          | 07372000            | Dugdemona River near Winnfield, Louisiana       | 31.975162                 | -92.652927                 | 0.78                     |
| Site number | USGS station number | USGS station name                  | Latitude (decimal degrees) | Longitude (decimal degrees) | Monthly mean flow average | Monthly mean flow average | \( O_{PR}/E_{PR} \) pre-1960 | \( O_{PR}/E_{PR} \) post-1960 | \( O_{PR}/E_{PR} \) dh20 | \( O_{PR}/E_{PR} \) f3 | \( O_{PR}/E_{PR} \) mh16 | Weighted \( R^2 \) for monthly mean flow |
|------------|---------------------|-----------------------------------|---------------------------|----------------------------|--------------------------|--------------------------|-----------------------------|-----------------------------|---------------------|----------------|----------------|------------------------------------------------|
| 53         | 07372200            | Little River near Rochelle, Louisiana | 31.754336                 | -92.344583                 | 0.86                     | 0.58                     | 1.14                        | 1.45                        | 0.00                 | 2.09           | 0.75           | 0.85                                                      |
| 54         | 07372500            | Bayou Funny Louis near Trout, Louisiana | 31.716282                 | -92.22358                  | 0.76                     | 0.71                     | 0.86                        | 0.83                        | 0.00                 | 1.83           | 1.32           | 0.93                                                      |
| 55         | 07373000            | Big Creek at Pollock, Louisiana      | 31.536287                 | -92.40847                  | 0.89                     | 0.69                     | 0.98                        | 0.69                        | 0.00                 | 0.15           | 0.42           | 0.7                                                       |
| 56         | 07381800            | Spring Creek near Glenmora, Louisiana | 31.00019                  | -92.966806                 | 0.94                     | 0.75                     | 1.34                        | 0.87                        | 0.00                 | 0.00           | 0.52           | 0.87                                                      |
| 57         | 08013000            | Calcasieu River near Glenmora, Louisiana | 30.96667                  | -92.67361                  | 0.85                     | 0.74                     | 0.81                        | 1.30                        | 0.00                 | 1.65           | 1.19           | 0.92                                                      |
| 58         | 08013500            | Calcasieu River near Oberlin, Louisiana | 30.640476                 | -92.81403                  | 0.91                     | 0.73                     | 1.00                        | 1.06                        | 0.00                 | 1.30           | 1.07           | 0.83                                                      |
| 59         | 08014000            | Simile Creek near Sugartown, Louisiana | 30.814638                 | -92.26264                  | 0.96                     | 1.05                     | 0.44                        | 0.94                        | 0.00                 | 0.00           | 0.79           | 0.88                                                      |
| 60         | 08014200            | Tenmile Creek near Elizabeth, Louisiana | 30.836582                 | -92.87404                  | 0.88                     | 0.91                     | 0.86                        | 1.04                        | 0.00                 | 1.00           | 1.00           | 0.92                                                      |
| 61         | 08014500            | Ouiska Chitto Creek near Oberlin, Louisiana | 30.69875                  | -92.89319                  | 0.94                     | 0.81                     | 1.28                        | 0.90                        | 0.00                 | 0.00           | 0.86           | 0.91                                                      |
| 62         | 08014800            | Bundick Creek near DeRidder, Louisiana | 30.818806                 | -93.23016                  | 0.99                     | 0.87                     | 0.86                        | 0.79                        | 0.00                 | 1.16           | 1.03           | 0.93                                                      |
| 63         | 08015500            | Calcasieu River near Kinder, Louisiana | 30.502556                 | -92.91541                  | 1.25                     | 1.04                     | 0.92                        | 1.03                        | 0.00                 | 0.53           | 0.84           | —                                                          |
| 64         | 08016400            | Beckwith Creek near DeQuincy, Louisiana | 30.471033                 | -93.35988                  | 0.83                     | 0.78                     | 1.01                        | 0.82                        | 0.00                 | 1.26           | 1.03           | 0.90                                                      |
| 65         | 08016600            | Hickory Branch near Kernan, Louisiana | 30.501588                 | -93.27932                  | 0.67                     | —                       | 1.19                        | —                           | —                    | —              | —              | —                                                          |
| 66         | 08016800            | Bear Head Creek near Starks, Louisiana | 30.33326                  | -93.62905                  | 0.73                     | 0.71                     | 0.85                        | 0.96                        | 1.71                 | 1.42           | 1.01           | 0.86                                                      |
| 67         | 08024000            | Bayou San Miguel near Zwolle, Louisiana | 31.652951                 | -93.65295                  | 0.56                     | 0.73                     | 1.12                        | 1.31                        | 4.71                 | 1.96           | 1.59           | 0.91                                                      |
| 68         | 08024060            | Blackwell Creek at Many, Louisiana | 31.580729                 | -93.46267                 | 0.00                     | 0.01                     | —                           | 0.93                        | 1.55                 | 1.74           | —              | —                                                          |
| 69         | 08024400            | Sabine River near Milam, Texas       | 31.467125                 | -93.74490                 | 2.62                     | 1.97                     | 0.96                        | 1.13                        | 0.00                 | 0.90           | 0.44           | —                                                          |
| 70         | 08024500            | Palo Gauchy Bayou near Hemphill, Texas | 31.386294                 | -93.83574                  | 0.68                     | 0.66                     | 1.13                        | 1.12                        | 2.50                 | 1.26           | 0.98           | 0.92                                                      |
| 71         | 08025500            | Bayou Toro near Toro, Louisiana     | 31.307127                 | -93.51573                 | 0.79                     | 0.85                     | 1.05                        | 0.80                        | 0.04                 | 1.15           | 0.78           | 0.96                                                      |
| 72         | 08028700            | Hoosier Creek near Merryville, Louisiana | 30.725756                 | -93.56017                  | 0.10                     | 0.07                     | 1.18                        | 0.67                        | 0.00                 | 0.00           | 0.41           | —                                                          |
| 73         | 08029500            | Big Cow Creek near Newton, Texas     | 30.818889                 | -93.78556                  | 0.88                     | 0.90                     | 0.89                        | 0.76                        | 0.00                 | 0.83           | 0.41           | 0.86                                                      |
| 74         | 08031000            | Cow Bayou near Mauriceville, Texas   | 30.18632                  | -93.90850                  | 0.24                     | 0.30                     | 0.83                        | 0.98                        | 0.20                 | 1.32           | 1.41           | —                                                          |
| 75         | 08039500            | Angelina River near Ebenizer, Texas | 31.015197                 | -94.15213                  | 1.46                     | 1.67                     | 0.85                        | 0.21                        | 12.87                | 2.51           | 0.37           | —                                                          |
| 76         | 08041500            | Village Creek near Kountze, Texas    | 30.397986                 | -94.26352                 | 0.89                     | 0.88                     | 0.92                        | 0.87                        | 0.00                 | 0.70           | 0.46           | 0.83                                                      |

Abbreviations: COE, U.S. Army Corps of Engineers; \( E_{PR} \), expected post reference; \( E_{R} \), expected reference; \( O_{PR} \), observed post reference; \( O_{R} \), observed reference; \( R^2 \), weighted correlation coefficient; USGS, U.S. Geological Survey.
month of October in 1938) from the start of the data to end of water year 2014, if available, or to the end of the period of record. A water year is defined as the 12-month period October 1, for any given year through September 30, of the following year. The observed mean monthly streamflows were divided into two periods, pre-1960 and post-1960. Pre-1960 values of streamflow were considered reference values and were used in conjunction with relevant (pre-1960) monthly climatic data and explanatory variables to create regression models to predict “expected” ($E$) values for both the pre- and post-1960 (post-reference) periods. The monthly climatic data were aggregated to match the period of streamflow record. The ratio of $O$ divided by $E$ ($O/E$) is the measure of the amount of hydrologic alteration—the greater the value of $O/E$ from 1.0, the greater the amount of hydrologic alteration. Observed streamflow from the period of record occurring after the reference period ($O_{PR}$, post-1960) was used to evaluate changes that occurred because of alteration to the hydrologic landscape within the study area by dividing $O_{PR}$ by $E_{PR}$.

More than 170 streamflow characteristics have been used in previous research as potential indices of hydrologic alteration (Henriksen et al., 2006 and Olden & Poff, 2003). The six characteristics selected for analysis in this study were chosen in consultation with representatives of natural resource agencies and organizations in Arkansas, Louisiana, and Mississippi and include the values of monthly mean streamflow, flood frequency ($fh11$), high streamflow duration ($dh20$), number of zero-flow days ($dl18$), frequency of low-pulse spells ($fl3$), and high flow-discharge index ($mh16$; Table 2). These are common indices used to represent biologically relevant streamflow attributes and are considered suitable for all stream types, except for $fh11$, which is considered suitable for superstable or stable groundwater perennial streams (Olden & Poff, 2003). All streamflow statistics were calculated using daily streamflow data available from the USGS National Water Information System (U.S. Geological Survey, 2014a). We calculated one observed value prior to 1960 ($O_0$) and one observed value post 1960 ($O_{1960}$) for each site for five of the streamflow statistics ($fh11$, $dh20$, $dl18$, $fl3$, and $mh16$). The $O_R$ for each site (for each statistic) was used to develop the expected value ($E_{PR}$) from the RF models using the same climate data and explanatory variables developed for the monthly models. We then calculated the degree of hydrologic alteration ($O_{PR}/E_{PR}$) for each statistic for the sites that had observed post-1960 streamflow data (Table 1).

### 2.3 Exploratory variables

Exploratory variables pertained to watershed size and geometry, meteorology (precipitation and temperature), geology, and soils. Watershed geometry and size were determined for this study using a geographic information system. Climate data were specific to the month and watershed for sites used in the regression analysis and were obtained from the Parameter-elevation Relationships on Independent Slopes Model dataset (PRISM; Daly et al., 2008). For each month of record for a station, a mean monthly value of precipitation and minimum and maximum temperature were determined from the PRISM grids. Using the extracted climatic data, evapotranspiration for the watershed was calculated using the Hargreaves method (Droogers & Allen, 2002; Hargreaves, 1994). In addition, the preceding monthly precipitation and minimum and maximum air temperature were also extracted for the previous 1 to 6 months. Evapotranspiration was then computed for the previous 1 to 6 months from the

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**TABLE 2** Streamflow characteristics, definitions, and performance metrics for select hydrologic characteristics to determine hydrologic alteration

| Statistical code | Definition | Performance metrics |
|------------------|------------|---------------------|
| **Monthly mean flow** | Mean monthly flow is the average flow for a given month of the year, as well as a mean monthly flow, by month, for the full period of record. | Weighted $R^2$ NRMSE (%) PBIAS (%) |
| $fh11$ | Flood frequency. Statistic here is the average number of events with flows above a threshold equal to flow corresponding to a 1.67-year recurrence interval. The $fh11$ is the average number of events (number of events/year−temporal). | 0.89 26.5 5.7 |
| $dh20$ | High-flow duration. Statistic here is the 75th percentile value for the entire flow record or the average duration of flow events with flows above a threshold equal to the 75th percentile value for the median annual flows. The $dh20$ is the average duration of the events (days−temporal). | 0.87 31.1 −0.1 |
| $dl18$ | Number of zero-flow days. Statistic here is the count of the number of zero-flow days for the entire flow record. The $dl18$ is the mean annual number of zero-flow days (number of days/year−temporal). | 0.63 42.4 7.7 |
| $fl3$ | Frequency of low-pulse spells. Statistic here is the average number of flow events with flows below a threshold equal to 5% of the mean flow value for the entire flow record. The $fl3$ is the average number of events (number of events/year−temporal). | 0.84 32.2 0.4 |
| $mh16$ | High flow-discharge index. Statistic here is the 10% exceedance value for the entire data record. The $mh16$ is the 10% exceedance value divided by the median flow for the entire record (dimensionless−spatial). | 0.74 38.5 1.6 |

Abbreviations: NRMSE, normalized root mean square error; PBIAS, percent bias; $R^2$, weighted correlation coefficient.
precipitation and temperature data. Soils data were obtained from the Soil Survey Geographic Database (U.S. Department of Agriculture, 2015), and a single mean value was assigned to each watershed. Explanatory variables describing the percent of each watershed’s position on the geologic time scale and origin of geologic units were obtained from Reed and Bush (2005). Topographic data were obtained from the National Elevation Dataset (U.S. Geological Survey, 2014b) and included the mean, minimum, maximum, standard deviation, and range for slope and elevation. Explanatory variable data used as input for the RF models and the estimated values for streamflow and the streamflow characteristics that support the findings in this paper are available from Hart and Breaker (2018).

2.4 Model evaluation and assessment of hydrologic alteration

To select the best number of trees and splits for the final RF model, a “leave-one-out” validation process was used. The process involved iterative runs of the RF model using specific values for number of trees and number of splits with the data from an individual station removed. After each iteration, the model was evaluated against data from the station left out of a specific run, and the root mean square error (RMSE) of the observed reference period (O\textsubscript{R}) and expected (or predicted) reference period (E\textsubscript{R}) data were recorded. This process was iterated through all stations, and the resulting values of RMSE were used to select the number of trees and splits for the final model. Performance metrics used to evaluate monthly streamflow included the weighted correlation coefficient (R\textsuperscript{2}; Tables 1 and 2), normalized RMSE (NRMSE), and percent bias (PBIAS; Moriasi et al., 2007). Performance metrics were computed for all regression equations for all values of O\textsubscript{R}/E\textsubscript{R} independently for monthly mean streamflow and for the entire reference period for fh11, dh20, dl18, fl3, and mh16 (Table 2). The weighted R\textsuperscript{2} ranged from 0.24 to 0.97 with an average of 0.89, indicating a good model fit and the ability to predict what unaltered streamflow would be in a currently altered landscape, such as the MAP. The weighted R\textsuperscript{2} for the five streamflow characteristics ranged from 0.63 to 0.89—model fit of dl18 was the lowest value. PBIAS ranged from −4.3 to 59.1 with an average of 5.7, and NRMSE ranged from 8.1 to 325.1 with an average of 26.5.

In addition, the observed monthly mean streamflow for the reference period (O\textsubscript{R}) was compared with the expected monthly mean streamflow for the reference period (E\textsubscript{R}) to evaluate overall model performance and validate the model’s ability to predict what unaltered streamflow would be in the currently altered landscape of the MAP. The values of O\textsubscript{R} were divided by the values of E\textsubscript{R} to obtain O\textsubscript{R}/E\textsubscript{R}.

FIGURE 3 Values of hydrologic alteration for select streams within the study area for (a) April mean monthly streamflow, (b) September mean monthly streamflow, and (c) annual mean monthly streamflow [Colour figure can be viewed at wileyonlinelibrary.com]
A value of $O/E_R$ near 1 indicated that the RF regression was a good predictor of streamflow statistics for the expected post-1960 monthly mean streamflow ($E_{PR}$). The resulting outputs from the RF regression model provided a reasonable comparison of expected to observed monthly mean streamflow (median value of 0.85) for sites in the study area using current climate data (Table 1). Furthermore, the $O/E$ value for monthly mean flow prior to 1960 for most sites was closer to 1 than the $O/E$ value post 1960.

$O/E_{PR}$ values below 0.8 and above 1.2 were considered representative of hydrologic alteration for this study. Furthermore, for monthly mean streamflow, if a value was below 0.8, that indicated there was less observed streamflow than what was expected, and a value above 1.2 indicated there was more observed streamflow than what was expected. For all other streamflow statistics, if the value was below 0.8, then there were less observed number of days, less observed frequency, and less observed duration than what was expected. A value above 1.2 indicated there were more observed values than what was expected.

3 | RESULTS AND DISCUSSION

For most streams, the monthly ratio of $O_{PR}/E_{PR}$ was less than 0.8, which indicated less streamflow was measured in the streams than what was currently expected (Table 1). We then chose to examine a range of hydrologic alteration representing a high (April) and a low (September) streamflow period (Figure 3). Observed monthly mean streamflows for April were shown to deviate from model predictions at a rate that increased to the end of the reference period (Figure 3a) for all stations. Station 07368000 (Site No. 47 in Table 1 and Figure 1) shows the greatest divergence from expected streamflow out of all sites. During the month of September (Figure 3b), the

![Figure 4](https://wileyonlinelibrary.com)
observed streamflow was greater than the expected streamflow (higher O/E values) indicating more extreme observed run-off events than should be expected beginning approximately in 1955. There is a distinct change in the degree of hydrologic alteration in annual mean streamflow O/E values for the select streams occurring from 1955 to 1960 (Figure 3c). This is coincident to when anthropogenic influences (i.e., groundwater withdrawals in Figure 2) in the hydrologic system began to increase in the study area.

We further examined Station 07368000 Boeuf River near Girard, LA (hereafter referred to as Boeuf River-Girard; Site No. 47 in Figure 1 and Table 1) as an extreme and clear example of hydrologic alteration. The hydrograph for mean April streamflow (high-flow period; Figure 4a) demonstrated model performance for matching the reference period expected (E_R) streamflows to the reference period (pre-1960) observed streamflows (O_R). From the beginning of the period of record (late 1930s) until about 1955, the expected

![FIGURE 5 Observed/estimated values for select hydrologic statistics within the study area for (a) fh11, (b) dh20, (c) dl18, (d) fl3, and (e) mh16. Triangles represent sites within the Mississippi Alluvial Plain [Colour figure can be viewed at wileyonlinelibrary.com]](image)
streamflow and the observed streamflow were closely aligned; however, beginning in about 1955, the observed and expected streamflows diverged and the degree of hydrologic alteration (O/E) increased (Figure 4a). During low-flow periods (September; Figure 4b), mean monthly streamflow also started showing a divergence between expected and observed values around 1960. However, there were two years (1963 and 1978) when the observed and expected mean monthly streamflows were about the same. The average \( \frac{O_{PR}}{E_{PR}} \) for the low-flow period and high-flow period was 0.22 and 0.16, respectively, indicating hydrologic alteration had less effect on low-streamflow periods at this site.

Streamflow characteristics indicative of frequency and duration in the study area varied in degree of alteration and in geographic location of altered streams (Figure 5a–d). The \( f_{h11} \) statistic is the average number of peak streamflow events with streamflows above a threshold equal to streamflows corresponding to a 1.67-year recurrence interval. Peak streamflows were computed from the peak flow file, and daily values were used to quantify the number of events per year above the 1.67-year recurrence interval. Over 80% of the sites in the study area showed no degree of hydrologic alteration in the flood frequency. Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 0.40 to 0.79 occurred at eight sites (Figure 5a; Table 1), inferring that fewer events above the 1.67-year recurrence interval are occurring at these sites relative to what occurred in the past during the reference period. \( \frac{O_{PR}}{E_{PR}} \) ranged from 1.21 to 1.4 at five sites, inferring that more events above the 1.67-year recurrence interval are occurring at these sites. The \( f_{h20} \) statistic is computed as the average number of daily streamflow events with streamflow below a threshold equal to 5% of the mean streamflow values. The frequency of low-pulse spells was greater in the southern part of the study area (Louisiana). Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 0.00 to 0.79 occurred at 22 sites (Figure 5d; Table 1), indicating a decrease in low-flow pulse spells. Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 1.21 to 2.51 occurred at 29 sites throughout the study area, indicating an increase in low-flow pulse spells at the respective location.

The \( dh_{20} \) statistic is computed as the average duration of daily streamflow events with streamflows above a threshold equal to the 75th percentile value for the median annual daily streamflows. The expected high-flow duration was unchanged in over half of the study sites. Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 0.21 to 0.79 occurred at 18 sites throughout the study area (Figure 5b; Table 1), indicating a decrease in the duration of daily mean streamflows above the 75th percentile value for the median annual daily streamflows. \( \frac{O_{PR}}{E_{PR}} \) values ranging from 1.21 to 1.7 occurred at 11 sites throughout the study area, demonstrating an increase in duration of streamflows above the 75th percentile value for the median annual daily streamflows. The \( dh_{18} \) statistic is computed as the number of zero-streamflow days, and almost all of the sites showed a change in this streamflow characteristic. Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 0.00 to 0.79 occurred at 48 sites throughout the study area (Figure 5c; Table 1), which showed a decrease in the amount of zero-flow days relative to the reference period. Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 1.21 to 12.87 occurred at 14 sites located in the southern half of the study area, which showed an increase in the amount of zero-flow days relative to the reference period.

The \( mh_{16} \) statistic is computed as the 10% exceedance value for the evaluated record divided by the median. \( \frac{O_{PR}}{E_{PR}} \) values ranging from 0.37 to 0.79 occurred at 23 sites throughout the study area (Figure 5e; Table 1), indicating a decrease in high flow-discharge index at the respective sites. Values of \( \frac{O_{PR}}{E_{PR}} \) ranging from 1.21 to 1.60 occurred at five sites located in the southern half of the study area, indicating an increase in the high flow-discharge index at the respective sites relative to \( O_R \).

For an area like the MAP, any alterations in streamflow and characteristics can be directly related to land use and water use changes. For instance, changes in the number of zero-flow days in a stream could be a result of increases in water use conservation and surface runoff to streams from land-leveling practices. There could also be influence from water-capture structures like weirs and dams.

4 CONCLUSIONS

Our analysis demonstrates that RF regression models can be created from historical streamflow data at undisturbed references sites. Although unaltered reference stations are not present in contemporary time, there were enough data available prior to landscape and water use changes (pre-1960) to calibrate a model of streamflow.
and select streamflow characteristics in the MAP and to estimate current, expected unaltered streamflow at up to 76 sites. As expected, there are some indicators of hydrologic alteration in streams of the study area; however, low-flow characteristics seemed to show a greater response than characteristics related to high flows.

Time spent on historical research, such as review of historical topographic maps, historical aerial photography, and literature review could prove helpful and be an effective exercise to help establish reference streamflow records in altered landscapes. Deviations from reference conditions can affect ecosystem health and future needs for water supply and recreation. Determining the degree of and the characteristics most impacted by hydrologic alteration, particularly in agricultural landscapes like the MAP, can inform water resource managers and their decisions related to future development of water resources in altered landscapes.

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