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Defining critical or hydrologic conditions as sampled during the Joint Study

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EXECUTIVE SUMMARY

The "Joint Study" was conducted to fulfill the obligations of the second "Statement of Joint Principles and Actions" agreed to by the states of Arkansas and Oklahoma. The "Joint Study" affirmed the magnitude of Oklahoma's Scenic River total phosphorus (TP) criteria (i.e., 0.037 mg/L), but it added the new caveat of applying the criteria to "critical conditions." The primary purpose of this paper was to define "critical conditions" based on the range in base flow proportions (BFP) of total streamflow on days that were sampled in the "Joint Study," where BFP is base flow discharge divided by total stream flow for a given site and sampling date. We focused on 20 stream sites that could be paired with USGS stream discharge monitoring stations where water samples were collected approximately 12 times over the two-year "Joint Study" (June 2014–April 2016). In fact, 93% of the water samples from the "Joint Study" used to measure TP concentrations were collected when base flow contributions were 80 percent or more of total stream flow (i.e., BFP greater than or equal to 0.80). A subset of these sites in northwest Arkansas have been monitored more frequently between 2015 and 2019, and data from these sites (plus one additional urban stream) was used to evaluate the relation between TP concentrations and BFP. Across all sites, TP concentrations decreased as a function of increasing BFP – that is, TP concentrations were less on average as the proportion of base flow discharge increased at each site. The change in TP concentration per 0.1 unit change in BFP was positively correlated to mean TP concentrations when BFP was greater than 0.80. Defining the appropriate hydrologic conditions to assess the magnitude of the Oklahoma Scenic River TP criteria (0.037 mg/L) definitely matters for streams with TP concentrations approaching 0.037 mg/L during "critical conditions." For example, if three water samples were collected at BFPs of 0.80, 0.70 and 0.60 with TP of 0.037 mg/L during "critical conditions," then the mean of those three samples could [theoretically] be 0.045 mg/L (exceeding the TP criteria magnitude). Thus, if the TP criteria was going to be applied outside the hydrologic conditions studied, it should be adjusted based on the relation between TP concentrations during "critical conditions" and change in TP concentration per 0.1 unit change in BFP.

BACKGROUND AND INTRODUCTION

The Illinois River Watershed has been the focus of environmental concerns and issues for decades, and the states of Arkansas and

Oklahoma signed a first "*Statement of Joint Principles and Actions*" in 2003 with the goal of improving and protecting water quality. This agreement continued several watershed management changes, including municipal phosphorus (P) effluent reductions, poultry litter export and nutrient management with a P index; these actions, among others, resulted in significant reductions in total P (TP) concentrations and loads across the watershed (Haggard, 2010; Scott et al., 2011). The elevated TP concentrations at the Illinois River can be traced upstream over 45 river km to the major effluent input (Ekka et al., 2006; Haggard, 2010). However, the TP concentrations in the Illinois River near the state border did not decrease to a level near the Scenic Rivers TP criteria (0.037 mg/L; OWRB, 2002).

The next step occurred when the states of Arkansas and Oklahoma signed a second "*Statement of Joint Principles and Action*"" in 2013 (hereafter, second statement), providing a continuation of the first statement's agreement for three years and setting up the requirements of the "Joint Study." This study of the Illinois River Watershed, Arkansas and Oklahoma, evaluated "the TP threshold response level at which any statistical shift in algal species composition or algal biomass production resulting in undesirable aesthetic or water quality conditions" occurred (Haggard et al., 2017). There were three important components to this, including the need to define TP threshold, to follow EPA's most recent guidance on stressor–response studies (EPA, 2010), and to include sampling sufficient to determine the frequency and duration component of the criterion. However, the latter was focused on assessment, not promulgation of the water quality standard.

The sampling sites selected for the "Joint Study" included 35 stream reaches with the majority of sites within five of the six watersheds of Oklahoma's Designated Scenic Rivers (mostly within the larger Illinois River Watershed). The stream reaches were selected to be not different in terms of an open canopy, type of substrate, and hydrology considering riffles with turbulent flow. Water and biological sampling was every other month during "**critical conditions"** from June 2014 to April 2016, where sampling, analytical, and data analysis details are available in the appendix to Haggard et al. (2017). The term "**critical conditions"** was subjectively defined as hydrologic conditions "where surface runoff is not the dominant influence of total flow and stream ecosystem processes" (Haggard et al., 2017). More specifically, this is the hydrologic condition with which the "Joint Study" was conducted.

Based on the multiple lines of evidence and a general focus on nuisance algal species in the "Joint Study" (see Haggard et al., 2017), the Joint Study Committee unanimously recommended "a six-month average TP level of not to exceed 0.035 mg/L based on water samples taken during the CRITICAL CONDITION, as previously defined, was necessary to protect the aesthetics beneficial use and scenic river (Outstanding Resource Water) designations assigned to the designated Scenic Rivers." This meant the magnitude identified by the "Joint Study" was within the strike zone (±0.01 mg/L) defined by the second statement, allowing Oklahoma to keep the magnitude of the existing Scenic Rivers TP criteria (0.037 mg/L; OWRB, 2002). Oklahoma is moving forward to revise the Scenic Rivers TP criteria, proposing "the total phosphorus six month rolling average of 0.037 milligrams per liter (mg/L) shall not be exceeded more than once in a one-year period and not more than three times in a five-year period" (OWRB, 2021). However, the new caveat is linking the magnitude to "**critical conditions**."

The purpose of this paper is to define the hydrologic conditions under which the "Joint Study" was conducted to better understand the term "***critical conditions***" defined by the six-person Joint Study Committee and scientific professionals. The objectives were to (1) define the range in base flow proportions (BFP) of total streamflow on days that were sampled in the "Joint Study", (2) evaluate the relation between TP concentrations and BFP across limited sites, and (3) present potential numeric adjustments to the magnitude if assessed outside the hydrologic conditions sampled during and relied upon to conduct the "Joint Study".

METHODS

The hydrology data from the US Geological Survey (USGS) stream gages (n=20) that were paired with or in close proximity to sampling sites within the 'Joint Study' was downloaded from the National Water Information System (NWIS). These pairs included [alphabetically] BARR1 Barron Fork at Dutch Mills, AR (USGS 07196900); BARR4 Barron Fork at Eldon, OK (USGS 07197000); BEAT1 Beaty Creek near Jay, OK (USGS 07191222); CANE1 Caney Creek near Barber, OK (USGS 07197360); FLIN1 Flint Creek near Springtown, AR (USGS 07195800); FLIN2 Flint Creek near West Siloam Springs, OK (USGS 07195855); ILLI2 Illinois River at Savoy, AR (USGS 07194800); ILLI3 Illinois River at HWY16 near Siloam Springs, AR (USGS 07195400); ILLI4 Illinois River South of Siloam Springs (USGS 07195430); ILLI5 Illinois River near Watts, OK (USGS 07195500); ILLI6 and ILLI7 Illinois River at Chewey, OK (USGS 07196090); ILLI8 Illinois River near Tahlequah, OK (USGS 07196500); LLEE1 Little Lee Creek near Nicut, OK (USGS 07249920); OSAG1 Osage Creek near Cave Springs, AR (USGS 07194880); OSAG2 Osage Creek near Elm Springs, AR (USGS 07195000); SAGE1 Sager Creek near West Siloam Springs, OK (USGS 07195865); SPAR1 Spring Creek at HWY112 near Springdale, AR (USGS 07194933); SPAV1 Spavinaw Creek near Maysville, AR (USGS 07191160); and SPAV2 Spavinaw Creek near Colcord, OK (USGS 071912213). Sixteen of these sites are within the drainage area of the Illinois River Watershed in Arkansas and Oklahoma.

The data from these sites were used in hydrograph separation (i.e., HYSEP, Sloto and Crouse, 1996) to quantify the base flow proportion on individual sampling dates specifically used in the study. Mean daily discharge records from each USGS gaging station were used in HYSEP with the R code from the USGS–R/DVstats GitHub (https://rdrr.io/github/USGS-R/DVstats/man/hysep.html). The hydrograph separation begins one interval (2*N, where N is five days) prior to the start of the dates selected and ends one interval after the final date of interest. The method within HYSEP selected was the sliding–interval method, which finds the lowest discharge in one half the interval [0.5(2*N-1)] before and after the date of interest and assigns that discharge to that day as base flow. These assigned discharges were connected to form the estimated base flow hydrograph and for computing the base flow proportion (base flow/total flow) for each sampling date in the "Joint Study." While all HYSEP methods were evaluated, the sliding interval approach was presented within to be consistent with OWRB's evaluation of hydrograph separation (OWRB, 2020). The BFP range on days that were sampled in the "Joint Study" was presented using box plots (*Objective 1*), where BFP is the base flow discharge in cubic feet per second (cfs) divided by the total discharge (cfs) at a site on a given sampling date.

At select streams in Northwest Arkansas, the Arkansas Water Resources Center (AWRC) has collected water samples following the same sampling procedures since ~2009 (see Scott and Haggard, 2019). These sites, which are paired with USGS gages, include the Illinois River at Savoy (ILLI2), South of Siloam Springs (ILLI4), and Watts (ILLI5), Osage Creek near Elm Springs (OSAG2) and at Highway 112 (OSAG1), Spring Creek at Highway 112 (SPAR1), Mud Creek at Fayetteville (not included in "Joint Study") and the Baron Fork at Dutch Mills (BARR1). Water samples are collected from bridges just below the surface using an alpha style horizontal sampler near the centroid of stream flow; water samples are collected 2–4 times per month across the range of flow conditions observed at each site. Total P was measured in water samples in the certified AWRC water quality lab using persulfate autoclave digestion and standard methods (APHA 4500-P J; EPA 365.1) on a Skalar Sans Plus wet chemistry auto–analyzer (Skalar Analytical BV, The Netherlands). Total P concentration data from CY 2015 through 2019 were paired with BFPs estimated at each site as described above. The relation between BFP and TP concentration was evaluated using simple linear regression (*Objective 2*), where TP concentrations changed near linearly with BFPs (typically BFP greater than 0.50 across sites).

The assumption is that TP concentrations and base flow proportion are related and that if one intends to apply nutrient threshold outside the conditions studied (i.e., range in base flow proportion), then the relation (i.e., linear regression and slope) could be used to adjust the magnitude to fit the desired conditions. The state of Oklahoma has proposed the Scenic River TP Criterion be extended to water samples collected with a BFP of 55% or greater (see OWRB, 2020) based on its own hydrograph separation analysis and interpretation of '**critical conditions**'. We used the slope of the linear regressions between BFP and TP concentrations to provide an adjustment factor, suggesting changes to the criteria magnitude if the nutrient threshold was applied or assessed outside the conditions sampled in the "Joint Study" (*Objective 3*).

RESULTS

Base Flow Proportion on Joint Study Sampling Dates

Base flow conditions were dominant on almost all dates sampled by the "Joint Study." The 35 sites used in the "Joint Study" were narrowed down to 20 sites that had USGS discharge gaging stations at or near close proximity, and these sites were sampled on dates (June 2014–April 2016) when BFP was greater than 0.75 on almost all dates. The 3rd percentile of calculated BFPs across all sites and dates was 0.75, showing that all but five events across all sites had BFPs at 0.75 or greater. These individual events were looked at more closely, showing:

(1) on or around 5 December 2014 at BARR1 a minor hydrograph peak of approximately 40 cfs occurred, resulting in a BFP of 0.35;

(2) on or around 18 June 2014 at BEAT1 there was ~100 cfs event, resulting in a BFP of 0.56;

(3) on or around 8 August 2014 at BEAT1 another minor hydrograph peak of approximately 20 cfs occurred, resulting in a BFP of 0.38;

(4) on 10 December 2015 ILLI3 was sampled on the receding limb of a larger storm event (peak discharge ~8300 cfs), when BFP was calculated to be 0.62; and

(5) on 7 December 2014 ILLI8 was sampled on the rising limb of a relatively modest storm event (peak discharge ~1600 cfs) when BFP was 0.74.

Base flow proportion was not calculated for two events at one stream (i.e., CANE1) because the "Joint Study" did not sample that site during Event 7 or 10. Including these five events above, mean and median BFPs calculated across all sites and sampling dates were 0.92 and 0.94, respectively. The BFP calculated across all sites and sampling dates exceeded 0.80 almost 93% of time during this study.

If we focused on the sites in the Illinois River Watershed, then that reduced our site numbers down to 16 sites with paired or close proximity USGS stream gages (excluding BEAT1, SPAV1, LLEE1 and SPAV2; Figure 1). The mean and median calculated BFPs were 0.92 and 0.94 across only the sites in this watershed. The BFP calculated across all 16 of these sites and sampling dates exceeded 0.80 almost 93% of time, showing that base flow conditions were dominant on almost all dates. If we focused exclusively on the sampling events and base flow conditions on the Illinois River (Figure 1, top graph; ILLI2–ILLI8), mean BFP was 0.92 across all sites. The two least BFPs sampled were noted in a preceding paragraph, and next least BFP was 0.77 across the sites on the Illinois River.

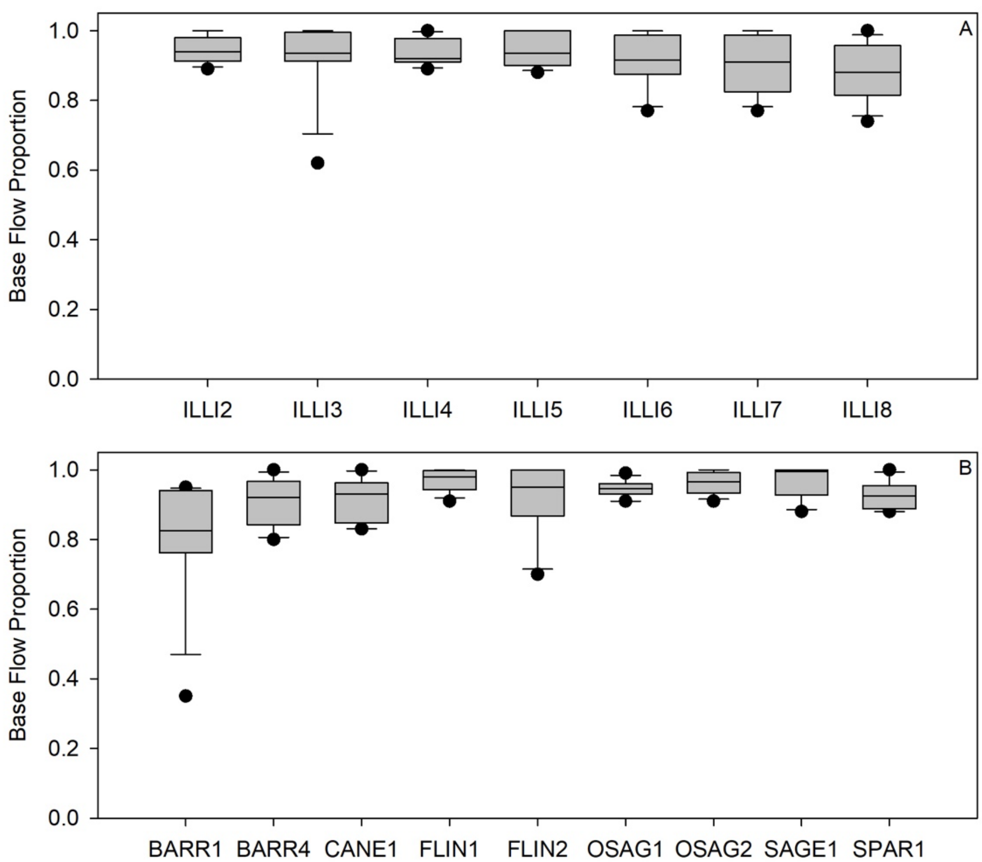

Figure 1. Base flow proportions (BFPs) calculated by HYSEP sliding interval approach across the stream sites and sampling dates from the "Joint Study"; site identification is ILLI (Illinois River, least number most upstream and greatest number most downstream), BARR (Barron Fork), CANE (Caney Creek), FLIN (Flint Creek), OSAG (Osage Creek), SAGE (Sager Creek), and SPAR (Spring Creek)

Therefore, 98% of the sampling dates on the Illinois River relied upon in the "Joint Study" had BFPs of 0.77 or greater across these sites. In fact, 93% of the sampling dates for the Illinois River had a BFP of 0.80 or greater during the "Joint Study."

Total Phosphorus Concentrations Relation with Base Flow Proportion

We focused on the relation between TP concentrations and BFP at the Illinois River near the Arkansas and Oklahoma border, i.e. ILLI4. Total P concentrations at the Illinois River (ILLI4) generally decreased within increasing BFP (Figure 2, graph A), where mean TP concentration of all data was ~0.145 mg/L. The mean TP concentration of the samples collected at ILLI4 decreased as BFP increased with the largest change occurring with BFPs greater than 0.30, where mean TP was ~0.075 mg/L. The mean TP concentration continued to decrease with increasing BFP, decreasing to ~0.049 mg/L when BFP was 0.90 or greater.

The TP concentration data at ILLI4 exceeded 0.037 mg/L in almost 2/3 of the water samples collected across the range of flow. The percent of samples with TP concentrations exceeding 0.037 mg/L decreased as BFP increased at this site. However, the reality was that the TP concentrations at the Illinois River (ILLI4) flowing into Oklahoma from Arkansas exceeded the Scenic Rivers TP criteria (0.037 mg/L) almost 50% of the time when BFP was greater than 0.80.

The $\log_{10}$ TP concentrations decreased linearly with BFP across the range observed (R^2=0.69, slope=-1.09, n=200, P<0.01), excluding one outlier from June 2019 when TP was ~0.8 mg/L under predominately base flow conditions. If we limited analysis to when base flow was more than half or the majority of total flow (i.e., BFP>0.50), then TP concentrations (not log-transformed) also decreased with increasing BFP. The linear decrease in TP concentrations was significant (P<0.01) with a slope of -0.127, but the coefficient of determination was less (R^2=0.27, n=142); this change in mean TP concentrations was ~0.013 mg/L per 0.1 BFP units at ILLI4.

All sites within the Upper Illinois River Watershed sampled more intensively by the AWRC showed that $\log_{10}$ TP concentrations significantly decreased with increasing BFP (Figure 2; R^2=0.56–0.75, P<0.01). If we focused on data when BFP was greater than 0.50, then each site showed that TP concentrations (not log-transformed) decreased with increasing BFP (P<0.01), except OSAG1 (P=0.08). This particular site had a gap in BFPs sampled between the 0.50 to 0.60, so the regression was extended to BFP greater than 0.20 where the TP increase was linear (R^2=0.39, n=134, slope=-0.086, P<0.01). The slopes of these linear relations were significantly (R^2=0.86, P<0.01) related to mean TP concentration when BFP exceeded 0.80 (i.e., mean TP concentration at dominant base flow conditions, TP_{BF}). If you used change in mean TP concentration per 0.1 BFP unit ($\Delta TP_{0.1BFP}$), the linear equation was $\Delta TP_{0.1BFP}=0.178*TP_{BF}+0.001$ (Figure 3). This observation showed that TP concentrations were more influenced by BFP when TP_{BF} was greater; in fact, $\Delta TP_{0.1BFP}$ was 0.008 at 0.037 mg TP L^{-1} compared to 0.019 at TP_{BF} of ~0.1 mg L^{-1}.

DISCUSSION

The use of nutrient [specifically P] thresholds in stream biological responses is becoming more prominent to help guide the establishment of water quality criteria or standards protecting beneficial uses like aquatic life; thus, the magnitude can be linked directly to the desired biological response. The response variable of interest and thresholds in these

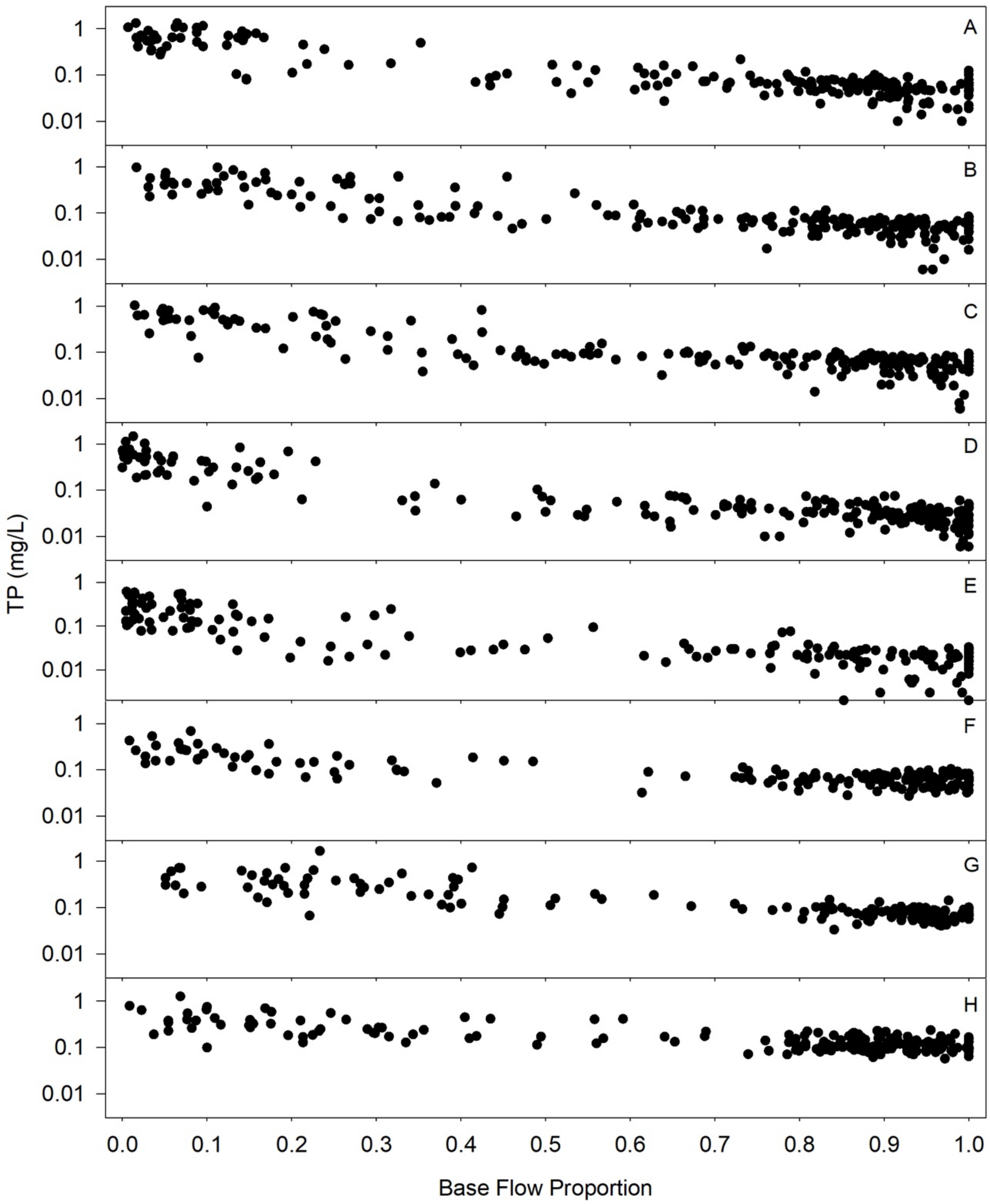

Figure 2. Total phosphorus (TP) concentrations as a function of base flow proportion (BFP) calculated using the HYSEP sliding interval approach from water quality monitoring project in the upper Illinois River Watershed, 2015–2019 (Scott and Haggard, 2019; Haggard, B.E. unpublished data); the graphs are A ILLI2, B ILLI4, C ILLI5, D BARR1, E Mud Creek, F OSAG1, G OSAG2, and H SPAR1.

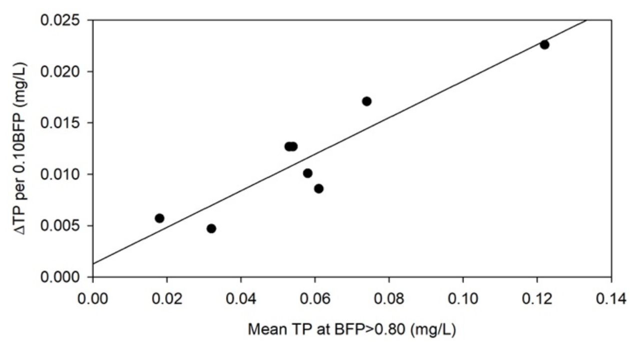

Figure 3. Change in total phosphorus (TP) concentrations per 0.10 proportional change in base flow proportion (BFP) as a function of mean TP concentrations from water samples collected when BFP is greater than 0.80 across limited sites in the upper Illinois River Watershed.

studies may vary by water body type (Poikane et al., 2019), watershed characteristics (D'Amario et al., 2019) and even stakeholders' interests and perceptions (West et al., 2016). For example, the magnitude to protect from changes in the natural assemblage of a stream algal community (Taylor et al., 2014, 2018; Tibby et al., 2019) would likely be less than that to protect from nuisance algal blooms (Wagenhoff et al., 2016). The "Joint Study" evaluated the magnitude of Oklahoma's Scenic River TP Criteria (0.037 mg/L), which was found to be protective of the river's designated uses and water quality conditions (Haggard et al., 2017).

These numeric thresholds are derived from some measure of the nutrient concentration on the x-axis. The nutrient concentrations in stressor response studies are bound to some sampling frequency, duration and hydrologic condition when the individual value is calculated for threshold analysis. For example, sestonic chlorophyll-a showed hierarchical structure and thresholds with nutrients across the Red River Basin (Haggard et al., 2013); the values used in the statistical analysis were medians from long-term databases with a minimum number of observations (Longing and Haggard, 2010). Thus, if nutrient criteria were promulgated from the referenced study, one would need to consider how nutrient and response values were calculated because that can influence assessment and potential water quality standard exceedances or violations (see Scott and Haggard, 2015).

The nutrient value used is usually tied to the calculation of some central tendency, e.g. mean, geometric mean (geomean) or median, across water samples collected over a length of time. For example, Taylor et al. (2014) used the mean of triplicate water samples collected at 38 different sites during base flow conditions to evaluate natural algal and fish assemblage changes across a sharp nutrient gradient. In fact, most stream studies evaluating various biological responses to increasing nutrient concentrations have been conducted during base flow conditions, because the researchers need to be able to get into the water safely to collect substrate and biological data. The "Joint Study" itself was conducted under "**critical conditions**" when water and substrate samples could be collected every other month.

The term "**critical conditions**" was subjectively defined, which may have been intentional to gain unanimous approval by the six-person committee overseeing the "Joint Study". However, the key to specifically defining this term may lie in the word "*dominant"* and the specific hydrologic conditions sampled during the "Joint Study". Dominant used as an adjective means "most important, strong, or influential" (Google, 2020) with synonyms of "controlling" and or "paramount". The definition "when surface runoff is not the dominant influence of total flow…" inherently suggests that streamflow would be dominated by base flow contributions.

The descriptive term used was "dominant influence" not simply base flow being the majority of total flow (i.e., BFP greater than 0.50).

The obvious question is can we quantify "dominant" in terms of base flow contributions? The best way would be looking at the specific hydrologic conditions sampled during the "Joint Study", which clearly showed that base flow contributions were dominant. In fact, 93% of the water samples from the "Joint Study" used to measure TP concentrations were collected when base flow contributions were 80 percent or more of total stream flow (i.e., BFP greater than or equal to 0.80). Based on calculated BFPs, base flow contribution to total streamflow was clearly dominant not just slightly more than half of total streamflow (i.e., BFP greater than 0.50). This is important because the TP criteria magnitude from the "Joint Study" was tied to these specific hydrologic or "**critical conditions**", which suggests that assessment of the TP criteria in Oklahoma's Scenic Rivers (0.037 mg/L; OWRB, 2002) should be tied to these same hydrologic or "**critical conditions**."

If assessment of the TP magnitude was applied outside the hydrologic conditions sampled, then some consideration should be given to how TP concentrations vary with BFP or total streamflow. Across this region and landscape, stream TP concentrations and loads increase with increasing discharge, especially if comparing base flow verse storm events (e.g., Haggard 2010; Scott et al., 2011; Giovannetti et al., 2013; Grantz et al., 2014; McCarty and Haggard, 2016). We showed across eight different sites that stream TP concentrations changed with discharge; in particular, stream TP concentrations significantly ($P<0.01$) decreased with BFP. In fact, the magnitude of change (i.e., $\Delta TP_{0.1BFP}$) varies with magnitude of stream TP during predominantly base flow conditions (i.e., TP_{BF}) across the Illinois River Watershed. Defining the hydrologic conditions used to assess the magnitude of the Oklahoma Scenic River TP criteria definitely matters at streams with TP_{BF} approaching 0.037 mg/L. For example, if three water samples were collected at BFPs of 0.80, 0.70 and 0.60 with TP_{BF} of 0.037 mg/L, then the mean of those three samples could [theoretically] be 0.045 mg TP L^{-1} (exceeding the TP criteria magnitude). Thus, if the magnitude was going to be applied outside the hydrologic conditions studied, then it should be adjusted based on both $\Delta TP_{0.1BFP}$ and TP_{BF} to limit risk of spurious exceedances and violations.

We see two potential arguments against limiting the magnitude to the hydrologic or "**critical conditions**" based on the "Joint Study," including (1) the question of how would limiting the magnitude to dominant base flow conditions address both point and nonpoint P sources, and (2) the ease of collecting water samples when BFP is 0.80 or greater across the duration assessed. First, we know that effluent discharges (i.e., point P sources) are an important driver of elevated stream TP concentrations throughout the region (Haggard et al., 2001, 2005; Ekka et al., 2006; Haggard, 2010; Jarvie et al., 2012) and globally (e.g., see Marti et al., 2004; Neal et al., 2005; Gibson and Meyer, 2007); elevated TP concentrations have been observed downstream from effluent discharges for tens of river kilometers. However, we also know that land use (i.e., potential nonpoint sources) is a driver of stream nutrient concentrations during base flow conditions within the region (Giovanetti et al., 2013; Sharpley et al., 2017) and globally (McDowell et al., 2020); stream P concentrations increase with the increasing potential for nonpoint source contributions. Thus, we would argue that applying stream TP criteria to base flow conditions at the Illinois River Watershed will capture the influence and contributions of both point and nonpoint sources (McCarty and Haggard, 2016).

The ability to collect water samples during hydrologic conditions when base flow is dominant might be easier than expected. It is clear by the relations between $\log_{10}$ TP concentrations and BFPs that most (54–72%) water samples over the five-year period (2015–2019) were from BFP greater than 0.75 across the eight sites within the upper Illinois River Watershed (Figure 2). The least percent (54%) was at the urban tributary Mud Creek at Fayetteville, whereas the range across the three sites on the Illinois River was 58 to 61%. Without intention, the AWRC was able to collect water samples when BFP was greater than 0.75 with relative ease. The "Joint Study" itself was able to meet these hydrologic conditions across almost all sites when limited to sampling every other month.

The ability to target hydrologic conditions when base flow contributions will vary seasonally and with episodic rainfall runoff events, but over a five year period water samples meeting this BFP criteria (i.e., BFP>0.75) were able to be collected each month (Figure 4). The lesser percent of all samples collected meeting this BFP criteria during spring months (i.e., March, April and May) is because the AWRC targets surface runoff events more frequently during the rainy season. Even during those rainy months, the AWRC was able to collect water samples when base flow was dominant with relative ease.

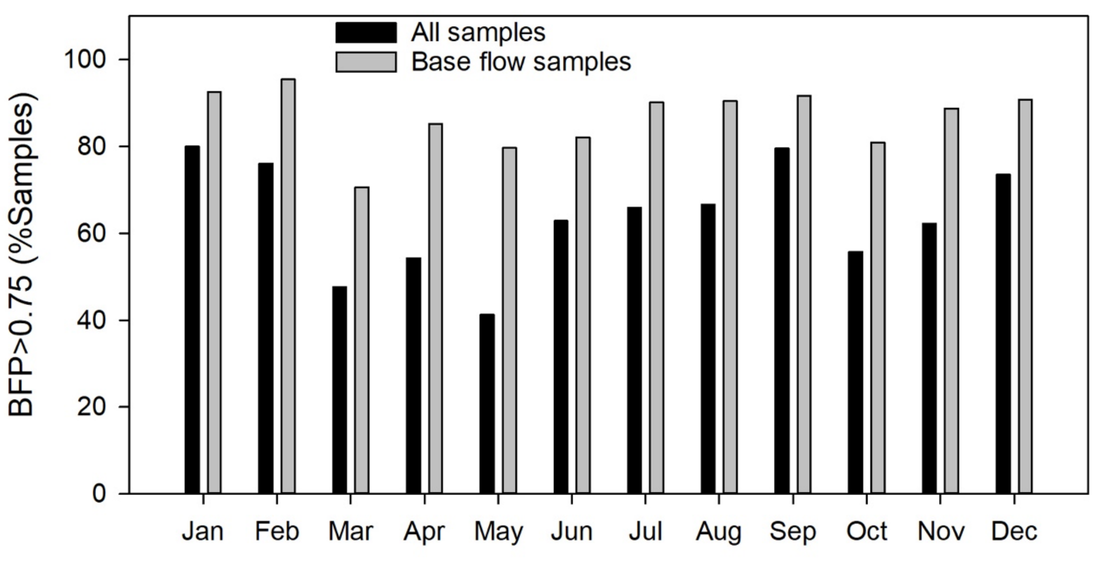

Figure 4. Frequency of water samples collected when base flow proportion (BFP) is greater than 0.75, as percent of all samples and percent of water samples when base flow was the majority of total flow (i.e., BFP>0.50), across all AWRC long-term monitoring sites from 2015 through 2019.

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