Observational Changes to the Natural Flow Regime in Lee Creek in Relation to Altered Precipitation Patterns and its Implication for Fishes

Michael R. Gatlin
Oklahoma Cooperative Fish and Wildlife Research Unit, Department of Natural Resource Ecology and Management, Oklahoma State University Stillwater, OK 74078

James M. Long
U.S. Geological Survey, Oklahoma Cooperative Fish and Wildlife Research Unit, Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078

Donald J. Turton
Department of Natural Resource Ecology and Management, Oklahoma State University, Stillwater, OK 74078

Abstract: The natural flow regime is important for structuring streams and their resident ichthyofauna and alterations to this regime can have cascading consequences. We sought to determine if changes in hydrology could be attributed to changes in precipitation in a minimally altered watershed (Lee Creek). The stream flow regime was analyzed using Indicators of Hydrologic Alteration (IHA) software, and data from a nearby climate station were used to summarize concurrent precipitation patterns. We discovered that Lee Creek hydrology had become flashier (i.e., increased frequency of extreme events of shorter duration) since 1992 coincident with changes in precipitation patterns. Specifically, our results show fewer but more intense rain events within the Lee Creek watershed. Our research provides evidence that climate-induced changes to the natural flow regime are currently underway and additional research on its effects on the fish community is warranted.

Introduction

A variety of perturbations can alter stream hydrology but precipitation is the ultimate factor and human-mediated climate change is predicted to affect precipitation patterns (Solomon et al. 2007). Significant deviations in the timing and magnitude of precipitation events could affect stream hydrology (Poff et al. 1997, Groisman et al. 2001). The effects of climate change are expected to vary across regions (Whitfield 2010), although some general trends are expected (Solomon et al. 2007), such as increased intensity of rain storms coupled with decreased frequency of rain events (Karl and Knight 1998, Easterling et al. 2000, Singh et al. 2013).

Modifications to precipitation patterns that ultimately affect streamflow will likely impact fishes and other aquatic organisms. For instance, a shift in flood timing could affect fish reproduction by inadvertently triggering spawning cues or causing larval mortality (Bunn and Arthington 2002, Lytle and Poff 2004). Changes in the natural flow regime are of particular concern for fishes of conservation need, especially those that occur on the edge of their natural range and are highly adapted to flow.

With the wide-ranging availability of precipitation data, it is possible to examine this force on streams. Lee Creek and its watershed in Oklahoma and Arkansas is a system where these criteria are mostly met and have implications for future decision makers to consider. Lee Creek is a 5th order stream and one of six scenic rivers in Oklahoma with head-waters in the Boston Mountains of northwestern Arkansas, which flows through Oklahoma and confluences with Arkansas River near Van Buren, AR (Figure 1). The watershed of Lee Creek is mostly forested (76.8%) with minimal change or disturbance (Gatlin 2013), making this an ideal setting to isolate the role of precipitation on hydrology. However, in 1992, the Lee Creek Dam and Reservoir was constructed lower in the watershed. Because it was constructed near the mouth of the creek, we limited our hydrological analyses to above the reservoir. The construction of Lee Creek Dam was thought to threaten the persistence of many fish species of "greatest conservation need" such as the wedgespot shiner *Notropis greenei*; Ozark minnow *Notropis nubilis*; sunburst darter *Etheostoma mihileze*; blackside darter *Percina maculate* and longnose darter *Percina nasuta* (ODWC 2005). Longnose darter in particular was of interest (FERC 1987) because Lee Creek was the last remaining river in Oklahoma that contained this species since it

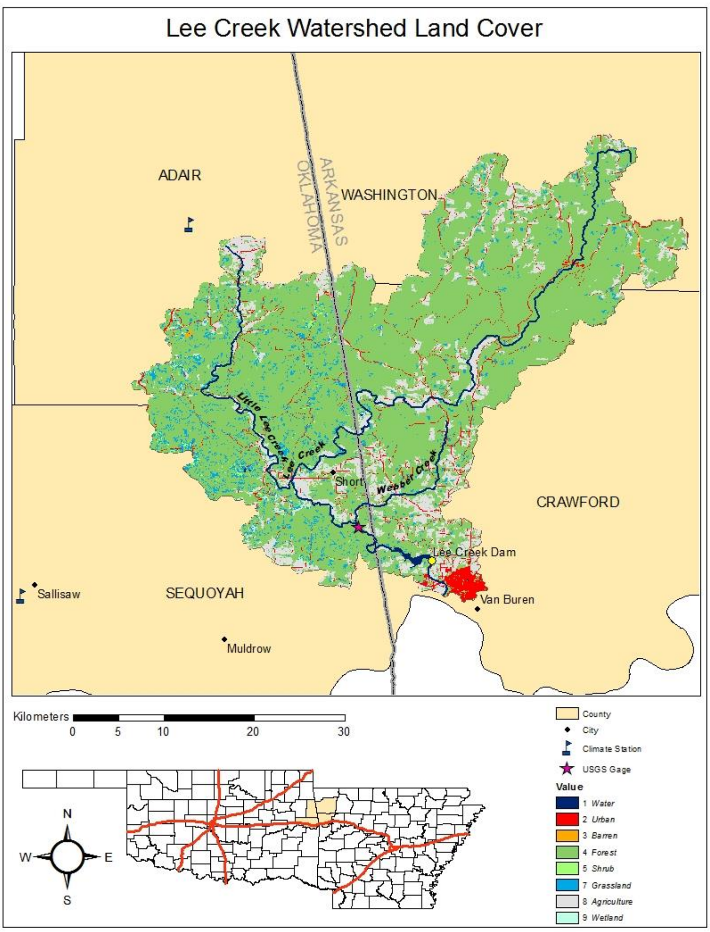

Figure 1. Map depicting the location, extent, and land cover types of the Lee Creek watershed in Oklahoma and Arkansas. Locations of climate stations and USGS stream flow gage station are provided.

became extirpated from the Poteau River after that system was dammed (Wagner 1985). As a result, the longnose darter is considered by the state of Oklahoma as "endangered"; the only fish species to be classified as such. As a result, understanding the role that climate change may have on the hydrology of Lee Creek would be beneficial to these future decisions. Thus, we sought to determine if changes in hydrology above the dam before and after 1992 would mirror any concomitant patterns in precipitation.

Methods

Hydrological analysis

To determine alterations in streamflow, we obtained daily streamflow data from the USGS gaging station on Lee Creek near Short, OK above Lee Creek Dam (gage# 07249985; Figure 1), split the data into pre- (1970-1991) and post-impoundment (1992-2013) periods, and used Indicators of Hydrologic Alteration (IHA) software to determine differences (Richter et al. 1996, Mathews and Richter 2007). The IHA analysis calculates 32 ecologically significant parameters for each period, based on the water-year (Oct. 1-Sept. 31), and was used to determine how flow duration, magnitude, frequency, or timing might have changed (Richter et al. 1996). Because the data were not normally distributed, we reported percentiles and medians (TNC 2009). High- and low-flow conditions were defined as median flow ± 25%. Streamflow that exceeded the two year return interval was considered a small flood; flow that exceeded the ten year return interval was a large flood. Extreme low-flows were defined as any flow that was in the lower 10% of the daily flows for the period. Range of variability analysis (RVA) bounds, which determine "natural" flow conditions based on the pre-impoundment period, were set to ± 17% of the median value for the period. We used significant count values (< 0.05) to determine statistical significance of IHA parameters (TNC 2009).

Precipitation Analysis

To determine changes in precipitation patterns, we obtained precipitation data for the period 1970-2010, which coincided with the hydrology analysis, from the nearest station that had a long-term record (Sallisaw, OK, Oklahoma Climatological Survey). Only those years with complete records were used. We defined a precipitation event as any day with precipitation ≥ 0.025 mm and used linear regression to determine the relationship between the number of precipitation events per year and the mean event magnitude. Differences in mean annual precipitation, mean number of precipitation events, and mean precipitation event magnitude were determined with a t-test (when data were normally distributed) or Mann-Whitney U test (when data were not normally distributed) pre- and post-impact (1992) to match the IHA analysis. All statistical analyses were performed using SigmaPlot v12.5 software and considered significant at $P \leq 0.05$.

Results

Hydrological analysis

Lee Creek's hydrology changed since 1992, mainly with increased frequency of high flows that were more variable in nature (Table 1). For example, during 1970-1991, the median frequency of high flows (median flow + 25%) was eight times per year, with 25th and 75th percentiles ranging from 7 to 11 (Figure 2). During the subsequent period (1992-2013), the median frequency of high flows increased significantly (significance count < 0.05) to 10.5 times per year, with an increased range of percentiles of these flows occurring (25th = 6.75 and 75th = 12.25). Other items that were found to occur significantly greater than chance (significance counts < 0.05) during the post-impact period compared to the pre-impact period included high pulse counts, high flow fall rate coefficient of dispersion (CD), and large flood rise rate CD; all of which support the findings of increased frequencies of high flows that were more variable. Related, 1-day minimum flows became more variable (CD from 3.286 to 15.9600), indicating further that the flow regime in Lee Creek had become more dynamic after 1992.

Table 1. Indicators of Hydrologic Alteration (IHA) scorecard generated from stream flow data collected at USGS gage #07249985 on Lee Creek near Short, OK investigating differences in hydrology before and after Lee Creek Dam was constructed in 1992. Significance counts can be interpreted similarly to a p-value where < 0.05 indicates significant deviation between pre- and post-impoundment values (bold).

	Medians		Coefficient of Dispersion (CD)		Deviation Factor		Significance Count	
	Streamflow (m^3)							
IHA Group	Pre-impact	Post-impact	Pre-impact	Post-impact	Medians	CD	Medians	CD
Group 1: Monthly								
October	0.623	1.203	7.281	1.903	0.932	0.739	0.153	0.177
November	3.589	4.212	6.085	2.827	0.174	0.535	0.771	0.426
December	6.853	8.226	2.538	1.760	0.200	0.307	0.749	0.572
January	5.536	6.499	2.224	2.774	0.174	0.247	0.732	0.582
February	11.780	13.830	0.885	0.822	0.174	0.071	0.483	0.894
March	24.820	12.980	0.789	1.429	0.477	0.811	0.333	0.120
April	17.290	16.120	0.998	1.161	0.068	0.163	0.891	0.654
May	11.670	9.826	0.751	1.666	0.158	1.218	0.305	0.070
June	3.617	3.157	1.568	2.692	0.127	0.717	0.762	0.315
July	0.411	1.076	2.229	2.943	1.621	0.320	0.079	0.535
August	0.197	0.231	3.442	3.690	0.173	0.072	0.897	0.895
September	0.166	0.248	2.917	7.550	0.489	1.588	0.295	0.230
Group 2: Magnitude and duration of annual extremes								
1-day minimum	0.015	0.007	**3.286**	**15.900**	0.524	**3.839**	0.560	**0.010**
3-day minimum	0.016	0.010	3.210	12.750	0.396	2.970	0.840	0.062
7-day minimum	0.017	0.015	3.313	8.838	0.108	1.667	0.948	0.106
30-day minimum	0.039	0.078	2.954	2.394	0.995	0.190	0.164	0.724
90-day minimum	0.595	1.090	1.754	2.247	0.831	0.281	0.099	0.493
1-day maximum	468.60	392.20	0.814	1.064	0.163	0.307	0.548	0.415
3-day maximum	288.70	234.60	0.689	0.774	0.188	0.123	0.483	0.760
7-day maximum	155.40	140.70	0.674	0.685	0.095	0.017	0.836	0.963
30-day maximum	63.680	68.60	0.520	0.687	0.077	0.322	0.608	0.299
90-day maximum	38.940	43.580	0.417	0.484	0.119	0.160	0.284	0.674
Base flow index	0.001	0.001	5.775	8.217	0.542	0.423	0.580	0.557

Table 1. Continued.

	Medians		Coefficient of Dispersion (CD)		Deviation Factor		Significance Count	
	Streamflow (m^3)							
IHA Group	Pre-impact	Post-impact	Pre-impact	Post-impact	Medians	CD	Medians	CD
Group 3: Timing of annual extremes								
Julian date of minimum	255	249.5	0.131	0.148	0.030	0.136	0.733	0.654
Julian date of maximum	123	114	0.389	0.253	0.049	0.351	0.718	0.572
Group 4: Frequency and duration of high and low pulses								
Low pulse count	3	3	0.667	0.417	0.00	0.375	0.288	0.404
Low pulse duration	18.00	22.00	1.569	2.165	0.222	0.379	0.628	0.431
High pulse count	**8.00**	**11.00**	0.625	0.546	**0.375**	0.127	**0.019**	0.515
High pulse duration	6.50	5.00	0.404	0.650	0.231	0.610	0.065	0.115
Low Pulse Threshold	0.570							
High Pulse Threshold	16.310							
Group 5: Rate and frequency of change in conditions								
Rise rate	1.104	0.998	1.470	2.205	0.096	0.500	0.831	0.289
Fall rate	-0.467	-0.531	-1.106	-1.260	0.136	0.139	0.754	0.726
Number of reversals	73.50	75.50	0.201	0.192	0.027	0.043	0.571	0.889
Environmental Flow Component (EFC) Results								
EFC Low flows								
October	0.793	1.161	3.625	1.820	0.464	0.498	0.323	0.249
November	2.294	3.469	3.568	2.140	0.512	0.400	0.390	0.403
December	6.173	6.683	1.095	1.230	0.083	0.123	0.803	0.717
January	4.863	5.097	1.596	1.397	0.048	0.125	0.768	0.642
February	8.814	10.260	0.560	0.563	0.165	0.004	0.135	0.992
March	10.730	9.741	0.546	0.688	0.092	0.259	0.712	0.586
April	10.730	8.169	0.582	0.964	0.239	0.656	0.542	0.098
May	7.030	6.180	0.713	1.079	0.121	0.515	0.550	0.127
June	2.945	2.534	1.238	1.781	0.139	0.438	0.719	0.180
July	0.411	1.034	2.134	2.451	1.517	0.149	0.076	0.776
August	0.368	0.312	1.907	2.607	0.154	0.367	0.867	0.403
September	0.249	0.312	3.341	8.491	0.250	1.541	0.818	0.116

Table 1. Continued.

IHA Group	Medians: Streamflow (m^3) Pre-impact	Medians: Streamflow (m^3) Post-impact	Coefficient of Dispersion (CD) Pre-impact	Coefficient of Dispersion (CD) Post-impact	Deviation Factor Medians	Deviation Factor CD	Significance Count Medians	Significance Count CD
EFC Parameters								
Extreme low peak	0.040	0.030	0.748	1.202	0.240	0.607	0.294	0.216
Extreme low duration	11.750	9.750	1.457	1.256	0.170	0.138	0.735	0.775
Extreme low timing	245.50	247.80	0.145	0.082	0.012	0.435	0.853	0.289
Extreme low freq.	1.500	2.00	1.333	1.500	0.333	0.125	0.465	0.953
High flow peak	71.450	55.220	0.585	0.708	0.227	0.211	0.077	0.548
High flow duration	5.750	5.00	0.457	0.650	0.130	0.424	0.340	0.264
High flow timing	65.750	64.50	0.210	0.258	0.007	0.226	0.997	0.312
High flow frequency	**8.00**	**10.50**	0.500	0.524	**0.313**	0.048	**0.044**	0.853
High flow rise rate	25.690	24.960	0.581	0.866	0.028	0.490	0.696	0.333
High flow fall rate	-10.690	-10.00	**-0.386**	**-0.744**	0.064	**0.928**	0.225	**0.033**
Small flood peak	546.50	626.50	0.487	0.228	0.146	0.531	0.426	0.203
Small flood duration	22.00	13.50	1.295	1.917	0.386	0.480	0.657	0.332
Small flood timing	301.00	122.00	0.234	0.398	0.978	0.702	0.092	0.145
Small flood rise rate	105.20	307.20	3.848	1.033	1.919	0.732	0.207	0.402
Small flood fall rate	-46.390	-55.660	-0.778	-1.000	0.200	0.285	0.494	0.582
Large flood peak	1007.00	1079.00	0.250	0.173	0.072	0.311	0.515	0.500
Large flood duration	24.00	27.00	0.0	0.630	0.125		0.554	
Large flood timing	326.50	115.50	0.014	0.148	0.847	9.850	0.152	0.057
Large flood rise rate	201.00	109.90	**0.250**	**1.533**	0.453	**5.137**	0.460	**0.024**
Large flood fall rate	-49.570	-66.630	-0.254	-0.568	0.344	1.234	0.239	0.067

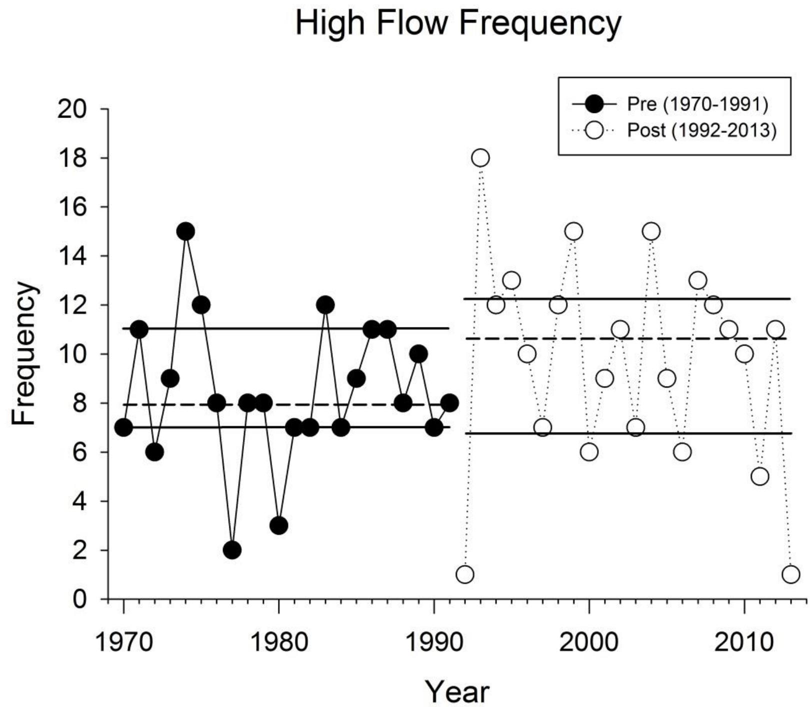

Figure 2. High flow frequency of Lee Creek, Oklahoma pre-impact (1970-1991) and post-impact (1992-2013). The dashed line is the median for each period and the solid lines are the 25th and 75th percentiles.

Precipitation Analysis

Full precipitation records existed from 1970 to 1990 for the pre-impact period and from 1996 to 2010 for the post-impact period. Precipitation varied according to the number of events and their magnitude. The mean magnitude of precipitation events was significantly related to the number of those events, declining at a rate of 0.1 mm per event ($r2 = 0.37$; $P < 0.01$; Figure 3). The mean annual precipitation did not change significantly between pre- and post-impact periods (Mann-Whitney U = 121.0; $P = 0.63$; Figure 4), with both periods receiving approximately 1200 mm of precipitation annually. However, the mean annual number of precipitation events significantly decreased from a mean of 114 pre-impact to 92 post-impact (t = 3.96; df = 31; $P < 0.01$) whereas the mean precipitation event magnitude increased from a mean of 10.8 mm/event pre-impact to 13.3 mm/event post-impact (Mann-Whitney U = 60.0; $P < 0.01$).

Discussion

Since 1992, high-flow events in Lee Creek above the impoundment have changed, resulting in a flashier system (Baker et al. 2004). The altered streamflow appears to be driven by long-term changes in precipitation (i.e., increased rain-event magnitude coupled with decreased rain-event frequency). While we did not examine the role of land cover changes on hydrology, previous analyses showed the watershed to be mostly forested (76.8%) with minimal change (less than 2 percentage points in any category from 1992 to 2006; Gatlin 2013) and would likely not have affected hydrology. These findings are consistent with predictions of climate change (Easterling et al. 2000, Meehl et al. 2000, Dore 2005, Solomon et al. 2007, Cheng et al. 2012), but because we only considered 40 years of record (20 years pre- and post-impoundment), these changes may not reflect climate-change *per se*. Precipitation

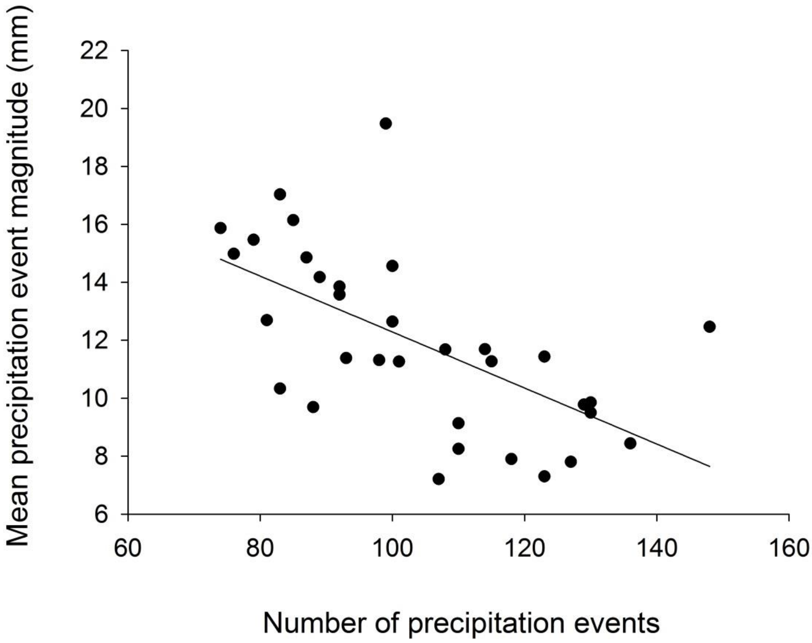

Figure 3. Relationship between number of precipitation events per year and mean annual event magnitude from 1970 to 2010 at Sallisaw, OK.

has fluctuated in this part of Oklahoma since records began in 1895 (OCS 2013) and whether the changes we observed are indicative of long-term climate changes are unknown. Moreover, we were only able to gather useful precipitation data from one point-location due to a lack of other long-term stations. As a result, we were unable to directly relate precipitation in the entire watershed to the hydrology, which would be more useful. Estimates of precipitation from RADAR coupled with GIS would improve this ability, but these data have only been available since the early 2000s (Zhang et al. 2011). Precipitation patterns are ultimately responsible for flow variability in streams (Hynes 1975, Changnon and Kunkel 1995, Poff et al. 1997) and stream flashiness has been shown to increase in concert with rain-event magnitude (Groisman et al. 2001, Kokkonen et al. 2004). If the pattern of decreased precipitation event frequency coupled with increased event magnitude patterns continues in the Lee Creek watershed, the resultant increased stream flashiness will likely have repercussions for the resident biota.

Most studies that investigated the effects of flooding on aquatic ecology describe negative effects on spawning behavior, success, and overall recruitment (see Poff and Zimmerman 2010) because larval fishes experience high mortality and displacement during flood events (Harvey 1987, Filipek et al. 1991, Jellyman and McIntosh 2010). Species that require specific substrate types for ovipositing, or require nest building to complete spawning, may experience reproductive failure during flooding because of reconfiguration of substrate (Jager et al. 1997, Carline and McCullough 2003). The redistribution of bed-load materials during flooding can destroy fish eggs deposited in or on the substrate (Swanston 1991). For instance, rock bass (*Ambloplites rupestris*) in streams had to repeatedly rebuild nests that were destroyed during spring flooding events (Noltie and Keenleyside 1986), decreasing nest success. A change in high flows would be of particular concern for fish species that reproduce in spring when these flows are more common.

Several fish species in Lee Creek spawn during the spring, including many that are of greatest conservation need in Oklahoma (i.e.,

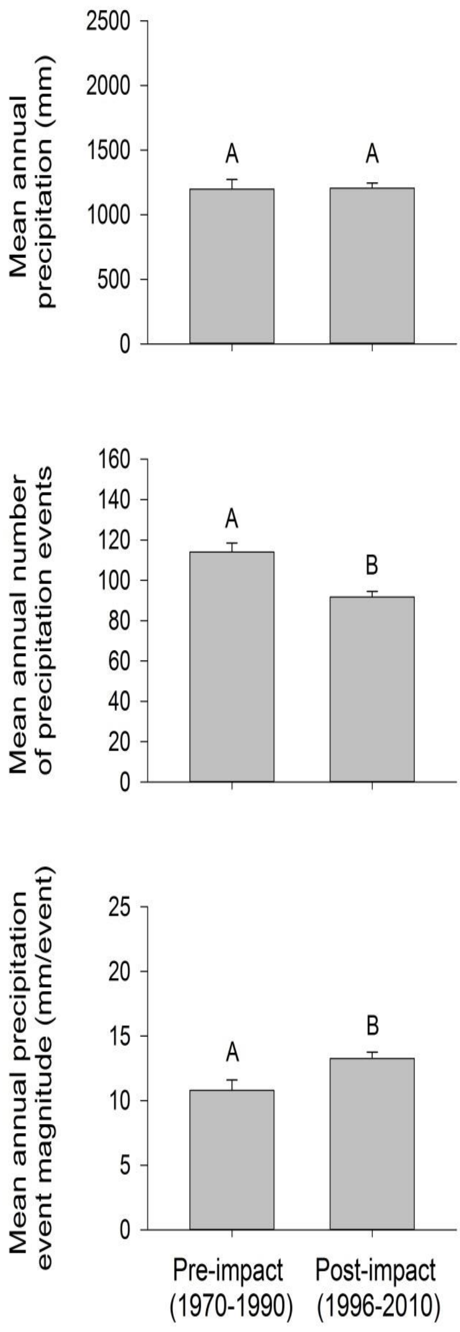

Figure 4. Measures of precipitation (mean ± 1 SE) pre- and post-impact at Sallisaw, OK. Different letters indicate significant difference between periods for each measure.

Ozark minnow *Notropis nubilus*, longnose darter *Percina nasuta,*and sunburst darter *Etheostoma mihileze*; Miller and Robison 2004) but data are lacking on how flooding will affect reproduction or recruitment for these species. Though it is unclear how climate-mediated changes in hydrology may affect population dynamics of Lee Creek's fishes, it may be substantial for imperiled species. For example, Lee Creek is the last remaining stream system within Oklahoma to support the longnose darter (Gatlin and Long 2011), which has very low fecundity (i.e., females produce < 4 eggs per day) and spawns intermittently (Anderson et al. 1998). Information on the natural breeding behavior for longnose darter is lacking (Anderson et al. 1998), but similar species (*Percina spp*) depend on gravel and cobble substrate for spawning. For example, shield darter (*P. pellata*), dusky darter (*P. sciera*), and leopard darter (*P. pantherina*) require small gravel and cobble for burying eggs, which can be disturbed during flooding (New 1966, James and Maughan 1989, James et al. 1991, Labay et al. 2004). The increased flashiness of annual flood events could affect longnose darter from Oklahoma by limiting their spawning success due to flooding related nest failure, although additional research on factors affecting longnose darter persistence would be needed to establish the level of this risk.

Research investigating the effects of climate change on fishes and fisheries has primarily focused on temperature (Tonn, 1990, Pörtner and Peck 2010), particularly for several salmonid species (Jonsson and Jonsson 2010, Wenger et al. 2011, Isaak et al. 2012); however, a paucity of information exists regarding warm-water fishes. It is imperative to consider how changing precipitation patterns as a predicted consequence of climate change will alter stream hydrology because it may determine a species' ability to persist (Poff et al. 1997). Our research provides evidence that climate-induced changes to the natural flow regime are currently underway and may negatively affect the fish community in an eastern Oklahoma scenic river, but more work is needed to reliably predict these effects across multiple systems.

Acknowledgements

We thank Chris Zou for providing comments on an earlier draft of this manuscript. Financial support was provided by the Oklahoma Department of Wildlife Conservation through the State Wildlife Grant Program Grant T-53-R and Oklahoma State University. The Oklahoma Cooperative Fish and Wildlife Research Unit is jointly supported by the U.S. Geological Society, Oklahoma State University, the Oklahoma Department of Wildlife Conservation, the Wildlife Management Institute, and the U.S. Fish and Wildlife Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

References

Anderson KA, Rosenblum PM, Whiteside BG, Standage RW, Brandt TM. 1998. Controlled spawning of longnose darters. Prog Fish-Cult 60:137-145.

Baker DB, Richards RP, Loftus TT, Kramer JW. 2004. A new flashiness index: characteristics and applications to Midwestern rivers and streams. J Am Water Resour As 40:503-522.

Bunn SE, Arthington AH. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ Manage 30:492-507.

Carline RF, McCullough BJ. 2003. Effects of floods on brook trout populations in the Monongahela National Forest, West Virginia. T Am Fish Soc 132:1014-1020.

Changnon SA, Kunkel KE. 1995. Climate-related fluctuations in Midwestern floods during 1921-1985. J Water Res Pl-ASCE 121:326-334.

Cheng CS, Auld H, Li Q, G Li. 2012. Possible impacts of climate change on extreme weather events at local scale in south-central Canada. Climatic Change 112:963-979.

Dore MHI. 2005. Climate change and changes in global precipitation patterns: what do we know? Environmental International 31:1167-1181.

Easterling DR, Meehl GA, Parmesan C, Changnon SA, Karl TR, Mearns LO. 2000. Climate extremes: observations, modeling, and impacts. Science 289:2068-2074.

Federal Energy Regulatory Committee (FERC). 1987. Lee Creek Project, FERC No. 5251, Final Environmental Impact Statement, FERC/FEIS-0043. Washington, D.C. 521 p.

Federal Register. 2010. Notices. Federal Register 75:65613-65614.

Filipek SP, Armstrong MA, Claybrook LG. 1991. Effects of a hundred-year flood on the smallmouth bass population of the upper Caddo River, Arkansas. In: Jackson DC, editor. First International Smallmouth Bass Symposium. Bethesda (MD): American Fisheries Society. p. 84-89.

Gatlin MR. 2013. The effects of hydrologic alteration on stream fish community structure in Lee Creek, Oklahoma [MSc thesis]. Stillwater (OK): Oklahoma State University. 96 p.

Gatlin MR, Long JM. 2011. Persistence of the longnose darter (*P. nasuta*) in Lee Creek, Oklahoma. Proc Okla Acad Sci 91:11-14.

Groisman PY, Knight RW, Karl TR. 2001. Heavy precipitation and high streamflow in the contiguous United States: trends in the twentieth century. B Am Meteorol Soc 82:219-246.

Harvey BC. 1987. Susceptibility of young-of-year fishes to downstream displacement by flooding. T Am Fish Soc 116:851-855.

Hynes HBN. 1975. A stream and its valley. Verhandlungen, Internationale Vereinigung fur Theoretische und Au-gewandte Limnologie 19:1-15.

Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL, editors.. 2007. Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press. 996 p.

Isaak DJ, Wollrab S, Horan D, Chandler G. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980-2009 and implications for salmonid fishes. Climatic Change 113:499-524.

Jager HI, Cardwell HE, Sale MJ, Bevelhimer MS, Coutant CC, Van Winkle W. 1997.

Modelling the linkages between flow management and salmon recruitment in rivers. Ecol Model 103:171-191.

James PW, Maughan OE. 1989. Spawning behavior of the threatened leopard darter, *Percina pantherina*. Southwest Nat 34:298-301.

James PW, Maughan OE, Zale AV. 1991. Life history of the leopard darter *Percina pantherina* in the Glover River, Oklahoma. Am Midl Nat 125:173-179.

Jellyman PG, McIntosh AR. 2010. Recruitment variation in a stream galaxiid fish: multiple influences on fry dynamics in a heterogeneous environment. Freshwater Biol 55:1930-1944.

Jonsson B, Jonsson N. 2010. A review of the likely effects of climate change on anadromous Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*, with particular reference to water temperature and flow. J Fish Biol 75:2381-2447.

Karl TR, Knight RW. 1998. Secular trends of precipitation amount, frequency, and intensity in the USA. B Am Meteorol Soc 79:231-241.

Kokkonen T, Koivusalo H, Karvonen T, Croke B, Jakeman A. 2004. Exploring streamflow response to effective rainfall across event magnitude scale. Hydrol Process 18:1467-1486.

Labay AA, Standage RW, Brandt TM. 2004. Selected methods for dusky darter captive propagation. N Am J Aquacult 66:146-152.

Lytle DA, Poff NL. 2004. Adaptation to natural flow regimes. Trends Ecol Evol 19:94-100.

Mathews R, Richter BD. 2007. Application of the Indicators of Hydrologic Alteration software in environmental flow setting. J Am Water Resour As 43:1400-1413.

Meehl GA, Zwiers F, Evans J, Knutson T, Mearns L, Whetton P. 2000. Trends in extreme weather and climate events: issues related to modeling extremes in projections of future climate change. B Am Meteorol Soc 81:427-436.

Miller RJ, Robison HW. 2004. Fishes of Oklahoma. Norman (OK): University of Oklahoma Press. 450 p.

New JG. 1966. Reproductive behavior of the shield darter, *Percina peltata peltata*, in New York. Copeia 1966:20-28.

Noltie DB, Keenleyside MHA. 1986. Breeding ecology, nest characteristics, and nest-site selection of stream- and lake-dwelling rock bass, *Ambloplites rupestris* (Rafinesque). Can J Zoolog 65:379-390.

Oklahoma Climatological Survey (OCS). 2013. Precipitation history – annual, east central district [online]. Available from http://climate.ok.gov/index.php/climate/climate_trends/precipitation_history_annual_statewide/CD06/prcp/Annual. (Accessed July 12, 2013).

Oklahoma Department of Wildlife Conservation (ODWC). 2005. Oklahoma comprehensive wildlife conservation strategy: planning for the future for Oklahoma's wildlife Final Report T-2-P-1, Oklahoma City, Oklahoma. 435 p.

Poff NL, Allen JD, Bain MB, Karr JR, Prestegaard KL, Richter BD, Sparks RE, Stromberg JC. 1997. The natural flow regime. BioScience 47:769-784.

Poff NL, Zimmerman JKH. 2010. Ecological responses to altered flow regimes: a literature review to inform science and management of environmental flows. Freshwater Biol 55:194-205.

Pörtner HO, Peck MA. 2010. Climate change effects on fishes and fisheries: towards a cause-and-effect understanding. J Fish Biol 77:1745-1779.

Richter BD, Baumgartner JV, Powell J, Braun DP. 1996. A method for assessing hydrologic alteration within ecosystems. Conserv Biol 10:1163-1174.

Singh D, Tsiang M, Rajaratnam B, Diffenbaugh NS. 2013. Precipitation extremes over the continental United States in a transient, high-resolution, ensemble climate model experiment. J Geophys Res-Atmos 118:7063-7086.

Swanston DN. 1991. Natural processes. In: Meehan WR, editor. Influences of forest and rangeland management on salmonid fishes and their habitat. Bethesda (MD): American Fisheries Society, Special Publication 19. p. 139-179.

The Nature Conservancy (TNC). 2009. Indicators of hydrologic alteration version 7.1 user's manual. 76 p.

Tonn WM. 1990. Climate change and fish

communities: a conceptual framework. T Am Fish Soc 119:337-352.

Wagner BA, Echelle AA, Maughan OE. 1985. Status and distribution of the longnose darter, *Percina nasuta*, and the Neosho madtom, *Noturus placidus*, in Oklahoma. Proc Okla Acad Sci 65:59-60.

Wenger SJ, Isaak DJ, Luce CH, Neville HM, Fausch KD, Dunham JB, Dauwalter DC, Young MY, Elsner ME, Rieman BE, Hamlet AF, Williams JE. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. P Natl Acad Sci USA 108:14175-14180.

Whitfield PH. 2010. Floods in future climates: a review. J Flood Risk Manage 5:336-365.

Zhang J, Howard K, Langston C, Vasiloff S, Kaney B, Arthur A, Van Cooten S, Kelleher K, Kitzmiller D, Ding F, Deo D-J, Wells E, Dempsey C. 2011. National mosaic and multi-sensor QPE (NMQ) system: Description, results, and future plans. B Am Meteorol Soc 92:1321-1338.

Received October 2, 2015 Accepted October 30, 20115