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Jonathan J. Spurgeon
University of Nebraska-Lincoln, jspurgeon2@unl.edu

Mike Rhodes
Mississippi State University, mcr432@msstate.edu

J. Wesley Neal
Mississippi State University, wes.neal@msstate.edu

Kristine O. Evans
Mississippi State University, kristine.evans@msstate.edu

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Aquatic habitat changes within the channelized and impounded Arkansas River, Arkansas, USA

Jonathan Spurgeon,[1] Mike Rhodes,[2]
J. Wesley Neal,[2] and Kristine Evans[2]

1 Department of Aquaculture and Fisheries, University of Arkansas at Pine Bluff, Pine Bluff, Arkansas
2 Department of Wildlife, Fisheries, and Aquaculture, Mississippi State University, Starkville, Mississippi

Correspondence — Jonathan Spurgeon, Department of Aquaculture and Fisheries, University of Arkansas at Pine Bluff, Pine Bluff, Arkansas.
Email: jspurgeon2@unl.edu

ORCID Jonathan Spurgeon https://orcid.org/0000-0002-6888-5867

Abstract

River-wide changes in morphologic character following channelization and impoundment alter the occurrence and distribution of surface water and available habitats for aquatic organisms. Quantifying patterns of creation, redistribution or disappearance of habitats at river-wide and decadal spatiotemporal scales can promote understanding regarding trajectories of different habitat types following alteration and prospects of direct habitat enhancement projects within altered alluvial rivers. Newly available remote-sensing tools and databases may improve detection of river-wide changes in habitat through time. We used a combination of remote-sensing data and

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generalized linear models to assess changes in surface water coverage from 1984 to 2015 among aquatic habitats of 496 km of the Arkansas River within Arkansas, USA. Changes through time in surface area of permanent and episodically inundated areas — and thus the availability of aquatic habitat — were variable along the river. Overall, the river lost a total 2.1% of permanent and 12.1% of episodic water surface area. The general trend of loss of off-main-channel habitat and increased coverage of permanent water along main-channel habitats may indicate a long-term transition (i.e. ramp-type disturbance) within areas of the Arkansas River where backwaters are transitioning to terrestrial environments, and habitat heterogeneity in the main channel is decreasing. As such, a decadal-scale change of channel form and backwater habitats may be the dominant pattern with limited regeneration of diverse habitat types. Understanding changes to permanent and episodic water availability may aid predictions regarding ecological effects of channelization and impoundments, including both increases and decreases in riverine productivity, biotic diversity and population abundances through space and time. Water resource managers and biologists can use information regarding river-wide changes in habitat availability obtained through remote sensing data to direct river management practices, including dredging and side-channel construction, and to assess ecological responses to such changes.

Keywords: backwater habitat, global water mapper, Landsat, remote sensing, river geomorphology, shifting habitat mosaic

1 Introduction

Aquatic habitat in river-floodplain systems resembles a shifting mosaic driven by river discharge (Arscott, Tockner, van der Nat, & Ward, 2002; Stanford, Lorang, & Hauer, 2005). Under natural conditions, erosion and deposition enable river channels to move across floodplains and create geomorphic features including backwaters, side-channels and oxbows (Stanford et al., 2005). The periodicity of river discharge events capable of moving sediments and changing the channel planform influence the persistence of habitat types at a location. For instance, flooding cycles in unaltered lowland rivers redistribute habitats longitudinally and laterally. As such, periodic pulse-type disturbances such as episodic and annual flooding promote habitat diversity and enable floodplain systems to support diverse species assemblages (Arscott et al., 2002; Sparks, 1995).

However, the configuration and spatial extent of different habitat types can change following human-induced modification to river systems (Gore & Shields Jr., 1995).

Channelization and impoundment can constrain river-channel planform and influence the matrix of habitat types available within a river-floodplain system (Gore & Shields Jr., 1995; Hohensinner, Habersack, Jungwirth, & Zauner, 2004). Channelization involves the placement of a combination of bank hardening (e.g. placing coarse rock on outside bends) and water-training structures (e.g. wing dikes). The intended result is establishing a self-maintaining channel through redirection of fluvial processes (e.g. channel incision vs. lateral migration; Jacobson & Galat, 2006) to transport sediment and maintain the navigation channel. River impoundment can alter the magnitude, timing, frequency, duration and rate-of-change of river discharges (Bunn & Arthington, 2002; Poff et al., 1997). Together, river channelization and altered river-discharge patterns may limit regeneration of habitats — particularly in off-channel areas that support backwater habitat — and set such habitats into a trajectory to a new state (e.g. backwater habitat converted to dry land) and may represent a decadal-scale ramp-type disturbance within the system. Continual loss of off-channel habitats may further restrict the level of biotic diversity within river-floodplain systems through time as these habitats are essential to sustaining biological diversity in floodplain-river systems (Lyon, Stuart, Ramsey, & O'Mahony, 2010).

Trends in the distribution and area of water coverage within river-floodplain systems can be monitored over decadal temporal scales with remotely-sensed imagery (Pekel, Cottam, Gorelick, & Belward, 2016; Schramm Jr., Minnis, Spencer, & Theel, 2008; Tyser, Rogers, Owens, & Robinson, 2001). Furthermore, assessments of year-to-year variation in habitat change along river systems may provide a mechanism to differentiate variation in habitat stemming from high- and low-flow years from systemic trends in habitat over decadal time-scales.

Improvements in image accessibility and automated processing methods allow for analysis of water distribution along rivers at multiple spatial and temporal scales. The European Commission Joint Research Center's (JRC) Global Surface Water dataset (GSW) was derived from the 1984 to 2015 Landsat archive and made available for research purposes (Pekel et al., 2016). Incorporating every available image in the Landsat catalogue, this dataset allows for constructing a complete annual time series of water presence throughout riverine environments and permits the separation of permanent (i.e. present throughout a year) and episodic (i.e. present only part of a year) surface water. Improved capacity to examine habitat configurations at river-wide scales may enable predictions regarding changes in habitat trajectories through time. Quantifying patterns of creation, redistribution or disappearance of habitats at river-wide and decadal spatio-temporal scales can promote understanding of trajectories of different habitat types following alterations. Therefore, this study's objective was to estimate the change in aquatic habitat area from 1984 to 2015 along an alluvial river that has undergone extensive alteration in the form of channelization and impoundment. We used the Arkansas River within the state of Arkansas as our focal river for this analysis. The Arkansas River is characterized by extensive morphologic and hydrologic changes to assist navigation. We predicted that given the initial press-type disturbances of channelization and impoundment (sensu Gore & Shields Jr., 1995) of the Arkansas River, the habitat mosaic may be undergoing large-scale changes (e.g. due to changes in erosion and deposition) that mimic a ramp-type disturbance. As such, habitats including backwater areas dependent on regenerating processes (i.e. episodic flooding with channel movement) may be in an overall state of decline at a river-wide scale.

2 Methods

2.1 Study area

The 716 km McClellan–Kerr Arkansas River Navigation System (MKARNS) was created by channelization and impoundment of the Arkansas River and tributaries. The MKARNS was completed in 1971 with 1,177 rock wing dikes to redirect water and shape sediment deposition to maintain the navigation channel. Approximately 410 km of rip-rap (i.e. large rock structure) was added along outside bends to restrict bank erosion (Schramm Jr. et al., 2008). Additionally, 18 mainstem lock-and-dams facilitate navigation for freight transport from the Mississippi River to the Port of Catoosa near Tulsa, Oklahoma

(Schramm Jr. et al., 2008). The combination of extensive channelization and impoundment along the length of the Arkansas River has altered the fluvial geomorphic character of the system. Increased water surface area followed completion of the MKARNS (Schramm Jr. et al., 2008). Sedimentation through time has resulted in declines of some habitats including backwater habitats following initial impoundment. Schramm Jr. et al. (2008) compared annual composites of Landsat images in 1973 and 1999 to measure habitat change in the MKARNS and found the aquatic area decreased by 9% (from 42,404 to 38,655 ha; Schramm Jr. et al., 2008). However, there is limited information regarding finer spatial and temporal resolution of changes along the MKARNS and characterization of the dynamic nature of habitat availability through time.

2.2 *Defining the study area*

We evaluated spatial and temporal trends in water surface area among aquatic habitats along the MKARNS from the beginning of Pool 2 (farthest downstream pool on the Arkansas River) upstream to the Arkansas-Oklahoma border within Pool 13 (**Figure 1**). We delineated the assessment area along the longitudinal gradient of the Arkansas River using the US Federal Emergency Management Administration (FEMA) National Flood Hazard Layer (version 1.1.1.0) 100-year floodplain classification, which included the river channel and all areas subject to a 1% and greater chance of flooding. The FEMA flood zone was not delineated in one river section, so we approximated it using a cost surface function. The cost surface function consisted of distance × slope up to a value of 5,000 m × slope from the river bank as defined by the USGS hydrologic dataset (Douglas, 1994). The assessment area included the FEMA flood zone within tributaries and backwaters up to 5,000 m from the Arkansas River confluence with connections substantial enough for access via a small watercraft. We excluded adjacent impoundments without open-water connections identifiable in aerial imagery (e.g. wastewater treatment plants, water-control reservoirs or aquaculture farms).

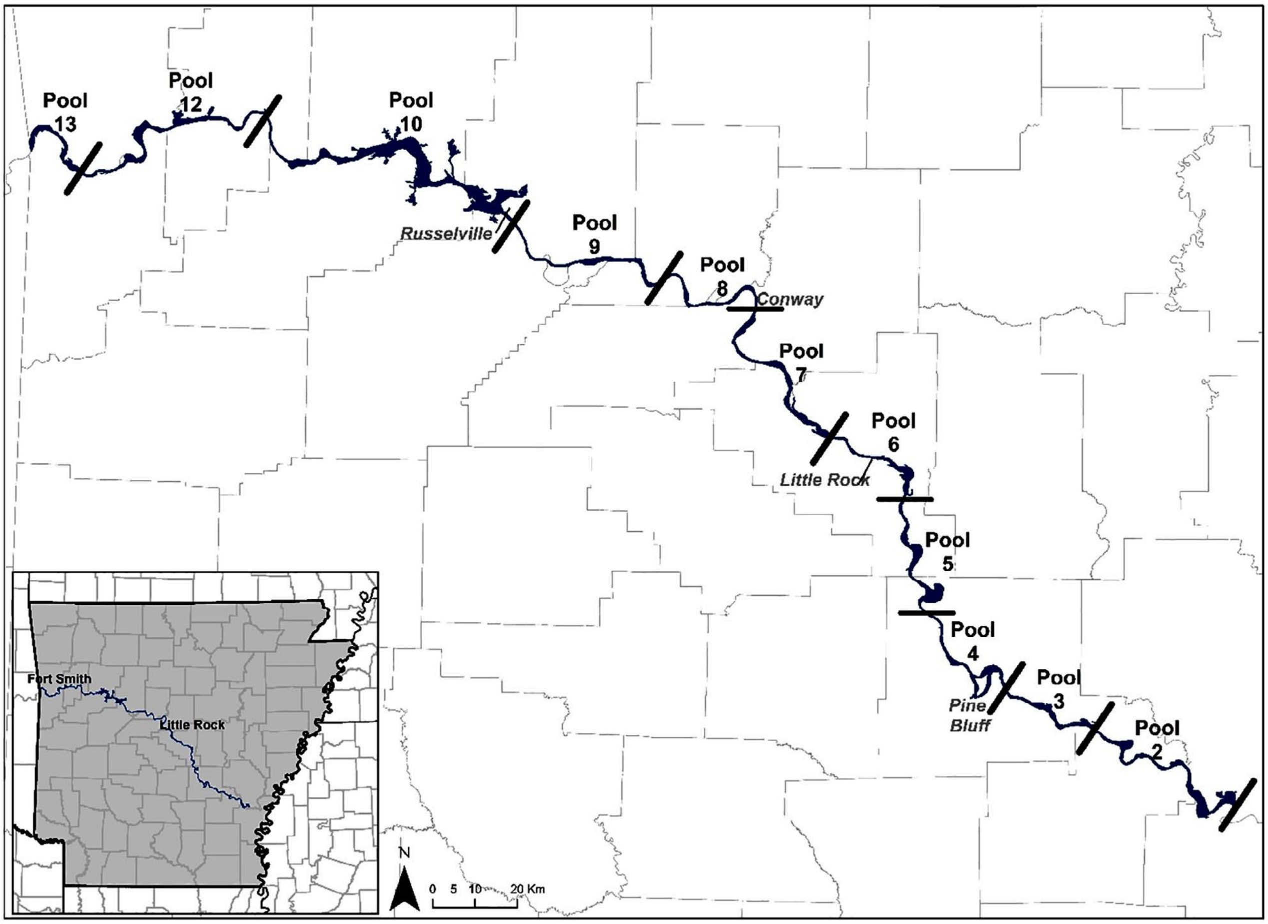

Figure 1 The McClellan–Kerr Arkansas River navigation system located along the Arkansas River, Arkansas, USA. Individual pools are numbered and separated at each lock-and-dam complex with thickened black lines.

2.3 Delineating river pools and aquatic habitat types

We used individual pools to divide the Arkansas River along its course through Arkansas. We further divided each pool into three habitat types including the main channel, dike-field habitats and off-main-channel backwaters (**Figure 2**). The main channel consisted of the open area extending from the outer bank bordering the navigation channel – designated in MKARNS navigation charts – to a boundary parallel with discharge training structures. Dike fields consisted of areas beginning at the boundary of discharge-training structures including wing dikes and L-dikes to the inside bank.

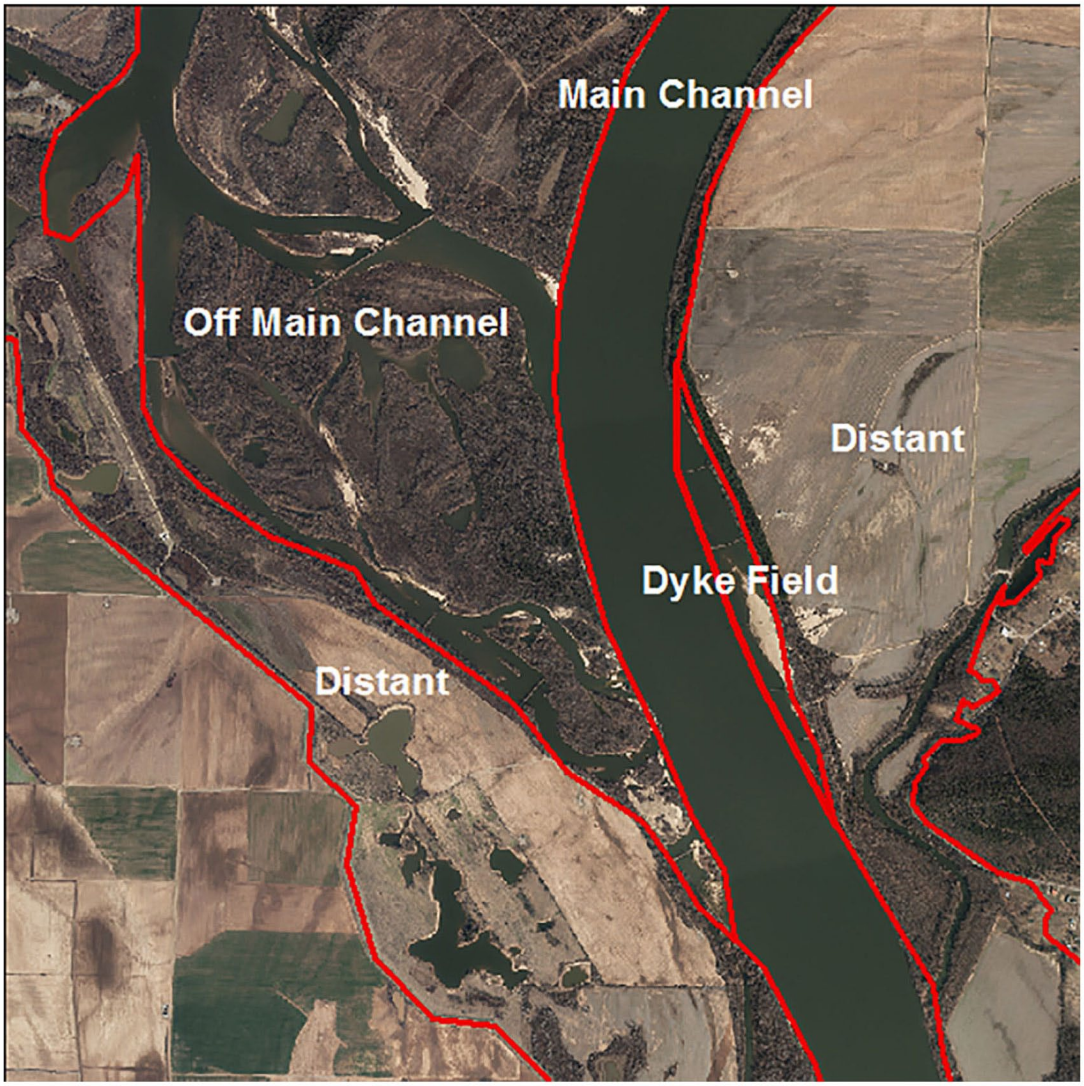

Figure 2 Examples of main-channel, off-main-channel and dike-field habitats used in the 1984–2015 assessment of aquatic habitat change along the length of the Arkansas River, Arkansas, USA. Distant habitat consisted of all land or water within the assessment area not connected to the river through channels or canals capable of supporting non-commercial navigation.

Off-main-channel backwaters were separated from the main channel and dike fields and included side channels, channel cutoffs with open, unobstructed connections to the river and tributary arms of reservoirs. We also included areas of water on islands as off-main-channel habitat under the assumption that these areas are regularly connected to the main channel during high water events. We excluded areas used for aquaculture or other artificial water features identified by unnaturally circular or rectangular ponds. A single observer manually delineated habitat-type boundaries using the 1984 National Agricultural Imagery Program imagery for use as the baseline condition with which to estimate area changes in water presence or absence through time. We included tributaries discharging into reservoirs along the Arkansas River (i.e. Pool 10, Lake Dardanelle) up to the point at which there was a narrowing in width, representative of lotic conditions. We considered all other land or water within the assessment area, or areas with obstructed connectivity to the main channel, as distant habitat that experienced limited, if any, inundation; these areas were not included in analyses.

2.4 Assessing water status

The GSW dataset provided a highly detailed (30 × 30 m pixel) analysis of Landsat images between 1984 and 2015. The expected number of images was the entire Landsat catalogue per year for a given area, which is estimated as an image per grid tile (5,000 × 5,000 30 m pixels) taken every 16 days and is approximately 23 images per year for each 30 × 30 m pixel along the Arkansas River. Pekel et al. (2016) used an expert system classifier to classify each pixel in each Landsat image tile over the 32-year Landsat catalogue to one of three classes including water, land or non-validated observation. The non-validated observations were where environmental anomalies were grouped and included pixels with clouds. Thus, each Landsat image tile was incorporated into the GSW dataset, and cloud cover issues were handled at the pixel level. Cloud detection within the GSW dataset was primarily based on Zhu and Woodcock (2012). Pekel et al. (2016) also performed monthly weighting to normalize and control for seasonal variation in the number of valid pixel observations. Each year, a 30 × 30 m pixel was classified as no water, permanent water or episodic water dependent on if and when water was present at that area throughout the year. We constructed a time series from the GSW dataset using annual records for each pool and aquatic habitat type to assess the year-to-year variation in surface area of permanent and episodic water along the Arkansas River. We used ArcGIS and the Google Earth Engine environment to process all images used in this study (Gorelik et al., 2017; Pekel et al., 2016) and included the entire Landsat image archive since 1984, spanning more than 1,000 images. Because of the limited geographic extent of the mapping project, we assume minimal variation in the frequency of observations across the MKARNS system. We used weighted reductions within Google Earth Engine to reduce the impact of edges with fractional pixels resulting from clipping to the FEMA flood zone or clipping the habitat types. As such, pixels on the edges that were clipped were given less weight than unclipped pixels when summing area. The total number of 30 × 30 m pixels, including the portion of each pixel on the edge of the study region and each habitat type, was converted to an area estimate (i.e. ha) and summed for each habitat type in each pool for each year.

2.5 Statistical analysis

We created generalized linear models using Program R (glm[] function; R Core Team, 2018) to assess how changes in permanent and episodic water surface area in the Arkansas River were occurring (**Table 1**). We chose a linear modelling approach as we intended to assess the presence of a steady change in each habitat type through time (i.e. ramp-type disturbance). Water surface area data for both permanent and episodic water categories were characterized by right-tailed skewness bounded at 0 (i.e. no negative habitat values possible) and did not conform to a normal distribution. As such, we used a gamma distribution and a log linkage for all generalized linear models. We used an information theoretic approach to evaluate relative support for 15 candidate models using the Akaike information criterion corrected for small sample sizes (AICc; Burnham & Anderson, 2002). Hypotheses within the candidate model set associated changes in permanent and episodic water surface area to individual, additive and interaction effects of pool, habitat type, year and water stage. We tested whether the area of permanent or episodic water area along the length of the Arkansas River in Arkansas was a function of (1) only year (i.e. water surface area increasing or decreasing through time), (2) only pool (i.e. water surface area differed by pool alone), (3) only habitat type (i.e. water surface area differed by habitat type), (4) an additive effect of year, pool and habitat type, (5) an additive effect of year, pool and habitat type with

Table 1 Models and model rankings using Akaike information criteria corrected for small sample size (AICc) for changes in both permanent surface water and episodic surface water area along the Arkansas River, Arkansas

Models	*AICc*	*ΔAICc*	*k*	*Wt.*
Permanent surface water models				
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Year}}X_{\text{Habitat}} + \beta5X_{\text{Year}}X_{\text{Pool}} + \beta6X_{\text{Year}}X_{\text{Habitat}}X_{\text{Pool}}$	10,655	0	67	1
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Stage\_cv}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Stage\_cv}}X_{\text{Habitat}} + \beta5X_{\text{Stage\_cv}}X_{\text{Pool}} + \beta6X_{\text{Stage\_cv}}X_{\text{Habitat}}X_{\text{Pool}}$	10,759	104	67	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Habitat}}X_{\text{Pool}}$	10,788	134	35	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Stage}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Stage}}X_{\text{Habitat}} + \beta5X_{\text{Stage}}X_{\text{Pool}} + \beta6X_{\text{Stage}}X_{\text{Habitat}}X_{\text{Pool}}$	10,811	157	67	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Stage}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Stage}}X_{\text{Habitat}}$	15,453	4,798	17	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}}$	15,454	4,799	15	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Year}}X_{\text{Habitat}}$	15,457	4,802	17	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Year}}X_{\text{Pool}}$	15,473	4,818	25	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Habitat}}$	16,349	5,694	4	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Pool}}$	16,508	5,853	12	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Pool}} + \beta3X_{\text{Stage\_CV}} + \beta4X_{\text{Pool}}X_{\text{Stage\_CV}}$	16,530	5,875	23	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Pool}} + \beta3X_{\text{Stage}} + \beta4X_{\text{Pool}}X_{\text{Stage}}$	16,530	5,875	23	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Stage}}$	16,922	6,268	3	0
$E(Y_{\text{Perm. Hab.}}) = 1$	17,023	6,368	2	0
$E(Y_{\text{Perm. Hab.}}) = \beta0 + \beta1X_{\text{Year}}$	17,025	6,370	3	0
Episodic surface water models				
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Year}}X_{\text{Habitat}} + \beta5X_{\text{Year}}X_{\text{Pool}} + \beta6X_{\text{Year}}X_{\text{Habitat}}X_{\text{Pool}}$	10,656	0	67	1
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Stage\_cv}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Stage\_cv}}X_{\text{Habitat}} + \beta5X_{\text{Stage\_cv}}X_{\text{Pool}} + \beta6X_{\text{Stage\_cv}}X_{\text{Habitat}}X_{\text{Pool}}$	10,668	12	67	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Habitat}}X_{\text{Pool}}$	10,695	39	35	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Stage}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Stage}}X_{\text{Habitat}} + \beta5X_{\text{Stage}}X_{\text{Pool}} + \beta6X_{\text{Stage}}X_{\text{Habitat}}X_{\text{Pool}}$	10,758	102	67	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}}$	12,776	2,121	15	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Year}}X_{\text{Habitat}}$	12,778	2,122	17	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Stage}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Stage}}X_{\text{Habitat}}$	12,785	2,130	17	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Year}} + \beta2X_{\text{Habitat}} + \beta3X_{\text{Pool}} + \beta4X_{\text{Year}}X_{\text{Pool}}$	12,786	2,131	25	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Pool}}$	12,915	2,259	12	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Pool}} + \beta3X_{\text{Stage\_CV}} + \beta4X_{\text{Pool}}X_{\text{Stage\_CV}}$	12,922	2,266	23	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Pool}} + \beta3X_{\text{Stage}} + \beta4X_{\text{Pool}}X_{\text{Stage}}$	12,930	2,274	23	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Habitat}}$	13,641	2,985	4	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Stage}}$	13,777	3,121	3	0
$E(Y_{\text{Episod. Hab.}}) = \beta0 + \beta1X_{\text{Year}}$	13,778	3,122	3	0
$E(Y_{\text{Episod. Hab.}}) = 1$	17,023	6,367	2	0

Note: ΔAICc is the difference in AICc from the top-ranking model; k is the number of model parameters, and wt. is the assigned model weight for each model.

an interaction between pool and habitat type, (6) an additive effect of year, pool, and habitat type with an interaction between year and pool, (7) an additive effect of year, pool, and habitat type with an interaction between year and habitat type, (8) an additive effect of year, pool and habitat type with an interaction between year, pool and habitat type. Changes in the Arkansas River's stage at each pool may influence the distribution and availability of the permanent and episodic water among the different habitat types. As such, we included additional models in our candidate model set testing whether the area of permanent or episodic water along the length of the Arkansas River in Arkansas was a function of (1) the annual mean river stage or coefficient of variation of river stage for each pool and year, (2) the annual mean stage along the river, (3) an additive effect of pool, mean annual river stage or coefficient of variation of river stage, and habitat type with an interaction between annual mean stage or coefficient of variation of river stage and habitat type, and (4) an additive effect of annual mean river stage or coefficient of variation of river stage, pool and habitat type with an interaction between annual mean river stage or coefficient of variation of river stage, pool and habitat type. We used the coefficient of variation of daily river stage as a way to assess how variation in river stage influenced water surface area among habitat types. For example, years with greater variation in flow may result in greater off-main-channel habitat due to more opportunities for the main channel to interact with the floodplain. Alternatively, greater variation in river stage may promote greater erosion and deposition within the main channel and influence the prevalence of permanent or episodic water area. We obtained daily river-stage data from the US Corps of Engineers for each lock-and-dam complex from 1984 to 2015. We also included a null model into the candidate set by setting the predictor variable to a constant. In total, we assessed 15 models each for permanent and episodic water. Both pool and habitat type were treated as categorical variables, whereas year and river-stage data were treated as numerical variables.

3 Results

The surface area of permanent and episodic water varied through time for each habitat type among pools (**Figures 3 and 4**). Variation in the area of episodic water was greater than permanent water area

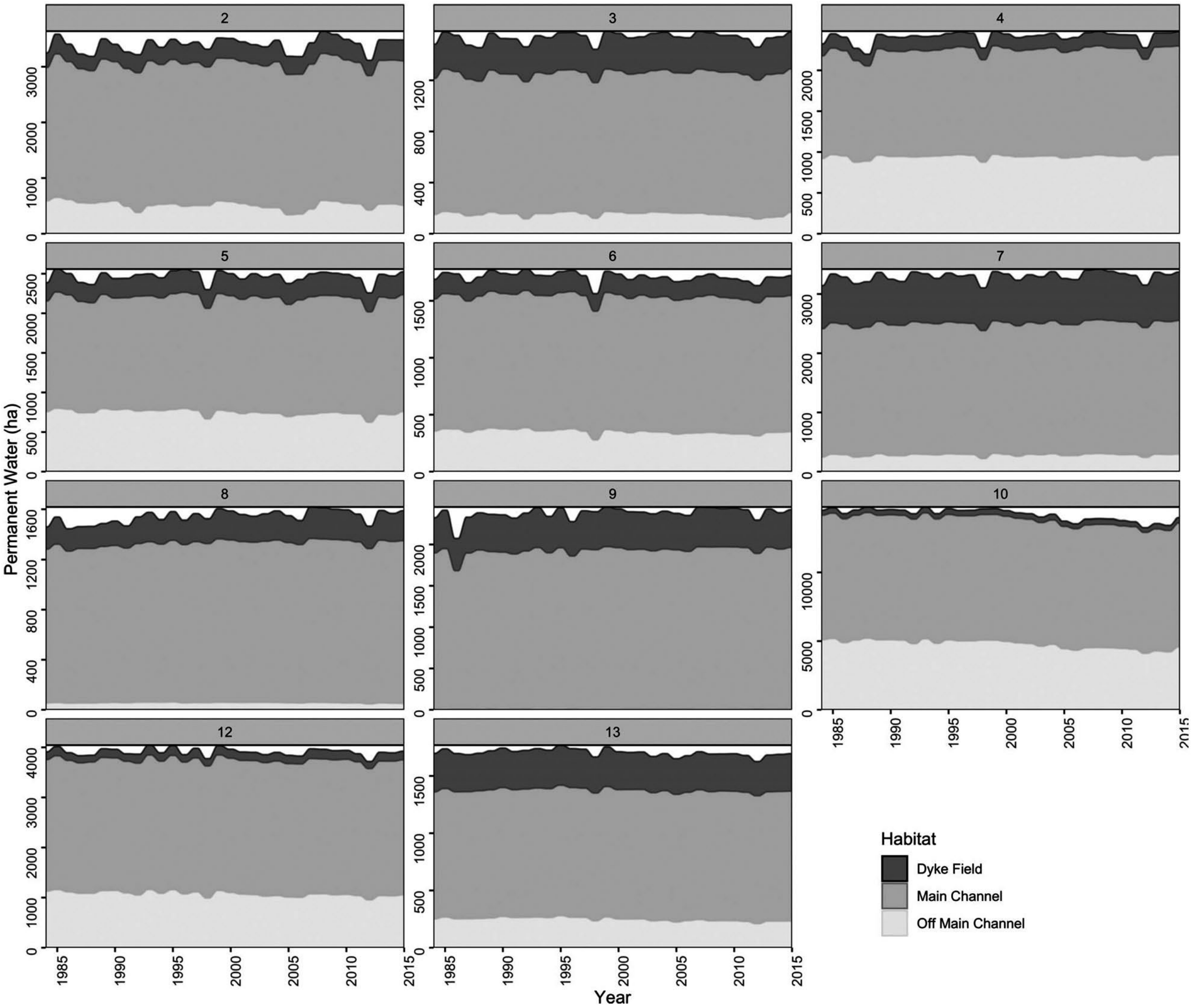

Figure 3 The temporal change (1984–2015) of permanent surface water among three habitat types along the Arkansas River, Arkansas, USA. Habitat types include: Dike Field (top of each plot), Main Channel (middle of each plot) and Off Main Channel (bottom of each plot). The plotted data are the estimated area (ha) of each habitat type derived from the European Commission Joint Research Center's (JRC) Global Surface Water dataset (GSW) using the 1984 to 2015 Landsat archive. Numbered panels refer to individual pools along the Arkansas River from farthest east (Pool 2) to farthest west (Pool 13) of the study area.

among all habitat types and pools (Figure 4). Variation in the area of permanent and episodic water may have resulted in part from variation in river stage (**Figure 5**). Changes in permanent- and episodic-water surface area along the Arkansas River suggested individual habitat types were undergoing different trajectories through time

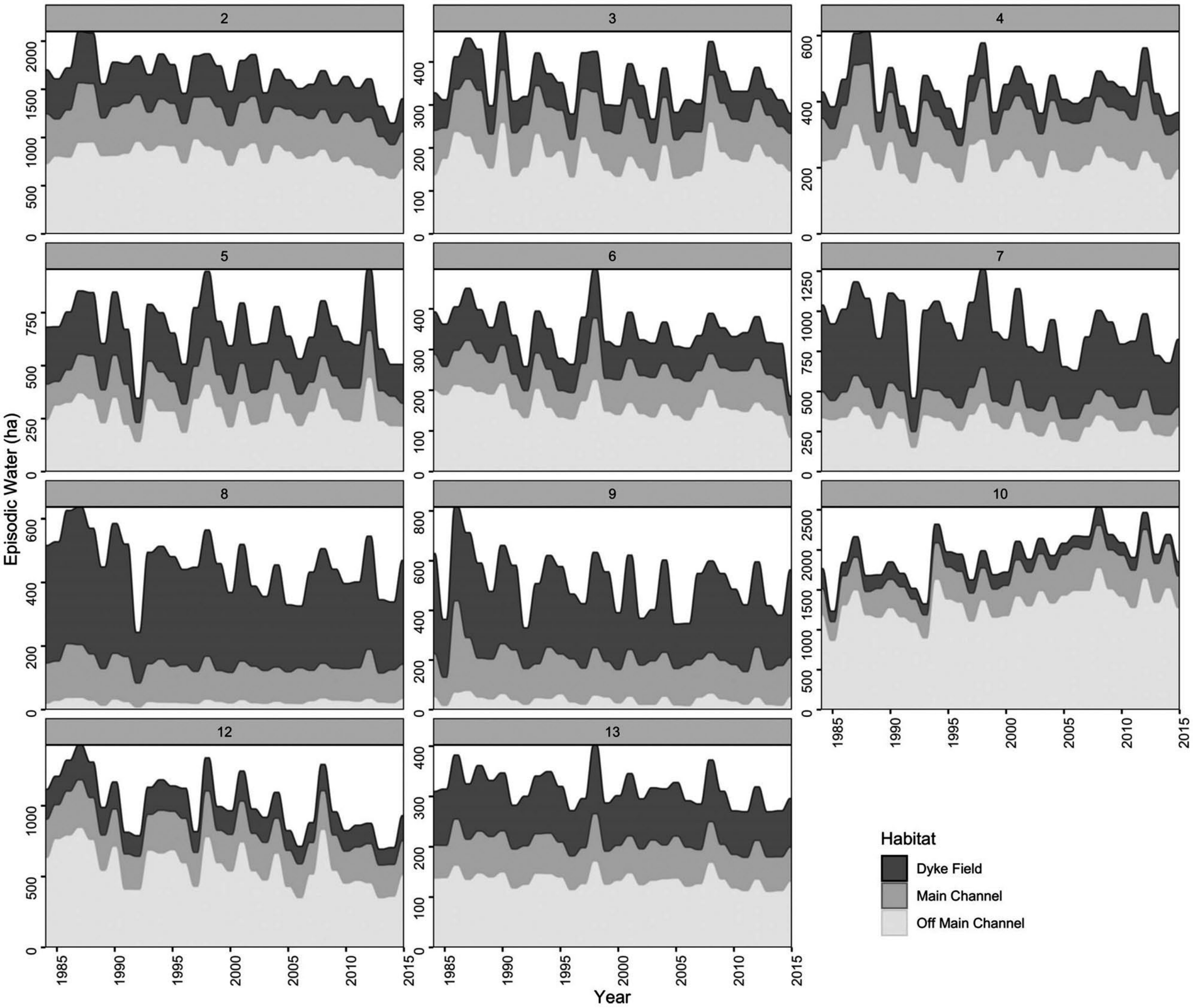

Figure 4 The temporal change (1984–2015) of episodic surface water among three habitat types along the Arkansas River, Arkansas, USA. Habitat types include: Dike Field (top of each plot), Main Channel (middle of each plot) and Off Main Channel (bottom of each plot). The plotted data are the estimated area (ha) of each habitat type derived from the European Commission Joint Research Center's (JRC) Global Surface Water dataset (GSW) using the 1984 to 2015 Landsat archive. Numbered panels refer to individual pools along the Arkansas River from farthest east (Pool 2) to farthest west (Pool 13) of the study area.

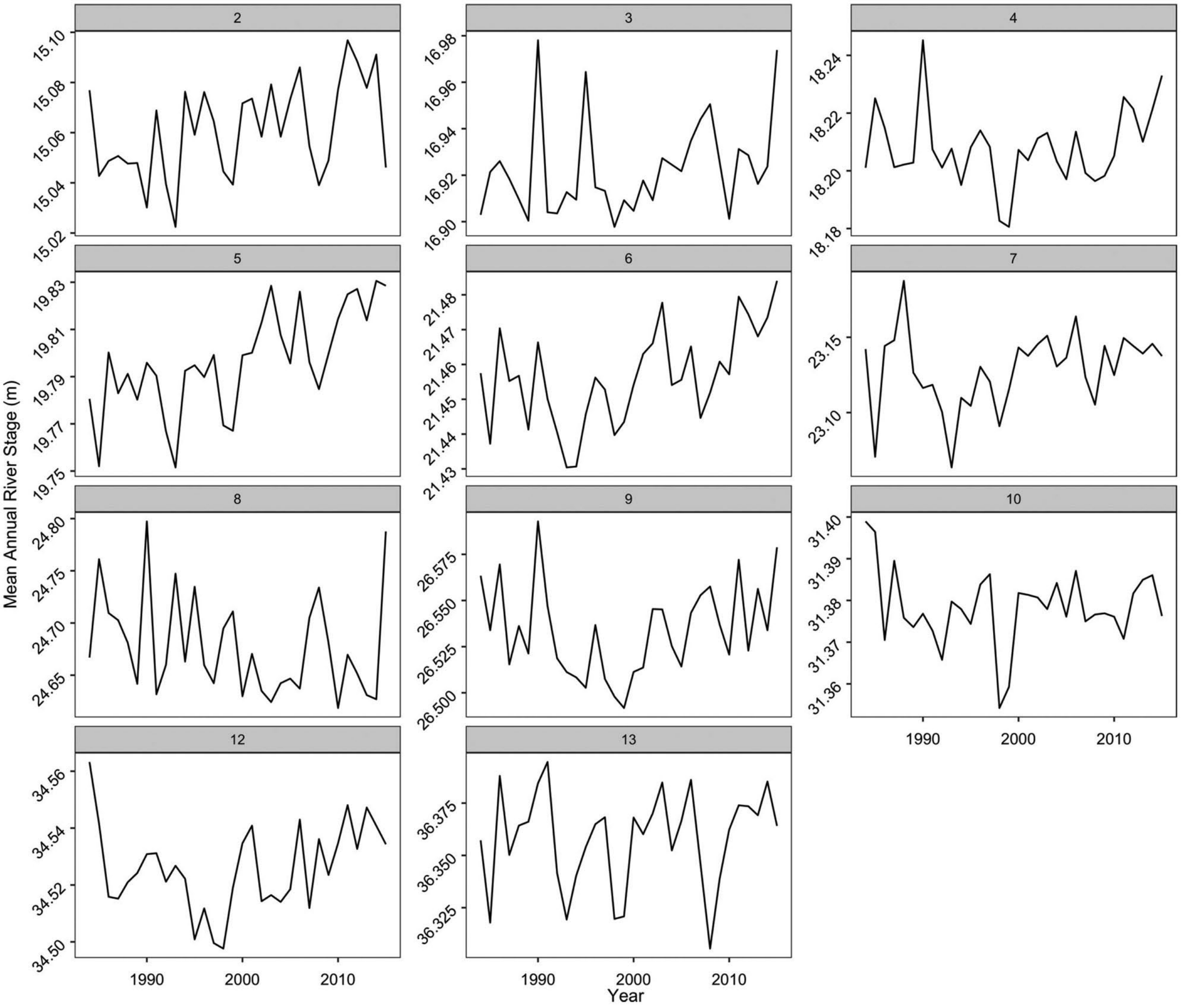

Figure 5 Annual mean river stage at each lock-and-dam included in this study along the Arkansas River between 1984 and 2015. Numbered panels refer to individual pools along the Arkansas River from farthest east (Pool 2) to farthest west (Pool 13) of the study area

and among pools given the interaction among year, pool and habitat type was in the most supported model (i.e. lowest AICc) among our candidate models (Table 1). The most supported model for changes to permanent-water surface area among habitats along the Arkansas River had a null deviance of 1,525 on 1,055 degrees of freedom and a residual deviance of 4.08 on 990 degrees of freedom suggesting the model fit the data. The most supported model for changes to episodic water surface area among habitats along the Arkansas River had a null deviance of 762.79 on 1,055 degrees of freedom and a residual deviance of 39.23 on 990 degrees of freedom suggesting the model fit the data. Models containing annual mean river stage or coefficient of variation in river stage were not well supported given the combination of low model weight and a difference of AICc of over 100 (Burnham & Anderson, 2002; Table 1), suggesting changes in river stage across years did not explain long-term increases or decreases in habitat area as well as models with year as a covariate. Systemic changes to river stage were not evident during the study period (GLM, model structure = river stage ~ year; *t*-value = 0.010, *p*-value = .992; Figure 5). However, Pool 5 did experience a minor increase in river stage that was significant (GLM, model structure = river stage ~ year*pool; *t*-value = 2.74, *p*-value = .007; range of observed annual mean river stage = 0.27 m; Figure 5). Hydrologic variation within and among years undoubtedly has a role in changes to abundance of surface water and available habitat. As such, changes in river stage data collected at each lock-and-dam complex may not fully represent the complex interaction between changing hydrologic conditions and water surface area at the pool spatial scale. The hydrologic data does suggest that systemic increases or decreases in river stage were not occurring across pools and likely did not result in the changes in habitat area observed over the course of the study. The Arkansas River from Pool 2 to the Oklahoma border (i.e. Pool 13) lost an average of 2.1% of permanent water and an average of 12.1% of episodic water area from 1984 to 2015 (**Tables 2 and 3**). The main channel habitat gained 1.2% in permanent water overall, with only Pool 10 (i.e. Lake Dardanelle) losing main channel habitat (2.5%). Dike fields gained permanent water overall (4.4%). Conversely, most pools lost considerable permanent off-main-channel habitat (13.1% overall), with 8 of 11 pools losing at least 10% of permanent water area in off-main-channel habitat. Areas of pixels that demonstrated within-year variability regarding the presence or absence of water (i.e. episodic water surface area) declined among all habitat types (main channel: 1.2%, dike field: 26.3%, off main channel: 8.5%). Episodic water in the main channel declined in 8 of 11 pools, although Pool 10 added 43.1% more episodically inundated

Table 2 Model predicted area (ha) of permanent water among habitat types and pools from 1984 to 2015

River Pool	*Habitat type*	*1984 predicted (SE)*	*2015 predicted (SE)*	*Change (%)*
2	Main channel	2,486 (53)	2,595 (55)	4
2	Dike field	310 (7)	374 (8)	17
2	Off main channel	557 (12)	479 (10)	−16
3	Main channel	1,083 (23)	1,120 (24	) 3
3	Dike field	279 (6)	289 (6)	3
3	Off main channel	161 (3)	144 (3)	−12
4	Main channel	1,273 (27)	1,330 (28)	4
4	Dike field	168 (4)	170 (4)	2
4	Off main channel	932 (20)	950 (20)	2
5	Main channel	1,424 (30)	1,473 (32	) 3
5	Dike field	258 (5)	283 (6)	9
5	Off main channel	784 (17)	710 (15)	−10
6	Main channel	1,182 (25)	1,192 (26)	1
6	Dike field	180 (4)	169 (4)	−6
6	Off main channel	371 (8)	330 (7)	−12
7	Main channel	2,198 (47)	2,250 (48)	2
7	Dike field	785 (17)	810 (17)	3
7	Off main channel	272 (6)	287 (6)	5
8	Main channel	1,245 (27)	1,306 (28)	5
8	Dike field	189 (4)	237 (5)	20
8	Off main channel	57 (1)	54 (1)	−6
9	Main channel	1,866 (40)	1,954 (42)	4
9	Dike field	443 (9)	457 (10)	3
9	Off main channel	20 (0.40)	16 (0.40)	−20
10	Main channel	9,134 (195)	8,914 (191)	−2
10	Dike field	399 (9)	390 (8)	−2
10	Off main channel	5,267 (113)	4,322 (92)	−22
12	Main channel	2,636 (56)	2,694 (58)	2
12	Dike field	166 (4)	176 (4)	6
12	Off main channel	1,131 (24)	1,018 (22)	−11
13	Main channel	1,119 (24)	1,133 (24)	1
13	Dike field	342 (7)	319 (7)	−7
13	Off main channel	269 (6)	227 (5)	−18

area. Episodic water declines among dike fields were at least 10.6% (Pool 4) and as great as 57.4% (Pool 12). In the off-main-channel habitat, 9 of 11 pools lost episodic water area, with the greatest loss in Pool 12 (61.1%). Pool 10 added 23.6% episodically inundated area in off-main-channel habitat.

Table 3 Model predicted area (ha) of episodic water among habitat types and pools from 1984 to 2015

River Pool	*Habitat type*	*1984 predicted (ha)*	*2015 predicted (ha)*	*Change (%)*
2	Main channel	504 (34)	403 (27)	−25
2	Dike field	468 (31)	324 (22)	−44
2	Off main channel	915 (61)	731 (49)	−25
3	Main channel	110 (7)	98 (7	) −13
3	Dike field	82 (5)	63 (4)	−31
3	Off main channel	187 (12)	168 (11)	−12
4	Main channel	140 (9)	159 (10)	7
4	Dike field	76 (5)	69 (5)	−11
4	Off main channel	241 (16)	206 (14)	−17
5	Main channel	167 (11)	152 (10)	−10
5	Dike field	275 (18)	204 (14)	−35
5	Off main channel	297 (20)	275 (18)	−8
6	Main channel	87 (6)	93 (6)	7
6	Dike field	106 (7)	82 (5)	−29
6	Off main channel	197 (13)	136 (9)	−45
7	Main channel	162 (11)	146 (10)	−11
7	Dike field	530 (35)	386 (26)	−37
7	Off main channel	346 (23)	257 (17)	−35
8	Main channel	136 (9)	100 (7)	−36
8	Dike field	379 (25)	261 (17)	−45
8	Off main channel	25 (2)	27 (2)	7
9	Main channel	193 (13)	149 (10)	−29
9	Dike field	342 (23)	275 (18)	−24
9	Off main channel	51 (3)	33 (2)	−55
10	Main channel	311 (21)	548 (37)	43
10	Dike field	202 (13)	161 (11)	−25
10	Off main channel	1,159 (77)	1,517 (101)	24
12	Main channel	286 (19)	239 (16)	−19
12	Dike field	221 (15)	140 (9)	−57
12	Off main channel	729 (49)	452 (30)	−61
13	Main channel	79 (5)	70 (5)	−12
13	Dike field	116 (8)	96 (6)	−21
13	Off main channel	145 (10)	125 (8)	−16

4 Discussion

The Arkansas River, within the study area, underwent nonrandom and directional changes in the spatial extent of surface water among habitat types from 1984 to 2015. Our results support evidence from Schramm Jr. et al. (2008) that habitat changes following channelization and impoundment may be particularly evident in the loss of off-channel habitats along the river. Additionally, permanent main-channel habitat increased across the river system except for Lake Dardanelle (i.e. Pool 10), where sedimentation likely resulted in a decline in permanent water in the main channel and a subsequent increase in episodic water in the main channel (Foster & Franco, 1977). Lake Dardanelle was constructed, in part, to be a sediment trap (Foster & Franco, 1977), and our model results are consistent with accumulation of sediment in the reservoir. The changes in aquatic habitat among pools are consistent with changes in the geomorphic character of anthropogenically altered river segments where main-channel habitats can become the dominant habitat and off-channel habitats decline (Hohensinner et al., 2004; Jacobson & Galat, 2006). Concentrated discharges in the main channel limit lateral channel migration and increase scouring to maintain the navigation channel, with a net loss of off-channel areas including backwaters (Gore & Shields Jr., 1995; Jacobson & Galat, 2006). Additionally, dredging operations redistribute sediments away from the main channel preventing sandbar establishment and maintaining permanent water conditions. The increased permanence of main-channel water and the separation of off-main-channel areas (from channelization) have reduced the amount of episodic surface water across the river – excluding Lake Dardanelle. Changes in river stage among years may still impose variation in episodic water as indicated by the GSW model. Despite variation in episodic water area, our models suggest an overall decline in episodic water area. River productivity models often cite the importance of aquatic-terrestrial transition zones and episodically inundated areas necessary for energy production and lifecycle completion for multiple species (Humphries, Keckeis, & Finlayson, 2014; Tracy-Smith, Galat, & Jacobson, 2012). The loss of episodic surface water across the Arkansas River may be a driver in changing system processes including productivity and population demographics of species dependent on episodic water availability. This phenomenon warrants further investigation.

Collectively, model results suggested that decadal-scale changes in habitat area that are primarily unidirectional (e.g. loss of permanent off-main-channel habitat and episodic main-channel habitat) along the Arkansas River may indicate an underlying ramp-type disturbance.

Such a disturbance is occurring independent of annual hydrologic cycles including flooding (i.e. pulse disturbances) that result in short-term (i.e. weeks to months) changes in surface water coverage along the system. Despite variation in water stages, the Arkansas River continued to undergo a long-term change in fluvial geomorphic character following channelization and impoundment. Our data indicate the river no longer functions as a natural lowland river in a state of dynamic equilibrium (i.e. creation and disappearance of habitats being relatively equal; Arscott et al., 2002; Stanford et al., 2005). Instead, the channel's constraints maintain the position and depth of the channel at the expense of habitats both within (e.g. loss of episodic habitat in the main channel) and outside (loss of off-main-channel habitat) of the river modifying structures. Habitat availability in the main-channel and off-channel habitats is changing and may influence the ecological function of the Arkansas River in its current form. The role of hydrologic changes influencing the spatial and temporal dynamics of habitat patches warrants further exploration as stage data collected at each lock-and-dam structure alone may not fully explain such variation. Additionally, our model results may underestimate the prevalence of local patches of habitat smaller than a 30 × 30 m pixel.

Lowland rivers in unaltered states usually contain abundant off-channel habitats, such as secondary channels, wetlands and remote backwaters (Arscott et al., 2002; Stanford et al., 2005) which are essential to many native aquatic species (Jenkins & Boulton, 2003; Lyon et al., 2010). Off-channel habitats are connected to the main channel with varying frequency but are characterized by reduced current velocity and depth and greater production of autochthonous energy sources (Eckblad, Peterson, Ostlie, & Temte, 1974; Humphries et al., 2014). Many species that depend on lentic conditions to complete their life history use permanent backwaters (e.g. Slipke & Maceina, 2007; Winemiller, 1997). Further, seasonally inundated habitats are important in the recruitment and growth of multiple aquatic taxa (Jeffres, Opperman, & Moyle, 2008; Jenkins & Boulton, 2003; Sammons, Bettoli, Iserman, & Churchill, 2002). The decline of backwater habitats in the Arkansas River may be of concern for both conservation and management of numerous aquatic taxa. For instance, multiple fish species use connected backwaters (Slipke, Sammons, & Maceina, 2005), including species of conservation concern like alligator gar (*Atractosteus* *spatula*; DiBenedetto, 2009) and juvenile Arkansas River shiner (*Notropis girardi*; Polivka, 1999). Backwater habitats, thus, increase complexity and productivity and lead to greater species richness and biomass (Andrews, Miranda, & Kroger, 2015; Petry, Bayley, & Markle, 2003). Previous research in the Arkansas River found that contiguous backwaters (i.e. permanently connected to the river channel), intermittent wetlands (i.e. periodic connectivity to the river channel) and isolated wetlands (i.e. no longer connected to the river channel) contained distinct fish assemblages (Adams, Williams, Schrodner, & Clark, 2007). Thus, it can be inferred that as backwaters continue to become fewer and more disconnected, community dynamics and possibly biodiversity of the system may further change. It is noted, however, that lentic habitat was greatly expanded in impounded reaches of the Arkansas River following completion of the MKARNS. It remains unclear that the main-channel lentic habitats serve similar ecological roles as lentic habitat available in the off-channel areas. Off-channel areas may possess unique habitat characteristics (e.g. established vegetation and wood structure) for completion of life stages by some fishes. Further, lentic habitat in the main channel may impede specific life stage needs of some fluvial-dependent fishes that do not use backwater or off-channel habitats (Galat & Zweimüller, 2001).

The Arkansas River underwent an extensive geomorphic transition following channelization and impoundment, whereby the channel was largely constrained. Subsequent to channelization, geomorphic changes continue in which backwaters in off-main-channel habitats and episodic water in main-channel habitats are decreasing in area throughout the river. As such, the system is not shifting habitats longitudinally and laterally as seen in functioning lowland river systems (Stanford et al., 2005). Furthermore, the Arkansas River no longer has the capacity to reorganize sediments outside of the main channel. Periods of flooding may work to inundate some of the off-channel habitats episodically. However, the transition to greater habitat homogeneity likely continues as permanent off-main-channel habitats are lost along the river.

Identification of alternative management activities may work to remediate the homogenization of habitats and facilitate increased habitat heterogeneity along the Arkansas River. Dike notching may promote the reestablishment of episodic habitat within the channel boundaries where sedimentation decreases dike-field habitat (Shields Jr., 1995). The construction of side channels may reconnect backwater areas, increase water permanence and subsequently support species diversity (Tockner et al., 1999). Furthermore, Lake Dardanelle (Pool 10) is the third largest reservoir in Arkansas and the largest reservoir on MKARNS within Arkansas. This pool is the most lentic of the 11 pools, and it has lost nearly 22% of its backwaters over the past two decades. Managers will need to understand how this loss of habitat will influence ecological processes (river productivity and population dynamics) and determine if remedial activities, such as dredging, are an option (Machesky et al., 2005). The use of remote sensing data and databases such as the GSW may provide resource managers a tool to assess habitat changes along rivers that inform biotic responses observed in ecological monitoring activities.

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Data Availability Data and code that were used in this study are available from the authors upon request and are available on the institutional repository at Mississippi State University. The data and code are available at https://hdl.handle.net/11668/16497 and https://hdl.handle.net/11668/20915 . The data sources are also available from Global Surface Water Explorer (https://global-surface-water.appspot.com/).

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